

## Geotechnical and geomechanical characteristics of the rocks along tunnel of Kulekhani III Hydro-electric Project

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### ABSTRACT

Geotechnical and geomechanical properties are important to understand tunnel behaviour and they differ according to rock types. Therefore, tunnel passing through different rock types is selected for the present study. The tunnel alignment of Kulekhani III hydroelectric project crosses five stratigraphic formations which comprise eight lithological units.

The rocks of the area have most dominantly three sets of joints in which the foliation plane is prominent. In geotechnical study of intact rock, seven geotechnical properties - viz unit weight ( $\gamma$ ), uniaxial compressive strength ( $\sigma_{ci}$ ), tensile strength ( $\sigma_{ti}$ ), young's modulus ( $E_i$ ), poisson's ratio ( $\nu$ ), friction angle ( $c_i$ ) and cohesion ( $\phi_i$ ) were measured in lab and on the basis of the intact rock properties five geotechnical properties - uniaxial compressive strength ( $\sigma_{cm}$ ), tensile strength ( $\sigma_{tm}$ ), young's modulus ( $E_m$ ), friction angle ( $c_m$ ) and cohesion ( $\phi_m$ ) of rock mass were determined.

RMR, Q and GSI were used for geomechanical classification and the distributions of the geomechanical class values were studied. The relationship between UCS of rock mass and geomechanical classifications RMR and Q were studied for all rock types. Quite similar results were observed with both RMR and Q systems. The trend of correlations of each rock type with both classification systems follows almost analogous order. Power type continuous equation is observed for Q and exponential type relation is obtained for RMR. The general trend of correlation of UCS rock mass with RMR and Q is calculated which has  $R^2$  more than 0.9. The observed relations were compared with empirical relations proposed by other researchers and the results of the present study lie between the upper and lower boundaries set by other researchers. Among them, harder rocks have better correlation than softer rocks. It is also observed that higher the poisson's ratio of the rock shown higher the order of linear correlation of rock mass properties with its geomechanical properties.

**Keywords:** Intact rock, rock mass, RMR, GSI, Q.

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### INTRODUCTION

Geotechnical and geomechanical properties of rocks play key role to understand present and time dependent behavior of tunnel. For design and construction of rock tunnel structures including support installation and for safe excavation and satisfactory performance require highly reliable rock mass properties (Hoek and Brown 1980a, Hoek and Diederichs 2006). Therefore, understanding of the geomechanical properties of rock mass is important along tunnel alignment for tunnel construction and safety.

Intact rock strength varies widely within same rock type because the strength is widely affected by the rock weathering, that is depends on different mineralogical contents, and other intact rock properties also diverges on the basis of weathering. Therefore, direct measurement was carried out to know the required properties of selected samples. It is a common practice to test the intact rock specimens in laboratory for determining different mechanical and strength properties.

Rock mass characteristics are very complex due to existence of discontinuities and rock mass properties are controlled by different properties - continuity, orientation and frequency of the discontinuities and discontinuities

characteristics. Properties of rock mass are calculated using intact rock parameters and other index parameters of rock mass. A commercially available computer program, Roclab (Rocscience Ltd. 2011) is used for evaluation of rock mass parameters using intact rock parameters and other index values. These rock mass properties include both mechanical properties i.e. rock mass strength, deformation modulus and tensile strength and strength parameters i.e. cohesion and friction angle (Hoek and Brown 1980 b). For the purpose, different empirical relationships were developed by several researchers. Among them, the Rock Mass Rating (RMR) (Bieniawski 1973), the Tunnelling Quality Index (Q) (Barton et al. 1974) and the Geological Strength Index (GSI) (Hoek and Brown 1997) are in common practice and are, here, also used for estimating rock mass properties.

Tunnel passing through different rock types was selected for the study. For the purpose under construction tunnel of Kulekhani III Hydroelectric Project situated at Makwanpur district near Hetauda is selected. The tunnel alignment crosses eight lithological units. The study focuses on to figure out the geotechnical and geomechanical characteristics of the different lithological units of the tunnel.

### GEOLOGY ALONG TUNNEL ALIGNMENT

The tunnel alignment lies partly in the Lesser Himalaya Zone and partly in the Higher Himalaya Zone of the Nepal Himalaya of the Kathmandu Complex and Nawakot Complex of Central Nepal (Table 1 and Fig. 1). The stratigraphic units are Bhainsedovan Marble, Raduwa Formation, Robang

Formation, Malekhu Limestone and Benighat Slates (Table 1 and Fig. 1). The tunnel crosses soft rocks of the Benighat Slates to massive and strong Dunga Quartzite. The topography and rock type along the tunnel alignment is shown in Fig. 1. The rock types found in different stratigraphic units covered by study area and their thicknesses are given in Table 1.

**Table 1: Stratigraphy of the study area (modified after Stöcklin 1980).**

Complex	Group	Unit	Lithology	Thickness (m)	Age
Kathmandu Complex	Bhimphedi Group	Markhu Formation	Marble, Schist	1000	Late Precambrian
		Khulekhani Formation	Quartzite, Schist	2000	Precambrian
		Chisapani Quartzite	Quartzite	400	Precambrian
		Kalitar Formation	Schist, Quartzite	400	Precambrian
		Bhainsedhovan Marble	Marble	800	Precambrian
		Raduwa Formation	Garnetiferous Schist, Quartzite	1000	Precambrian
-----Mahabharat Thrust (MT) -----					
Nawakot Complex	Upper Nawakot Group	Robang Formation	Phyllite, Quartzite	200-1000	Paleozoic
		Malekhu Limestone	Dolomite	800	Paleozoic
		Benighat Slates	Slate	500-3000(?)	Paleozoic

### ROCK MASS STRENGTH PARAMETERS

Generalised Hoek-Brown criterion coupled with Geological Strength Index (GSI) of rock has become one of the industry standards for estimating rock mass properties on international tunneling projects. The rock mass strength measuring parameters were estimated based on the generalised Hoek-Brown criterion. The rock mass strength properties given in Table 2 are estimated based on following equations.

