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# CORRELATION OF ROCK MASS RATING (RMR), TUNNELLING QUALITY INDEX (Q) AND GEOLOGICAL STRENGTH INDEX (GSI) IN PRE-CAMBRIAN DOLOMITE BASED ON FIELD DATA

PUSKER RAJ JOSHI[1], MILAN KHAREL[2], ASHOK POUDEL[2], GANESH RAJ JOSHI[3], DIPAK SAPKOTA[3]

[1] *SKJV-Tanahu Hydropower project*

[2] *SKJV-Tanahu Hydropower project*

[3] *Geo-Environment Nepal,*

[3] *Tanahu Hydropower Project*

## Abstract

Over the recent decades, several authors have documented empirical associations among rock mass classification systems, which derive from extensive measurements and observations under particular site conditions and in various geological regimes. This underscores how important the reliability of a correlation equations is, and how critical is the apprehension of each systems objective. Consequently, none of these formulas can claim universal applicability in the contemporary context. Further to this, to ensure effective design and evaluation of an underground opening, it is essential to possess a comprehensive understanding of the geological, structural geological, hydrogeological, and geotechnical attributes of the excavated rock. In the context of Tanahu Hydropower Project (Nepal), diversion tunnels and auxiliary galleries are being excavated in dolomite. 642 tunnel profiles were mapped, and rock mass was classified using three empirical systems; GSI, RMR and Q. After processing and plotting the in-situ data, correlation equations for the three indices were analyzed using regression modeling aiming to identify the most optimal equation and to present a precise relationship between RMR, Q and GSI in the particular Lesser Himalaya formation. These relationships were then compared with those found in existing literature. The developed regression models reveal reliable correlations between RMR, Q, and GSI indices, enabling the engineering geological evaluation for a broad range of rock mass qualities. These formulations of geo-mechanical indices will serve as valuable tools for tunnelling professionals during decision-making processes, preliminary design phases, stability assessments, and estimates of temporary support systems.

## Key words

Rock mass classification, RMR, Q system, GSI, Dolomite, Empirical correlation

## 1 Introduction

The classification of rock masses has evolved into an indispensable tool for the underground excavation industry, particularly in the design and construction of tunnels and caverns. It plays a crucial role in predicting the necessary support structures for underground spaces. Among the rock mass classification systems used in underground work worldwide, the RMR system [1] the RMi system [2] the NGI-index Q-system [3] and the GSI [4]. Tunnelling Quality index (Q) [3] and RMR[1] system are the most commonly and frequently employed system in the all the countries [5-9]. In the context of the Nepal Himalaya, Q [3] and RMR [1] systems have been prevalent in underground excavation design and support activities[10]. Most existing classification systems have their roots in civil engineering case studies from Europe and America [4,7,11-13]. The attention to detail that various classification systems take on various factors and the rating levels for these parameters vary from one classification system to another. Due to the varying nature of classification system, at least two methods should be used at any site during the early stages of a project [1,14]. The multiple classification systems offers a comprehensive understanding of rock mass characteristics, enabling the estimation of strength and deformation properties, and thus, contributing to a more accurate initial and final support strategy. Detailed calculations for all parameters in both classification systems are not always feasible. Therefore, correlations between these systems are invaluable for the quick determation of various design parameters. Numerous correlations have been developed by researchers and scientists at different stages for different rock mass classification systems. These correlation equations provide a rapid verification of resulting rock mass rating values without the need for extensive recalculations. Despite of having correlation between two systems, from the start of the origin to till date, an efficient correlation between these classification systems has always been felt by researcher and the rock engineering practitioner in Nepal. This is associated with the fact that each previously generated phrase was the result of a set of particular data and site conditions. The accuracy of the base data from which these expressions were derived is critically important to their validity [15].

## 2 Description of Projects

In recent times, within the realm of Himalayan geology, there has been a surge in underground construction activities, driven primarily by the construction of hydropower projects, water supply infrastructure, and irrigation systems. The utilization of underground spaces for various purposes has been steadily on the rise. Within this context, the need for correlations between different classification systems has become paramount, particularly in the Nepal Himalaya. To contribute to the evaluation of tunnelling cases with respect to the himalayan geology, Tanahu Hydropower Project, currently under construction (Figure 1), was selected as a focal point.