Generalised form of the non-linear Hoek-Brown Failure criterion is (Hoek 1994, Hoek et al. 2002).

$$\sigma'_1 = \sigma'_3 + \sigma_{ci} \left( m_b \frac{\sigma'_3}{\sigma_{ci}} + s \right)^a \quad (1)$$

Where  $\sigma'_1$  and  $\sigma'_3$  are the major and minor effective principal stresses at failure,  $\sigma_{ci}$  is the uniaxial compressive strength (UCS) of the intact rock. The value of  $m_b$  is given by:

$$m_b = m_i e^{\frac{GSI-100}{28-14D}} \quad (2)$$

Material constant  $m_i$  mainly depends upon rock type, its texture and composition (Hoek and Brown 1980a).  $D$  is Disturbance Factor ( $D$ ) which depends upon the degree of disturbance during construction to which the rock mass has

been subjected by blast damage and stress relaxation.  $s$  and  $a$  are fixed constants for rock mass, which can be calculated by using following equations 3 and 4.

$$s = e^{\frac{GSI-100}{9-3D}} \quad (3)$$

$$a = \frac{1}{2} + \frac{1}{6} \left( e^{\frac{-GSI}{15}} + e^{\frac{-20}{3}} \right) \quad (4)$$

The uniaxial compressive strength (UCS) of rock mass ( $\sigma_{cm}$ ) is obtained by setting  $\sigma'_3 = 0$  in equation 1, that is

$$\sigma_{cm} = \sigma_{ci} \cdot s^a \quad (5)$$

Similarly, by putting  $\sigma'_3 = \sigma'_3 = \sigma_{tm}$  in equation 1, the uniaxial tensile strength of rock mass ( $\sigma_{tm}$ ) is given by equation 6.

$$\sigma_{tm} = \left( - \right) \frac{s \sigma_{ci}}{m_b} \quad (6)$$

Rock mass modulus of deformation ( $E_m$ ) is calculated (in GPa) by using equations 7 and 8. Equation 7 applies for  $\sigma_{ci} \geq 100$  MPa and for  $\sigma_{ci} > 100$  MPa, equation 8 is applied.

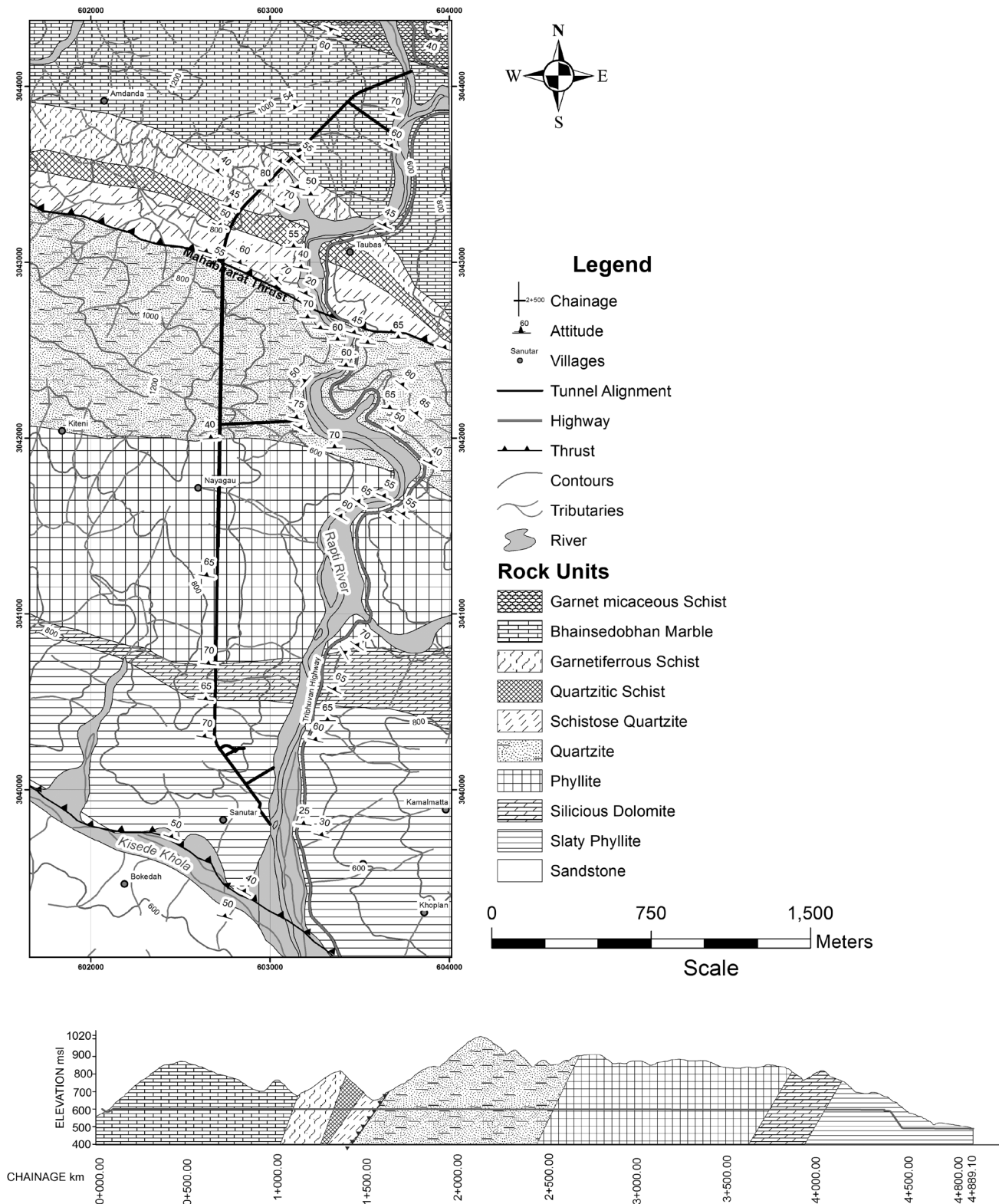


Fig. 1: Geological map of the study area and L-section of the tunnel alignment.

$$E_m = \left(1 - \frac{D}{2}\right) \sqrt{\frac{\sigma_{ci}}{100}} \cdot 10^{\left(\frac{GSI-10}{40}\right)} \quad (7)$$

$$E_m = \left(1 - \frac{D}{2}\right) 10^{\left(\frac{GSI-10}{40}\right)} \quad (8)$$

The modified equation for determining the modulus of deformation of rock mass (in GPa) after Hoek and Diederichs (2006) is given as equation 9.

$$E_m = E_i \left[ 0.02 + \frac{1-D/2}{1+e^{\left(\frac{60+15D-GSI}{11}\right)}} \right] \quad (9)$$