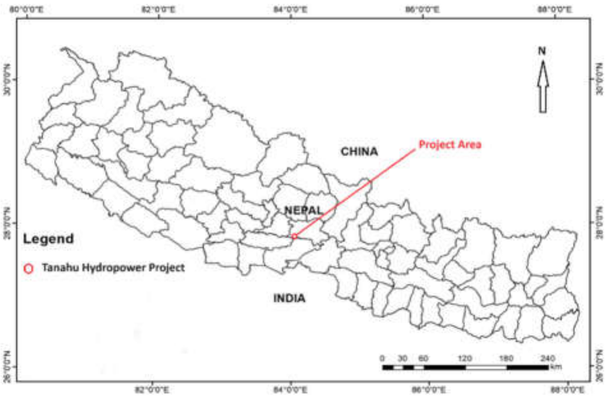

**Figure. 1** Location map of the project

**Figure. 2** Dolomite Rock present in the study area

## 3 Geology and Geomorphology of Projects

With respect to the geomorphology, Nepal divided into eight distinct geomorphic regions spanning from the east to the west: the Terai, Churia Range, Dun Valley, Mahabharat Range, Midland, Fore Himalaya, Higher Himalaya, and Inner and Trans Himalaya[19, 20]. Similarly, Nepal features five divisions within the primary tectonic zone, including the Gangetic Plain (Terai), the Sub-Himalayan Zone (Siwaliks), the Lesser Himalayan Zone, the Higher Himalayan Zone, and the Tibetan-Tethys Himalayan Zone [20, 21]. These primary Himalayan thrusts and faults demarcate the aforemention tectonic zones and include the Main Frontal Thrust (MFT), the Main Boundary Thrust (MBT), the Main Central Thrust (MCT), and the South Tibetan Detachment System (STDS), arranged from south to north [22].Tanahu Hydropower Project site is situated 150 km west of Kathmandu on Seti River,Tanahu District, Gandaki Provionce. The project comprise a reservoir storage type project designed with a targeted installed capacity of 140 MW [16]. The geological composition of the area primarily consists of low-grade metamorphic rock units encompassing slate, intercalations of Phyllite, Quartzite, and Dolomite (see figure 2). A concrete gravity dam with a maximum height above foundation level of 140m and an estimated total concrete volume (including dam body, spillway, and appurtenant structures) of over 920,000 $m^3$ will form [17]. 25km long reservoir with a total volume of 295 million $m^3$.River water is diverted by two diversion tunnel having total length 1167m (inner diameter 11.4 m). The reservoir will feed the concrete lined head race tunnel (1469.6 m long, 7.4m internal diameter)[16-18]. Before reaching the underground powerhouse, the headrace tunnel intersects with a restricted Orifice type surge shaft (61.5 m height, 25.5 m diameter)[18].

## 4 Literature Review

### 4.1 Rock Mass Classification System

The Rock Mass Classification System is an important tool in the field of geotechnical engineering which is widely used to evaluate the quality and stability of rock masses for different project development. This system categorizes rock masses based on specific properties and parameters, which enables geotech engineers to make better decisions of the project design, development, and safety measures. There are different rock mass classification systems which have distinct and unique methodology and applications. However, the most commonly used rock mass classification systems include the Rock Mass Rating (RMR), the Geological Strength Index (GSI) and the Q-system.

### 4.1.1 Tunnelling Quality Index (Q) System

Nick Barton of the Norwegian Geotechnical Institute (NGI) developed a Tunnelling Quality Index, Q-system, based on around 200 tunnels and caves case histories [3]. This system is primarily used to characterize rock mass and estimate the necessary tunnel support. It classifies rock mass quality into different categories based on six parameters: rock quality designation (RQD), joint number (Jn), joint roughness number (Jr), joint alteration (Ja), joint water reduction factor (Jw), and stress reduction factor (SRF). The Q value, which indicates the quality of the rock mass in an underground opening, is calculated as the product of the ratios of these six parameters. The Q value is determined by the product of the ratios of above six parameters which provides a quantitative measure of rock mass quality for underground openings. The Q value is widely used to determine an appropriate support system for tunnels and other underground excavations. It predicts the behavior of the rock mass and helps to select suitable support measures such as rock bolts, shotcrete, and steel sets. which ensure the safety and stability of underground projects.The formula of the Q value is derived from the following equation:

$$Q = (\mathrm{RQD}/Jn) \times (\mathrm{Jr}/Ja) \times (\mathrm{Jw}/\mathrm{SRF}) \quad (1)$$

### 4.1.2 Rock mass rating (RMR) System

The Rock Mass Rating (RMR) System is one of the widely used classification methods for identifying the quality of rock masses. Z.T. Bieniawski established the Rock Mass Rating (RMR) system or Geomechanics classification during the 1970s in South Africa in the 1970s [1]. The system has been revised several times with the increments of additional case data since its first variant.Significant changes were made over the years with revisions in 1974, 1975, 1976 and 1989. In the beginning, the system was established only for tunnels but with time, the system was also introduced for foundations, rock slopes and mining cases [5]. For the classification of rock mass, this approach uses six fundamental factors.The RMR system provides a systematic way to evaluate the rock mass characteristics and determine the necessary support systems for tunnels, mines, and foundations. Moreover, by providing a reliable and systematic approach to classifying rock mass quality, the RMR system helps engineers to make decisions about excavation methods, support systems, and safety measures. This system is particularly valuable in preliminary design phases and for assessing the stability and performance of rock masses in various geological conditions. For the classification of rock mass, this approach uses six fundamental factors. RMR value is calculated from equation (2).

$$RMR = R1+R2+ R3+R4+ R5+ B \tag{2}$$

R1 corresponds to rating related to the intact rock strength, R2 relates to RQD, R3 refers to the spacing of discontinuities, R4 comprises a series of joint surface condition parameters (i.e. persistence, aperture, roughness, infill material and weathering), R5 represents groundwater conditions, and B is the rating adjustment for joint orientations. The derivative value range from 0 to 100, and with reference to the excavation span. The system defines specific stand-up times, a recommendation for optimal excavation strategy, and recommends estimated rock support measures.

### 4.1.3 Geological Strength Index (GSI)

Hoek, E. (1994). "Strength of rock and rock masses." ISRM News Journal, 2(2), 4-16. In this paper, Hoek introduced a more practical index, the Geological strength index (GSI) . The GSI is effective for both weak and hard rock masses. GSI is less time consuming than the aforementioned existing classification system. GSI links qualitative observational assesment of rock mass to geotechnical engineering values, ie. Mohr–Coulomb, Hoek–Brown strength parameters or rock [23]. In 1999, and aiming to introduce surface condition rating (SCR) and structure rating (SR) Sonmey and Ullusay, [24] attempted to a more quantitative numerical basis for evaluating GSI.

Cai et al. (2004) enhanced the GSI system by providing a more detailed and quantitative approach to classifying and evaluating rock mass structures. Their work allows for a more precise estimation of rock mass properties, which is crucial for various engineering applications.

According to V. Marinos et al. (2005), There are some limitations of GSI which are Subjectivity (visual) in Assessment, Experience Dependency, Scale and Sampling Issues, Sampling Bias, Surface Conditions (Weathering Effects) Variability, Infill Material, Complex Geological Settings (Heterogeneity), Anisotropy, Empirical Nature, Lack of Theoretical Foundation, Quantitative to Qualitative Transition, Integration with Other Systems (Compatibility)**.** These highlighted limitations that need to be addressed for more accurate and reliable assessments. Overcoming these limitations involves improving.

Hoek et al. (2013) made significant advancements in the Geological Strength Index (GSI) system particularly in the linearization and quantification of the axes used in GSI charts. These improvements aimed to enhance the reliability and ease of use of the GSI system in practical engineering applications. The refined GSI charts and enhanced empirical relationships contributed to a better understanding and prediction of rock mass behavior, ultimately supporting more effective and safe engineering practices.

Day et al. (2019) introduced the composite GSI which represents a significant advancement in rock mass classification for heterogeneous conditions. By integrating individual GSI values from multiple domains and using a weighted average approach, composite GSI provides a more accurate and holistic assessment of rock mass quality. This method enhances the reliability of geotechnical evaluations and supports better-informed engineering decisions in complex geological settings.

V. Marinos in 2017 significantly advanced the application of the Geological Strength Index for flysch formations. By developing a specific GSI chart and detailed guidelines tailored to the unique characteristics of flysch, Marinos provided a more accurate and practical tool for assessing rock mass quality in these complex geological settings. The adapted GSI for flysch improves the reliability of geotechnical evaluations and supports better-informed engineering decisions, ultimately enhancing the safety and effectiveness of engineering projects involving flysch.

### 4.1.4 Existing Relationship

Various researchers have developed several relationships between rock mass classification systems. Most of the relationships have from research cases in individual yet different regimes, in terms of geological formations, tectonic regimes, and geomorphology, stress enviroments etc. Existing correlation equations between RMR and Q, RMR and GSI and GSI and Q which are presented in Table 1.