Cohesion and internal friction angle of the rock mass parameters have been considered widely in rock mechanics to solve geotechnical problems. Mohr-Coulomb Criterion in rocks involves determining equivalent angle of friction ( $\phi'$ ) and cohesive strengths ( $c'$ ) for each rock mass and stress range, which can be used for analysis of failures in tunnels and slopes and Hoek 1990, Hoek et al. 1992). Mohr-Coulomb theory is used to predict for linear response of rocks where Hoek-Brown criteria is applied for non-linear response. Therefore, it is required to establish relationships that are equivalent between the Hoek-Brown and Mohr-Coulomb criteria. This is done by fitting an average linear relationship to the curve generated by equation 1. The fitting process involves balancing the areas above and below the Mohr-Coulomb plot and friction ( $\phi'$ ) and cohesive strengths ( $c'$ ) can be obtain by using equations 10 and 11.

$$\phi' = \sin^{-1} \left[ \frac{6am_b(s+m_b\sigma'_3)^{a-1}}{2(1+a)(2+a)(s+m_b\sigma'_3)^{a-1}} \right] \quad (10)$$

$$c' = \sigma_{ci} \left[ \frac{[(1+2a)s+(1-a)m_b\sigma'_3](s+m_b\sigma'_3)^{a-1}}{(1+a)(2+a)\sqrt{6am_b(s+m_b\sigma'_3)^{a-1}/(1+a)(2+a)}} \right] \quad (11)$$

**Table 2: Geotechnical properties of intact rock.**

Stratigraphy	Lithology		$\sigma_{ci}$ (MPa)	$\sigma_{ti}$ (MPa)	$E_i$ (GPa)	$\gamma$ (kN/m <sup>2</sup> )	$\nu$	$c_i$ (MPa)	$\phi_i$
Bhainsedobhan Marble	Marble	Mean(8)	122	11.7	26	26.81	0.18	42	37
		Range	109-138	9.2-12.5	13-38	-	-	-	-
Raduwa Formation	Garnetiferous schist	Mean(6)	78	8.6	19	27.40	0.16	32	26
		Range	53-101	6.8-10.3	13-21	-	-	-	-
	Psammitic schist	Mean(8)	91	10.3	22	26.84	0.20	43	31
		Range	61-118	6.9-13.1	14-29	-	-	-	-
	Schistose quartzite	Mean(7)	109	13.8	29	27.13	0.17	38.5	38
		Range	78-124	9.8-14.6	19-34	-	-	-	-
Robang Formation	Quartzite	Mean(8)	190	23.2	33	27.32	0.17	60	41
		Range	173-232	21.5-27.1	21-52	-	-	-	-
	Phyllite	Mean(5)	82	10.4	9	26.82	0.26	27	26
		Range	77-94	9.8-11.7	7.2-12.7	-	-	-	-
Malekhu Limestone	Siliceous dolomite	Mean(7)	169	21.3	51	28.16	0.18	36	29
		Range	127-213	15.8-24.1	36-68	-	-	-	-
Benighat Slates	Slate	Mean(7)	93	6.4	1.5	26.84	0.23	31	28
		Range	76-110	5.3-7.8	0.6-1.8	-	-	-	-

## DISCONTINUITY GEOMETRY OF THE STUDY AREA

The area comprises three sets of joints and some have one extra random set (Fig. 2). Each rock units have one prominent and very good persistent joint that is foliation and rest of other are less prominent and persistent. Second set which is within  $\pm 40^\circ$  with strike of foliation is more frequently occurring set in almost all lithology except marble and quartzite. The general strike of the second set lies between  $120^\circ$  and  $140^\circ$  and dip is between  $45^\circ$  and  $80^\circ$ . In the marble and quartzite the distribution of joint sets, other than foliation, is more uneven than other rock units. Similarly, set whose strike lies between angle  $\pm 70^\circ$  and  $\pm 90^\circ$  with strike of foliation is third set. The general strike of the third set lies between  $345^\circ$  to  $20^\circ$  and dip  $50^\circ$  to  $75^\circ$ .

Discontinuities assortment of each rock type varies. The strike diversity of each set also varies within same rock unit. The strike of the discontinuity sets in slate, dolomite, schistose quartzite and marble were less diverse than other rock types. Similarly, frequency of observance of J1, J2 and J3 was in descending order for each rock unit. The discontinuity frequency and strike diversity pose variation in rock mass properties and rock mass class.

## GEOTECHNICAL PROPERTIES OF INTACT ROCK AND ROCK MASS

Rocks of the eight rock units with five formations were tested in laboratory and determined seven geo-technical properties, unit weight ( $\gamma$ ), uniaxial compressive strength ( $\sigma_{ci}$ ), tensile strength ( $\sigma_{ti}$ ), young's modulus ( $E_i$ ), poisson's ratio ( $\nu$ ), friction angle ( $c_i$ ) and cohesion ( $\phi_i$ ), of intact rocks from each rock units were determined. The measure properties results are given in Table 2. Similarly, uniaxial compressive strength ( $\sigma_{cm}$ ), tensile strength ( $\sigma_{tm}$ ), young's modulus ( $E_m$ ), friction angle angle ( $c_m$ ) and cohesion ( $\phi_m$ ) of rock mass were also calculated which are given in Table 3.

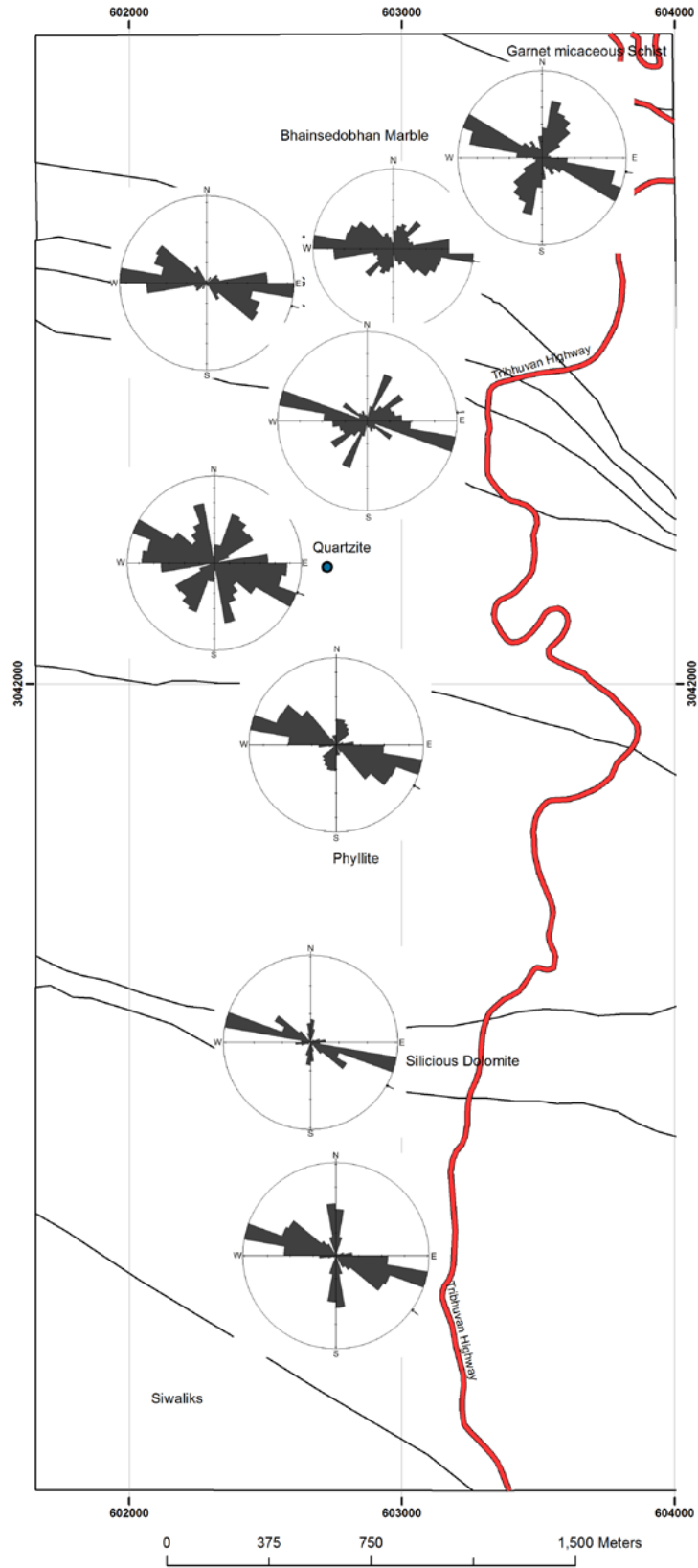


Fig. 2: Discontinuity orientation pattern of the rocks of the study area along tunnel alignment.



In intact properties, quartzite of the Robang Formation has highest average mean of UCS 190 MPa, tensile strength 23.2 MPa, young’s modulus 33 GPa, cohesion 60 MPa, and friction angle 41° and phyllite of the Robang Formation has lowest poisson’s ratio 0.26 where garnetiferous schist of the Raduwa Formation has lowest average mean of UCS 78 MPa,

the Benighat Slates has lowest average mean of tensile strength 6.4 MPa and young’s modulus 1.5 GPa and cohesion 31°, phyllite of the Robang Formation has lowest value of cohesion 26 MPa and garnetiferous schist of the Raduwa Formation and phyllite of the Robang Formation have lowest angle of friction 27°.

**Table 3: Geotechnical properties of rock mass.**

Stratigraphy	Lithology		$\sigma_{cm}$ (MPa)	$\sigma_{tm}$ (MPa)	$E_m$ (GPa)	$c_m$	$\phi_m$	$m_i$	GSI
Bhainsedobhan Marble	Marble	Mean	20	0.3	37.56	0.9	56	9	49
		Range	8-40	0.03-2.4	109-5	0.2-5.0	48-60		16-77
Raduwa Formation	Garnetiferous schist	Mean	12.8	0.09	37.2	0.7	48.5	12	38
		Range	5.3-22	0.01-0.15	0.6-85.92	0.3-1.3	40-52		13-57
	Psammitic schist	Mean	21	0.25	9.6	1.6	52	14	40
		Range	8-26	0.02-0.26	1.14-11.2	0.6-2.1	44-52		26-54
	Schistose quartzite	Mean	20	0.07	4.7	1.5	51	17	40
		Range	10.4-29	0.02-0.2	1.3-11.7	0.7-1.6	46-55		27-52
Robang Formation	Quartzite	Mean	33	0.07	3.5	1.5	53	20	34
		Range	18-53	0.02-0.21	0.8-13.2	0.9-3	45-53		16-47
	Phyllite	Mean	10.8	0.18	2	1.1	41	7	45
		Range	3.5-18.5	0.01-0.8	0.2-7.2	0.35-2.3	27-46		11-62
Malekhu Limestone	Siliceous dolomite	Mean	20	0.14	5.7	1.1	47	9	35
		Range	15-34	0.1-0.5	4-20	0.9-2.1	44-52		3-49
Benighat Slates	Slate	Mean	10.2	0.1	0.02	0.6	45	7	36.9
		Range	5.6-15.5	0.03-0.3	0.03-0.5	0.3-1.2	41-52		22.1-47.6

In rock mass properties, quartzite of Robang Formation has highest mean of UCS 33 MPa and Bhainsedovan Marble has highest average mean of tensile strength 0.3 MPa, young’s modulus 37.56 GPa, cohesion 0.9 MPa and friction angle 56° where the Benighat Slates has lowest mean value of UCS 0.3 MPa, young’s modulus 0.02 GPa, and cohesion 0.6 MPa, quartzite of Robang Formation has lowest average mean of tensile strength of 0.07 MPa and phyllite of Robang Formation has lowest value of friction angle 41°.

**Geo-mechanical classification of rock mass**

Empirical relations on the basis of classification schemes such as the Rock Mass Rating (RMR) of Bieniawski (1973), the Tunnelling Quality Index (Q) of Barton et al. (1974) and the Geological Strength Index (GSI) by Hoek and Brown (1997) were used to classify the rock mass of study area. The observed values of three classifications are plotted in graph (Fig. 3) and maximum, minimum and average values are given in tables 4, 5 and 6.