**Table 1** Literature correlation equation between RMR, Q and GSI

| Existing correlations | Proposed by | Existing correlations | Proposed by |
|---|---|---|---|
| RMR = 9InQ + 44 | Bieniawski [1] 1989 | RMR = 8.15lnQ + 44.88 | Laderian and Abaspoor [46] 2012 |
| RMR = 5.9InQ + 43 | Rutledge and Perston [25] 1978 | RMR = 6.3lnQ + 43 | Ranasooriya and Nikraz [47] 2012 |
| RMR = 5.4lnQ + 55.2 | Moreno [26] 1980 | RMR = 8.09lnQ + 43.08 | Rafiee [48] 2013 |
| RMR = 5InQ + 60.8 | Cameron-Clerke and Budavari [27] 1981 | RMR = 5.7lnQ+ 43.65 | Castro Caicedo and Pe´rez Pe´rez [49] 2013 |
| RMR = 7.5InQ + 42 | Baczynski [28] 1983 | RMR = 2.87lnQ +48.71 | Ali et al. [50] 2014 |
| RMR = 10.5InQ + 41.8 | Abad et al. [29]1983 | RMR = 4.52lnQ + 43.635 | Sayeed and Khanna [51] 2015 |
| RMR = 43.89–9.19InQ | Celada Tamames [30] 1983 | RMR = 6.55lnQ + 59.53 | Senra [52] 2016 |
| RMR = 5.3InQ + 50.81 | Udd and Wang [31] 1983 | RMR = 8.8832InQ + 43.26 | Rezaei and latifi [53] 2018 |
| RMR = 8.7lnQ +38 | Kaiser and Gale [32] 1985 | RMR = 12.334InQ+ 26.01 | Sadeghi et al. [54] 2020 |
| RMR = 6.8 InQ + 42 | Sheorey [33] 1993 | GSI = RMR-5 | Hoek and Brown [4] 1997 |
| RMR = 9lnQ + 49 | Al-Harthi [34] 1993 | GSI = 0.42RMR + 23.07 | Cosar [44] 2004 |
| RMR = 12.11lnQ + 50.89 | Choquet and Hadjigogiu [35] 1993 | GSI = 0.687RMR +4.714 | Morales et al. [55] 2004 |
| RMR = 7lnQ + 44 | El-Naqa [36]1984 | GSI = $6^{e}$0.05RMR | Osgoui and Unal [56] 2005 |
| RMR = 6.1 InQ + 53.4 | Rawlings et al. [37] 1995 | GSI = 0.692RMR + 22.32 | Hashemi et al. [45] 2010 |
| RMR = 15lnQ + 50 | Barton [38] 1995 | GSI = 1.35RMR – 16.4 | Irvani et al. [57] 2013 |
| RMR = 7lnQ + 36 | Tugrul [39] 1998 | GSI = 0.73RMR – 4.38 | Singh and Tamrakar [58] 2013 |
| RMR = 5.97 InQ + 49.5 | Sunwoo and Hwang [40] 2001 | GSI = 0.99RMR – 4.9 | Ali et al. [50] 2014 |
| RMR = 4.2 InQ + 50.6 | Asgari [41] 2001 | GSI = 1.21RMR – 18.61 | Zhang et al. [59] 2019 |
| RMR = 3.7lnQ + 53.1 | Sari and Pasamehmetoglu [42] 2004 | GSI = 0.9143RMR + 6.132 | Sadeghi et al. [54] 2020 |
| RMR = 6.4lnQ + 49.6 | Kumar et al. [43] 2004 | GSI = 1.61In Q+ 42.99 | Cosar [44] |
| RMR = 2.8lnQ + 45.19 | Cosar [44] 2004 | GSI = 5.96InQ+ 47.85 | F. Deak et al. [60] |
| RMR = 5.37lnQ + 40.48 | Hashemi et al. [45] 2010 | GSI = 12.638InQ + 28.538 | Sadeghi et al. [54 ] |

## 5 Methodology

To establish correlations between RMR, Q, and GSI, an extensive face mapping was undertaken. This encompassed the examiation of each chainage, covering a total of 1.63 kilometers in the Diversion tunnels and grouting gallery tunnels. 643 tunnel segments were assessed and mapped. The excavation methodology employed was drill and blast. The RMR system used for this classification, referred to as RMR89 (1989 version), account for the correction of discontinuity orientation, while the Q system denoted as Q94, incorporate the latest updates pertaining to the Support Requirement Factor (SRF) aiming phenomena such as sliding, cracking, and rock burst. Following the processing and refinement of raw data, a comprehensive assessment was conducted to determine the accuracy of the existing expressions. A series of mathematical expressions with particular formats (i.e, linear, exponential, logarithmic, and power), were scrutinized to pinpoint the most suitable equation of the highest correlation coefficient and the minimal error margin. Subsequently, a thorough accuracy analysis was performed using key metrics including the Mean Absolute Error (MAE), the Mean Absolute Percentage Error (MAPE), the Root-Mean-Square Error (RMSE), the Pearson's Coefficient for Correlation (R), and the Coefficient of Determination (R2), in order to ascertain the reliability of the derieved expressions. Every individual analysis method possesses its own distinct characteristics and significance for comprehending and interpreting results. The correlation coefficient, denoted by R, measures the strength and direction of a linear relationship between two variables. Its value ranges from -1 to 1, means perfect positive and negative linear relationship and R=0, means no linear relationship. R helps in understanding how strongly two variables are related linearly. R-squared ($R^2$) represents the proportion of the variance in the dependent variable that is predictable from the independent variable(s). Its value ranges from 0 to 1, where $R^2$= 1, The model explains all the variability of the response data around its mean. $R^2$= 0,The model explains none of the variability of the response data around its mean.

A higher $R^2$ means a better fit of the model to the data. MAE is the average of the absolute differences between predicted values and observed values. It measures the average magnitude of the errors in a set of predictions, without considering their direction. It gives a clear indication of how close the predictions are to the actual outcomes. RMSE is the square root of the average of squared differences between predicted and observed values. It measures the average magnitude of the error. It gives a higher weight to larger errors compared to MAE, which can be useful if larger errors are particularly undesirable in the application context. MAPE is the average of the absolute percentage errors between predicted and observed values. It expresses the accuracy of the forecasting system as a percentage and useful for understanding the error relative to the size of the actual values, making it easier to interpret in percentage terms. They were expressed as follows:

$$r = n\sum xy - (\sum x)(\sum y) \div \sqrt{n(\sum x^2) - (\sum x)^2}\sqrt{n(\sum y^2) - (\sum y)^2} \quad (3)$$

$$R^2 = \frac{1}{N}\{\sum(x_i - x) \times (y_i - y)/\sigma_x - \sigma\}^2 \quad (4)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |x_i - x| \quad (5)$$

$$\mathrm{RMS}E_{fo} = [\textstyle\sum_{i=1}^{N}(z_{fi} - z_{oi})^2/\mathrm{N}]^{½} \quad (6)$$

$$\mathrm{MAPE} = \frac{100}{N} \times \textstyle\sum_{i=1}^{N} \left| \frac{xi - x\hat{}i}{xi} \right| \quad (7)$$