**Table 4: Geomechanical classification on the basis of Q.**

Lithology	Chainage		Q max	Q min	Average (AM)	SD	coefficient of variation (CV)
	From	To					
Marble	0+000	0+795.00	18.75	0.03	2.76	2.67	96.62%
Garnetiferous schist	0+795	1+029.73	2.50	0.05	1.05	0.69	65.49%
Psammatic schist	1+029.73	1+339.00	3.00	0.37	1.35	0.78	57.68%
Schistose quartzite	1+339.00	1+420.00	2.71	0.27	1.26	0.74	58.85%
Quartzite	1+420.00	2+476.00	6.25	0.10	1.48	1.06	71.69%
Phyllite	2+476.00	3+826.00	6.25	0.07	1.97	1.11	56.07%
Silicious dolomite	3+826.00	4+073.00	1.41	0.17	0.79	0.39	49.48%
Slate	4+073.00	+	1.50	0.17	0.92	0.47	50.91%

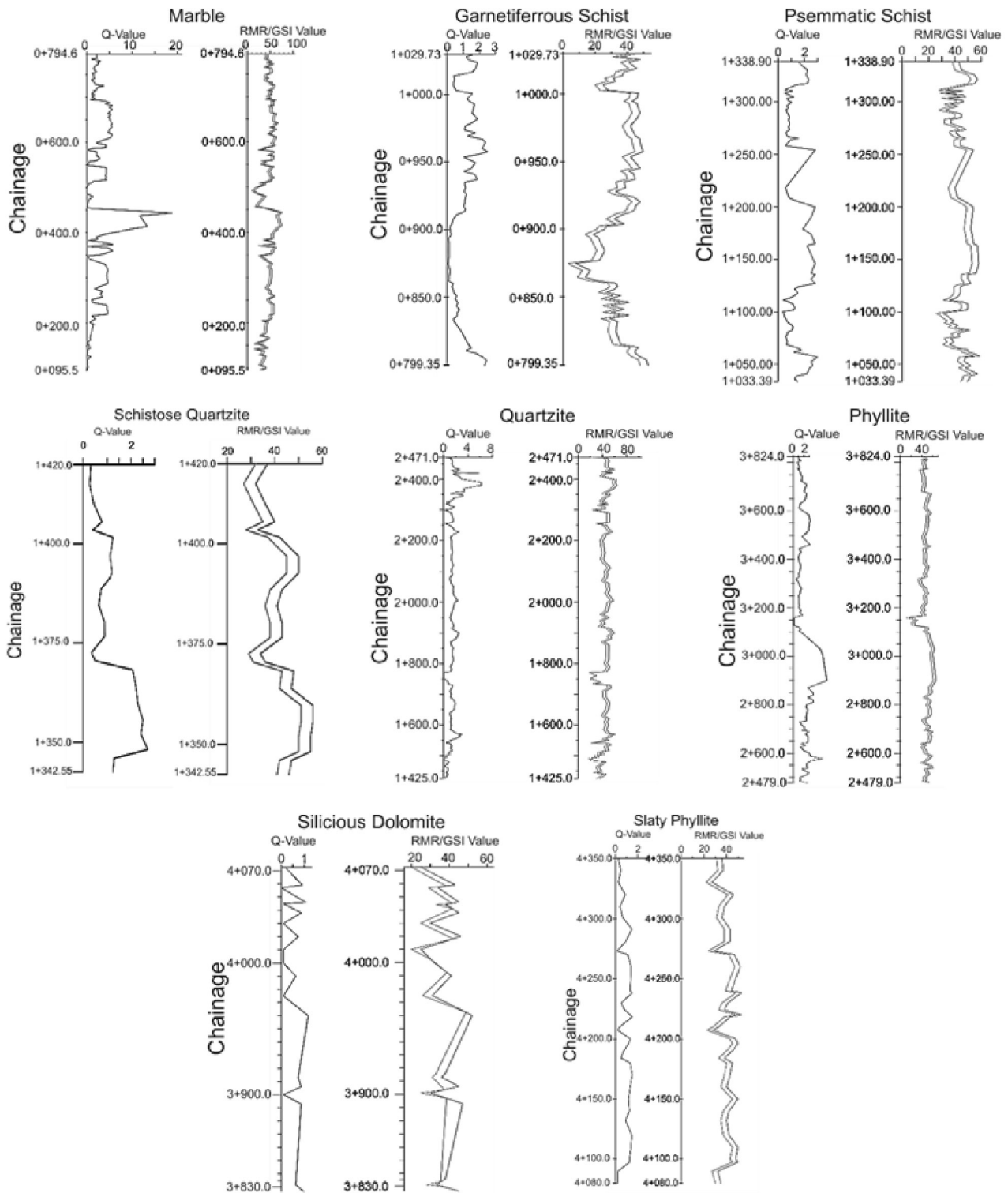


Fig. 3: Observed rock mass classification values in each rock units.

**Table 5: Geomechanical classification on the basis of RMR.**

Lithology	Chainage		RMR max	RMR min	Average(AM)	SD	coefficient of variation (CV)
	From	To					
Marble	0+000	0+795.00	76.4	15.4	48.8	11.31	23.18%
Garnetiferous schist	0+795	1+029.73	57.0	13.0	42.5	9.85	23.18%
Psammatic schist	1+029.73	1+339.00	58.8	31.1	45.1	6.47	14.33%
Schistose quartzite	1+339.00	1+420.00	56.5	32.2	44.3	7.37	16.66%
Quartzite	1+420.00	2+476.00	51.3	20.3	38.8	7.81	20.11%
Phyllite	2+476.00	3+826.00	66.5	15.6	48.5	7.23	14.59%
Silicious dolomite	3+826.00	4+073.00	54.1	27.4	40.2	7.47	18.58%
Slate	4+073.00	+	52.6	27.1	41.9	6.96	16.64%