## 6 Results

The primary goal of this research constitutes an attempt to present a new, precise relationship between RMR, Q and GSI in the Dolomite rock of Nepal Himalaya [61]. For this purpose, the data obtained from Diversion tunnels and different Grouting Gallery tunnels of the Tanahu Project were analyzed. Each tunnel has its own specific geology, and characterised by individual geomorphological and stress conditions. For reference, the data range of rock mass qualities based on the geological mapping records along with highest, lowest, mean and frequent values of Q system, RMR and GSI is shown in Table 2, below.

**Table 2:** Actual RMR, Q and GSI based on lithology of THP (642 data)

| | Highest value | Lowest value | Mean value | Frequent value |
|---|---|---|---|---|
| Q-value | 7.5 | 0.2 | 1.465 | 0.5 |
| RMR | 64 | 36 | 52 | 62 |
| GSI | 65 | 20 | 51 | 48 |

The first attempt in this study was made to correlate RMR versus Q, GSI versus RMR and GSI versus Q within the project area [61]. The correlation derivatives between RMR, Q and GSI of the Tanahu project were developed from 642 tunnel segments (1.63 km) respectively, and are presented in Table 3. The analysis of different mathematical expressions [61] for Dolomite rock is presented in Table 3., It is evident that the logarithmic relationships represent the most suitable expressions for RMR versus Q, GSI versus RMR and GSI versus Q.

**Table 3**: Comparison of various relationship between RMR, Q and GSI of Tanahu hydropower project

| Approach | Expression (RMR Vs Q) | R2 | Expression (GSI Vs RMR) | R2 | Expression (GSI Vs Q) | R2 |
|---|---|---|---|---|---|---|
| Linear | RMR = 4.579Q + 46.129 | 0.4654 | GSI = 0.8155RMR + 7.6732 | 0.7516 | GSI = 3.208Q + 46.065 | 0.2619 |
| Power | RMR= 51.27Q0.1952 | 0.7505 | GSI= $1.5598RMR^{0:8773}$ | 0.7523 | GSI= 49.346Q0.1688 | 0.5261 |
| Exponential | RMR = $45.732^{e}0.0881Q$ | 0.3752 | GSI= $20.537^{e}0.0168RMR$ | 0.7469 | GSI= $45.311^{e}0.0674Q$ | 0.2119 |
| Logarithmic | RMR = 10.057 ln Q + 52.079 (8) | 0.7891 | GSI = 42.203 ln RMR – 116.02 (9) | 0.7557 | GSI = 8.0311 ln Q + 50.161 (10) | 0.5688 |

The best-fit regression models resulting from RMR versus Q, GSI versus RMR and GSI versus Q were further analyzed with the utilization statistical matrix in order to evaluate the accuracy of the results [61]. The results obtained in table 4 from analyzing R, MAE, RMSE and MAPE indicate very good implementation . To generate the relationship for the whole data set, correlation was conducted [61]with Dolomite, i.e., lesser Himalaya rock mass. The coefficient of determination $R^2$ ranges from 0.3752 to 0.7891 for RMR versus Q (Figure. 3), 0.7469 to 0.7557 for GSI versus RMR (Figure. 4) and 0.2119 to 0.5688 for GSI versus Q (Figure. 5), with all best-fit relationships corresponding to logarithmic regression lines for all of the combinations. (Table 4).

**Table 4**: Evaluation of accuracy of relationship between RMR,Q and GSI of Precambrian Dolomite at THP

| Relationship | Approach | R2 | MAE | RMSE | MAPE(%) | R |
|---|---|---|---|---|---|---|
| RMR vs Q | Logarithmic | 0.7891 | 3.799 | 5.055 | 6.22% | 0.8883 |
| GSI vs RMR | Logarithmic | 0.7557 | 3.22 | 4.43 | 322.40% | 0.8693 |
| GSI vs Q | Logarithmic | 0.5688 | 4.25 | 5.62 | 1.39% | 0.7541 |

$$\mathrm{RMR} = 10.057 \ln Q + 52.079 \tag{8}$$

$$\mathrm{GSI} = 42.203 \ln \mathrm{RMR} - 116.02 \tag{9}$$

$$\mathrm{GSI} = 8.0311 \ln Q + 50.161 \tag{10}$$

Therefore, from this particular research, equation (8) and (10), having MAPE is 6.216%, 1.39% (MAPE provides a clear and understandable measure of prediction accuracy. By expressing the error as a percentage, it allows for easy comparison across different datasets and scales. A lower MAPE value indicates a more accurate forecasting equation, while a higher MAPE value suggests less accuracy) which shows minimum percentage than other equations and it is proposed as the preferred formulae for estimating relation between RMR versus Q, and GSI versus Q but for equation (9) , the percentage of MAPE is very high ie. 322.4% which suggest less accuracy so it is not reliable (see Table 5).

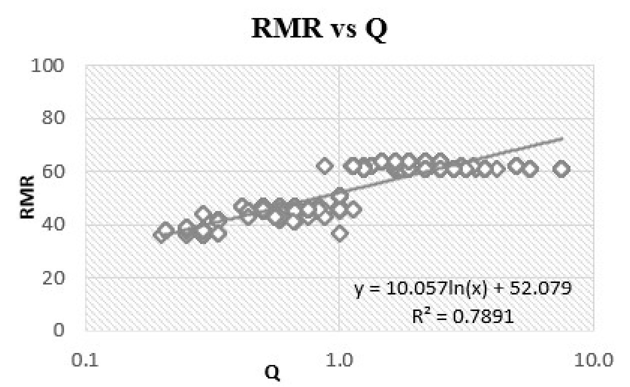

**Figure 3**: Relation between RMR and Q system (best-fit graph)

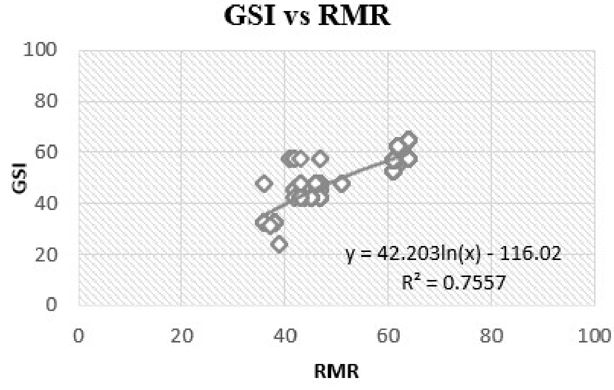

**Figure 4**: Relation between GSI and RMR (best-fit graph)

**Table 5**: Best suitable relationship between RMR, Q and GIS of Precambrian Dolomite

| Approach | Equation | R² | Relationship |
|---|---|---|---|
| Logarithmic | RMR = 10.057 ln Q + 52.079 (8) | 0.7891 | RMR vs Q (Best) |
| Logarithmic | GSI = 42.203 ln RMR - 116.02 (9) | 0.7557 | GSI vs RMR (not reliable) |
| Logarithmic | GSI = 8.0311 ln Q + 50.161 (10) | 0.5688 | GSI vs Q |

The results obtained from the analysis of RMR versus Q has been compared with some of the existing equations from various researchers (Table 1). The research equation indicates a similar trend to the equation proposed by Choquet and Hadjigogiu (1993) [35] for Q values ranging from 1 to 3. For $Q < 2$, Mereno (1993) [26] predicts lower RMR values than the research equation, whereas for $Q > 2$, it predicts higher RMR values. Barton (1995) predicts lower RMR values than the research equation for $Q < 1.5$ and higher RMR values for $Q > 1.5$.The comparison of derived trend-line with previous research works is shown in Figure. 6.

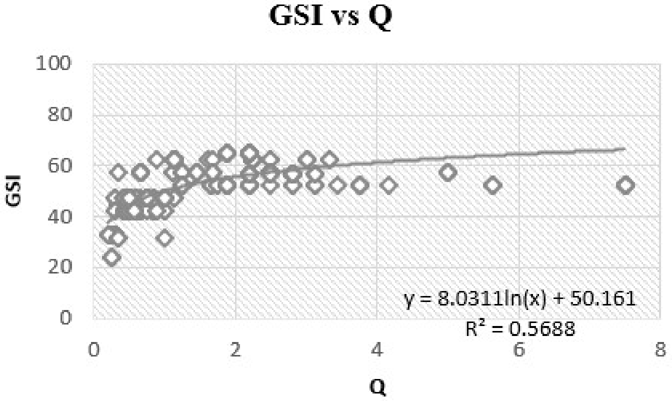

**Figure 5**: Relation between Q and GSI (best-fit graph)

The results obtained from the analysis of GSI versus RMR were compared with the Hoek and Brown [4], Cosar [44], Singh and Tamarkar [58], and Hashemi et al.[45] equations (Fig. 7). From RMR values of 35 to 65, Hoek and Brown (1997) [4] and Morales et al. (2004) [55] predict a similar pattern to the research equation with the same values of GSI. In contrast, Cosar [44] and Hashemi et al. [45] predict higher GSI values than the research equation for $RMR > 50$, and lower GSI values for $RMR < 50$. Additionally, Chaulagai and Dahal (2023) [61] and Zhang et al. (2019) [59] equations consistently predict higher GSI values than the research equation.

The results obtained from the analysis for GSI versus Q were compared with the existing equations proposed by Cosar [44], F. Deak [60] and Sadeghi et al. [54]. The equation proposed by F. Deak [60] follows a similar pattern but predicted higher values. As illustrated in Figure 8, the highest variability between these equations occurs when Q values lies in between 0.4 and 0.6, i.e., poor to fair rock mass.The equation proposed by Cosar[44] and Sadeghi et al. [54] predicted higher values as compared to the research equation and does follow the proposed equation pattern.