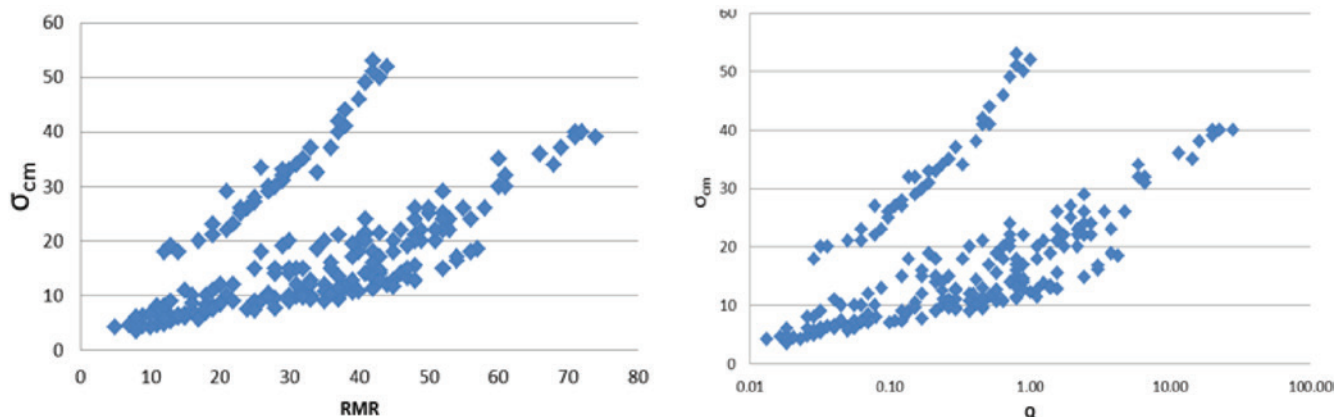
**Table 6: Geomechanical classification on the basis of GSI.**

Lithology	Chainage		GSI max	GSI min	Average(AM)	SD	coefficient of variation (CV)
	From	To					
Marble	0+000	0+795.00	72	11	43.8	11.3	0.258
Garnetiferous schist	0+795	1+029.73	52	8	37.5	9.85	0.26
Psammatic schist	1+029.73	1+339.00	54	26	40.1	6.46	0.16
Schistose quartzite	1+339.00	1+420.00	52	28	39.3	7.37	0.18
Quartzite	1+420.00	2+476.00	46	16	33.8	7.8	0.23
Phyllite	2+476.00	3+826.00	62	11	44.5	7.22	0.16
Silicious dolomite	3+826.00	4+073.00	49	23	35.2	7.47	0.21
Slate	4+073.00	+	48	22	36.9	6.96	0.18

The Bhaisedhovan Marble has highest average mean of RMR 48.8 and dolomite of the Malekhu Limestone has lowest average mean of RMR 41.9. The Bhaisedhovan Marble has highest average mean of Q 2.76 and dolomite of the Malekhu Limestone has lowest average mean of Q 0.79. Similarly, phyllite of the Robang Formation has highest GSI 46 and dolomite of the Malekhu Limestone has lowest average mean of GSI 35.

**UCS OF ROCK MASS AND GEOMECHANICAL CLASSES**

Rock mass properties of the rocks are calculated almost in equal, in 25±5m, interval along the tunnel. The calculated UCS of rock mass is compared with geomechanical classification in each point which also shows the representation train of other parameters. Here, relationship between  $\sigma_{cm}$  and rock mass classes were tried to find out, therefore graph of UCS of rock mass with RMR and Q were plotted. The observed results are shown in Fig. 4.



**Fig. 4: Relation between rock mass UCS with RMR and Q.**



In both graphs distribution of relations shows almost similar pattern but indistinct trends. From the distribution pattern it can be clearly say that as UCS of rock mass increases as rock class value increases in some extent. The indistinct trend may be because the plots are mixture of all rock types. Therefore, the plot is segregated according to rock type to

understand the distribution relation. For each rock type, relationship of  $\sigma_{cm}$  with rock mass classes offered very good trends which are given in Fig. 5 that shows the relation between rock mass UCS and RMR and Fig. 6 shows the relationship between rock mass UCS and Q for different rock types.

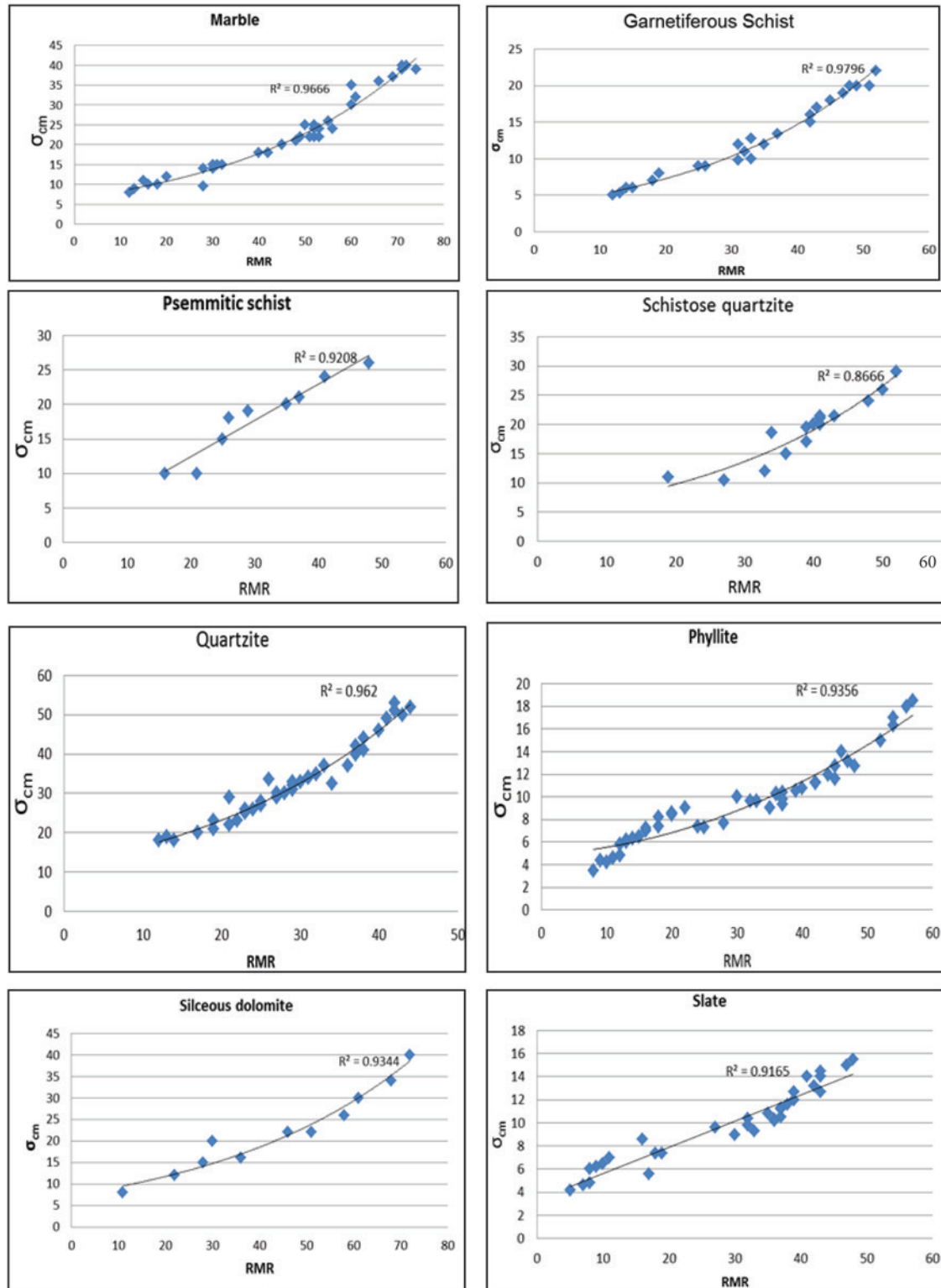


Fig. 5: Relationship between rock mass UCS and RMR for different rock types.

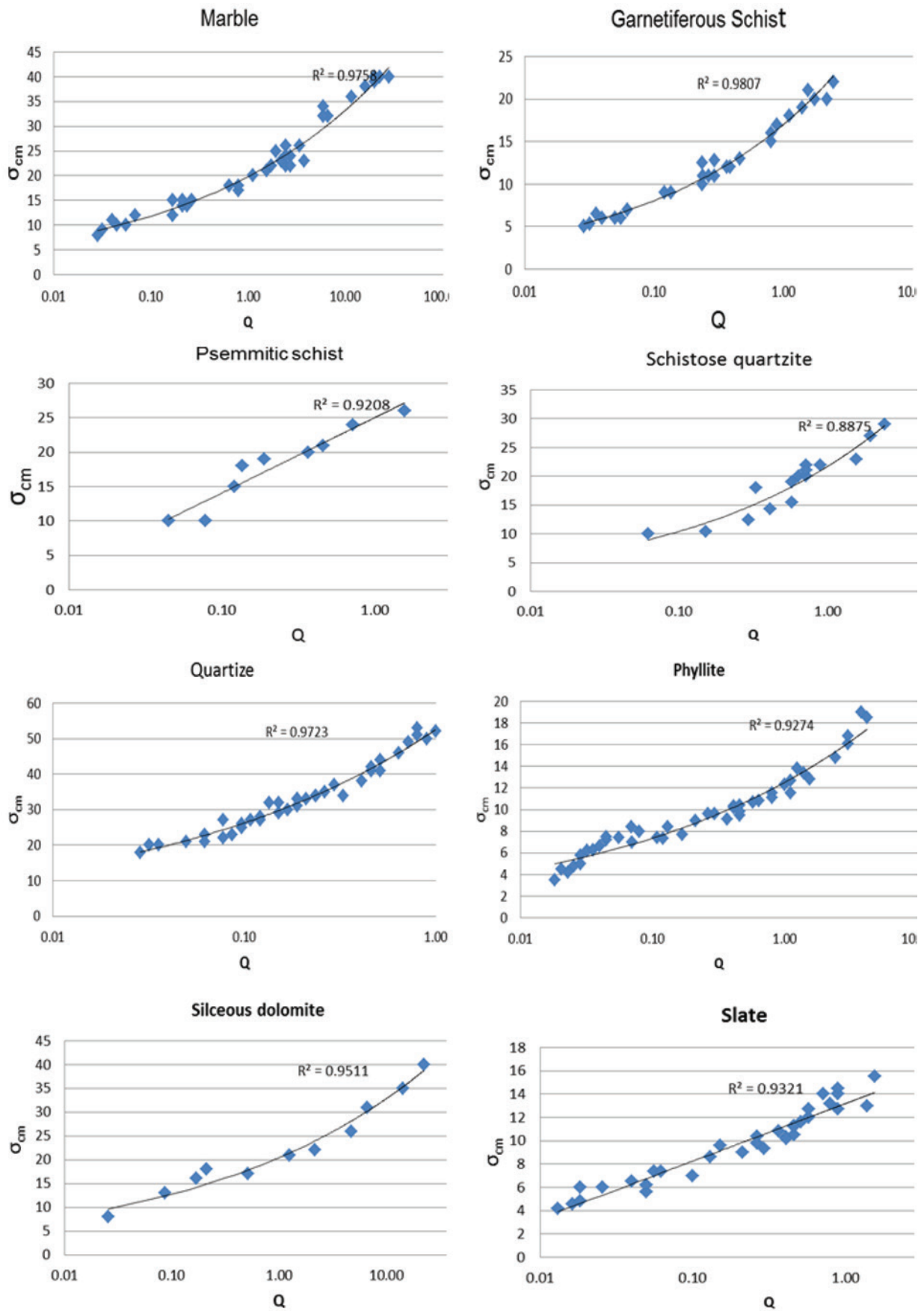


Fig. 6: Relationship between rock mass UCS and Q for different rock types.

The best fitting trend lines were drawn for each rock types. They are quiet fitting having correlation coefficient, R<sup>2</sup>, more than 0.90. The equations of the trend lines for each rock types were drawn given in Table 7.

**Table 7: Relationships of UCS of rock mass with RMR and Q.**

Rock type	Relation between Rock mass UCS and RMR	Relation between Rock mass UCS and Q
Marble	$\sigma_{cm} = 6.5176e^{0.0251RMR}$	$\sigma_{cm} = 19.824Q^{0.2243}$
Garnetiferous schist	$\sigma_{cm} = 3.605e^{0.0351RMR}$	$\sigma_{cm} = 17.001Q^{0.3253}$
Psammatic schist	$\sigma_{cm} = 0.5273RMR + 1.824$	$\sigma_{cm} = 4.7455\ln Q + 25.024$
Schistose auartzite	$\sigma_{cm} = 5.0164e^{0.0334RMR}$	$\sigma_{cm} = 21.696Q^{0.3187}$
Quartzite	$\sigma_{cm} = 11.706e^{0.0342RMR}$	$\sigma_{cm} = 52.567Q^{0.3014}$
Phyllite	$\sigma_{cm} = 0.0032RMR^2 + 0.0338RMR + 4.8692$	$\sigma_{cm} = 12.505Q^{0.2302}$
Silicious dolomite	$\sigma_{cm} = 7.402e^{0.0229RMR}$	$\sigma_{cm} = 20.437Q^{0.2056}$
Slate	$\sigma_{cm} = 0.2253RMR + 3.374$	$\sigma_{cm} = 2.1409\ln Q + 13.176$

The relation between  $\sigma_{cm}$  and RMR has exponential relation with different trend for most of rock types but slate, phyllite and psammatic schist shows linier trend. Similarly, relation between  $\sigma_{cm}$  and Q has power law relation of all rock types except slate and psemmatic schist. The slate and psemmatic schist shows logarithmic positive relations.