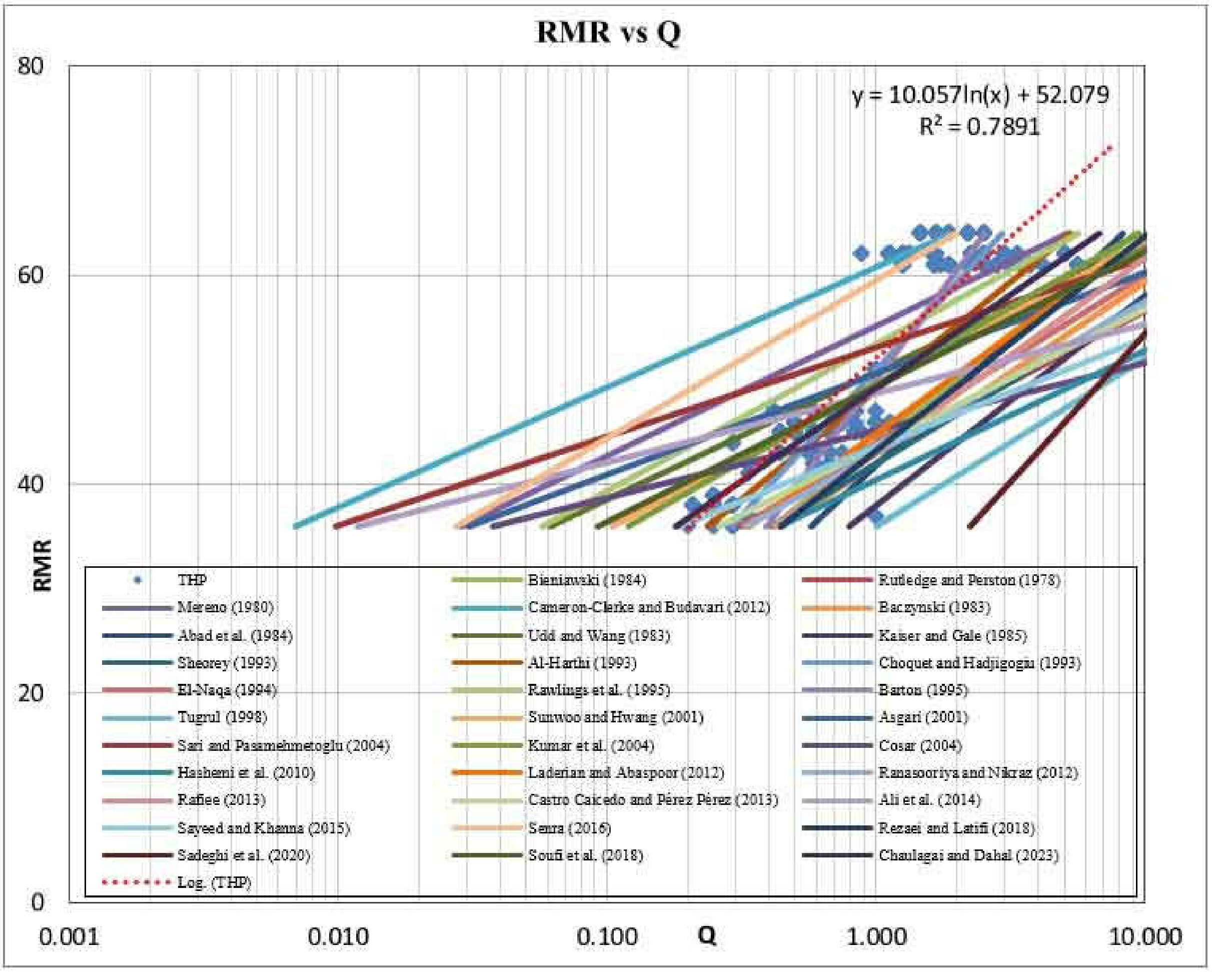

**Figure. 6:** Comparison of trend line of existing research with previous research works for RMR versus Q

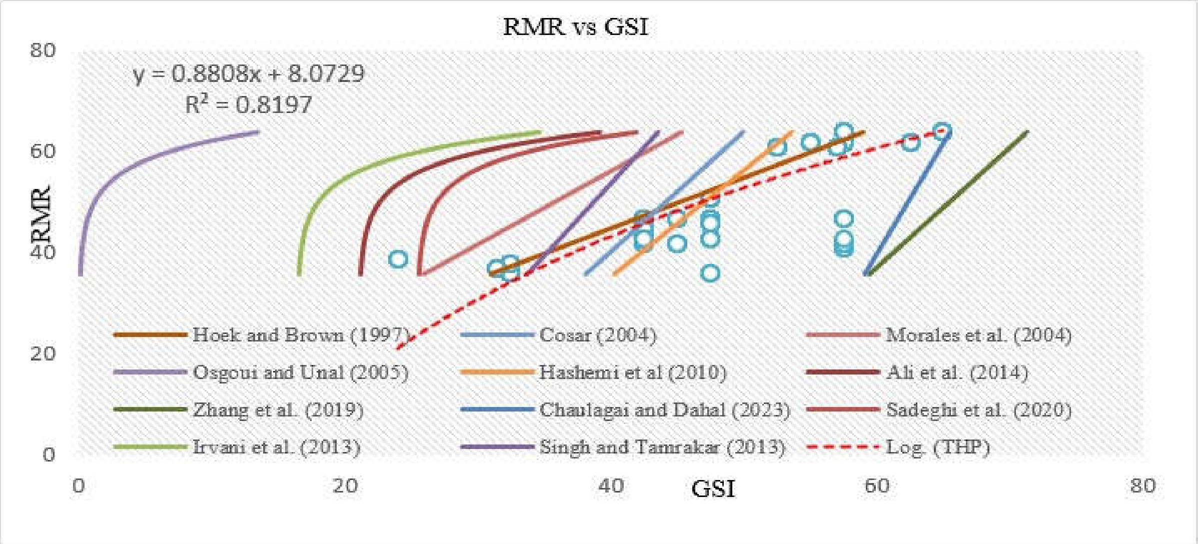

**Figure. 7**: Comparison of trend line of existing research with previous research works for RMR versus GSI

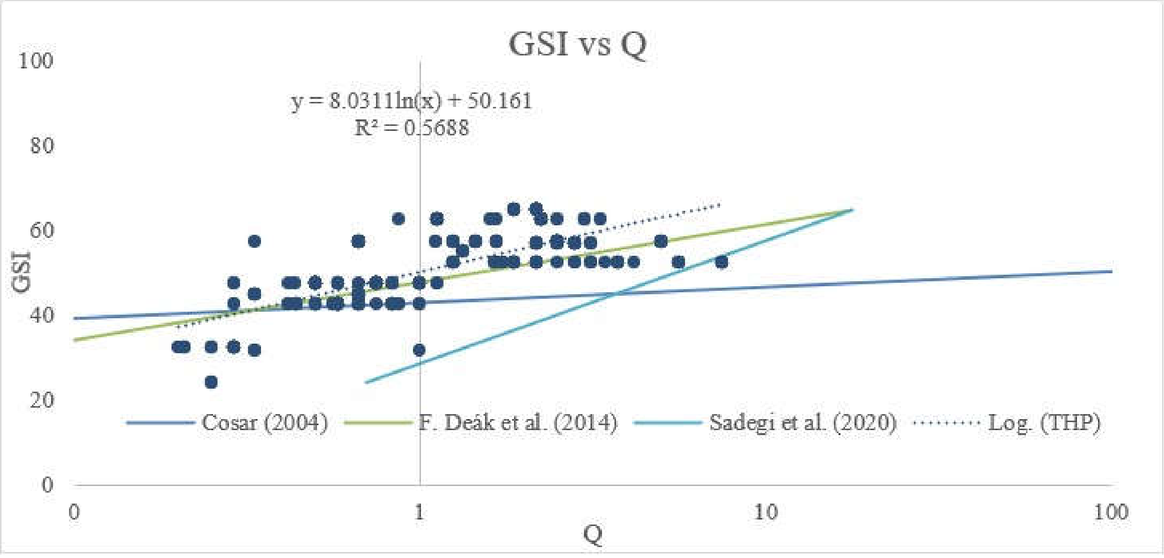

**Figure. 8:** Comparison of trend line of existing research with previous research works for GSI versus Q

## 7 Conclusion

Exponents in the field of rock engineering often rely on correlation equations between classification systems, particularly when multiple classification systems are required. The ongoing development of correlation equations between rock mass classifications is driven by the evolving needs of specific site conditions and the accumulation of extensive local data. The significant volume of construction activities in the Lesser Himalayan region, particularly in tunneling projects, has intensified the demand for tailored correlation equations between the most commonly applied classification systems.

To address this, a comprehensive evaluation and analysis of data from 642 tunnel profiles from Project, underground excavations was undertaken. Statistical analysis revealed that results obtained from the project data sets outperforms the results from equations available in relevant literature by previous researchers. This underscores the importance of accounting for specific geological conditions when applying previously established relationships. Upon comparing the relationships developed in this study with existing equations, it is evident that some exhibited similar trends to one or more previous relations [35] [55] [4] [60]. However, the majority of the compared equations did not display such similarities.

In light of the numerous equations [8] [9] and [10] generated from the analysis of the entire tunnel data set, it is recommended to utilize the equation [8] that demonstrates the strongest relationship derived from this data set. This suggested equation offers a practical and efficient solution for the preliminary and final stage studies, as well as the site selection process, particularly within the Precambrian Dolomite Rock in the lesser Himalayan region. It is important to note that the research relationship is generated from data sets of the Lesser Himalaya rock unit, so the researched equation [8] functions well in the Lesser Himalaya. However, caution should be exercised when applying this relationship to the Higher Himalaya and Sub-Himalayan Zone (Siwaliks), and it is advised to avoid using these relationships outside the scope of this study's geological conditions.

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