**DISCUSSION AND CONCLUSIONS**

The geotechnical data and geomechanical properties of the rocks along the tunnel alignment of the Kulekhani III Hydro-electric Project were analysed. The intact rock properties of each rock types were determined in laboratory and geomechanical properties of the rocks were determined from field using widely using rock mass classification schemes. Using both geomechanical properties and intact rock properties, rock mass properties were determined.

Only rock mass compressive strength values area analyzed because similar trend was observed with other parameters. Quite similar results were observed with both RMR and Q systems. The trend of correlations of each parameter for each rock type with each classification system follows almost analogous order. The general trend of correlation of UCS rock mass with RMR and Q is given in Table 7 which has R<sup>2</sup> more than 0.9.

Several researchers have purposed several relationships between  $\sigma_{cm}$  and rock mass class and some widely used are given in Table 8. All of these equations consider  $\sigma_{ci}$  as a scale parameter except Trueman (1998). Bieniawski (1973), Barton et al. (1974) and Hoek and Brown (1997) have expressed that the  $\sigma_{cm}$  can be estimated by reducing the  $\sigma_{ci}$  based on the quality of rock mass such as RMR, GSI or Q value. Most of the studies are based on RMR and only two studies are based on Q. Result from present study has also similar trend as Trueman (1998) for most of rock type except slate, phyllite and psemmatic schist. If the trend of slate, phyllite and psemmatic schist is

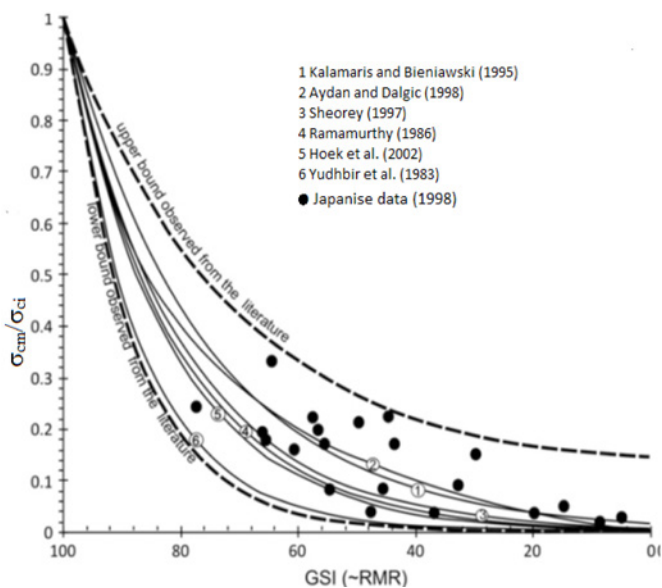
plotted in exponential trend the R<sup>2</sup> values slightly reduced than the preset observed value. The results of the present study also show similar trend as previous study but having different slope.

**Table 8: Relationship between compressive streageth and rock mass classification proposed by various authors.**

Researchers	Equation (units MPa)
Hoek and Brown (1980b)	$\sigma_{cm} = \sigma_{ci} \exp^{[(RMR-100)/18]}$
Yudhbir et al. (1983)	$\sigma_{cm} = \sigma_{ci} \exp^{[7.65(RMR-100)/100]}$
Ramamurthy (1986)	$\sigma_{cm} = \sigma_{ci} \exp^{[(RMR-100)/18.75]}$
Kalamaris and Bieniawski (1995)	$\sigma_{cm} = \sigma_{ci} \exp^{[(RMR-100)/24]}$
Bhasin and Grimstad (1996)	$\sigma_{cm} = (\sigma_{ci}/100)7\gamma Q/13$
Sheorey (1997)	$\sigma_{cm} = \sigma_{ci} \exp^{[(RMR-100)/20]}$
Trueman(1998)	$\sigma_{cm} = 0.5 \exp^{(0.06RMR)}$
Aydan and Dalgic (1998)	$\sigma_{cm} = RMR/[RMR+6(100-RMR)] * \sigma_{ci}$
Palmstrom (2000)	$\sigma_{cm} = RMR = \sigma_{ci} j p$
Barton (2002)	$\sigma_{cm} = 5\gamma [Q (\sigma_{ci}/100)]^{1/3}$
Hoek et al. (1990)	$\sigma_{cm} = \sigma_{ci} s^a$

Till today, the question of “which empirical relation is the best for rock mass strength prediction?” cannot be definitively answered yet even the study has long history of the study. In fact each empirical relation has the highest predictive capacity for those rock masses included in their original databases created for development of the various empirical relations. For this reason, a unique reducing curve form empirical equation has limited application to estimate  $\sigma_{cm}$  for the vast range of rocks masses formed of the variety of rocks from soft to hard.

However, almost all empirical equations in the literature produce almost same  $\sigma_{cm}/\sigma_{ci}$  ratios when the rock quality indexes of the rock masses are similar (Fig. 7). The observed equations of almost all rock types presented in Table 8 also fall in the limits of equations proposed by previous studies given in Fig. 7. As can be seen from Fig. 7, the empirical equations curves occupy a zone of failure envelope instead of a unique curve envelope. Almost of all rock type follows the similar trend of power type continuous equation for Q except for slate and psammatic schist and exponential for RMR except slate, phyllite and psammatic schist. In this study instead of a definite unique curve form equations, a power type continuous equation is observed. The curves of equation become closer to the lower bound (harder rock mass) given in Fig. 7 by increasing the  $\sigma_{ci}$  and elastic modulus of intact rock material ( $E_i$ ).



**Fig. 7: Some well-known empirical relations plotted with normalized  $\sigma_{cm}/\sigma_{ci}$  and qualities of rock mass such as GSI or RMR. (Modified after Dinc et al. 2011).**

The intact rock properties and rock mass properties of all rock types are almost power or exponentially correlated. Among them, harder rock has good correlation than softer rocks. It is also observed that higher the poisson's ratio of the rock shown higher the order of power correlation of rock mass properties with geo-mechanical properties of rock mass.

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