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Performance Evaluation of Various Rock Classification Systems and Its Comparison with Existing Correlations for Rock Support

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Abstract: Rock mass classifications aim to provide a qualitative evaluation of the rock mass for the preliminary design of structures in rocks. The support system based on the rock mass classification has been applied to a variety of applications such as tunnels, powerhouses, and crude oil storage in Pakistan, and around the world. Bieniawski's Rock Mass Rating (RMR), Barton's Q System and Hoek and Brown Geological Strength Index (GSI) are the most widely known rock mass classification system and efforts have been made by various researchers around the world to develop correlations between them, the lesser-known systems Rock Condition Rating (RCR) and Rock Mass Number (QN) were also checked for its use in the construction industry since these systems omit some parameters used during field investigation. This research is an attempt to develop a correlation between RMR, GSI, and Q System of Rock mass classifications on a statistical approach using 240 data points recorded through a geological logs of exploratory drifts and tunnel logs during excavation for the Gulpur Hydropower Project, Pakistan. The correlations presented in this research were developed using various statistical approaches (i.e., linear, logarithmic, power, exponential, and polynomial) to develop correlation which not only allows us to compare the results of various statistical approaches but also tells us which approach gives the best results for correlation between two rock mass classification systems.

Keywords: Rock Mass Classification, Regression analysis, Correlation Coefficient, Rock Mass Rating (RMR), Rock Quality Rating (Q), Geological Strength Index (GSI), Rock Condition Rating (RCR), Rock Mass Number (QN).

1. INTRODUCTION

Rock classification systems have been widely used by rock engineers as well as engineering geologists because of their design simplicity. These systems are categorized in two forms either descriptive, numerical; or in some cases both, they are further classified into general or functional types [1]. An overview of all these classification systems developed through numerous researches can be found in Table 1. Descriptive and numerically formed systems have distinct features i.e. (i) numerical system aims to interpret the results in numeric/index values (ii) application of this system for rock masses that are hard (iii) the resulting values might be used for the estimation of strength. The use of these systems is imperative for engineering projects that involve stabilization of slope, drift driving, tunneling and Underground Storage Caverns. Usage of the rock classification system is based on the strength properties due to the inherent characteristics of rock material to have a large scatter in strength, which in some cases might be in the order of 10 [2]. Classification systems are developed as a tool during predesign stage to determine the type of support system that is required for engineering projects where excavation in rock is performed [3]. The initial version of Rock Mass Rating (RMR) was used for evaluating the period during which the excavated area remained stable without the use of external support in shale and clay-bearing rocks which were also vulnerable to moisture and wetting-drying cycles.

The use of the classification is beneficial in the construction process owing to the material characterization, the manpower required and keeping the economic impact of an engineering project as tunneling is a repetitive construction operation and various simulations can be used for analyzing these processes [4-6]. In case of feasibility studies before any excavation or disturbance in rock mass the rock classification systems are the most effective and efficient methods for the determination of rock type, joint orientation, water/moisture content, discontinuities and compressive strength of rocks [7]. Inadequate strength and stability of tunnels made of fragile and fragmented rocks, such as phyllites, schists, and gneiss, make them susceptible to high stress levels, resulting in the formation of a plastic zone around the tunnel [8]. This, in turn, causes significant and time-dependent displacement or deformation. The physical and mechanical properties of rock mass are a prominent feature during the investigation stage and the determination of these individual properties is essential for the feasibility of constructions carried out in rocks. Mineralogy and structural features of rock helps the geological engineer in identifying the above-mentioned properties for an accurate representation of faults, joints, discontinuities, and composition [9]. The behavior of rock can be predicted by knowing its physical and mechanical properties. Consequently, in rock engineering standard methods for classifying these rocks based on various parameters exists i.e., Rock Mass Rating (RMR), Q-system, and Rock Mass Index (RMi) [10]. Numerous classification systems have been developed which serve as a modified form of the three above-mentioned classification systems. The standard practices used during the identification of index properties can designate the properties of rock mass in a more difficult environment and dispense a more definite basis for judicious use of rock and selection of congruous mechanical properties [11]. The use of RMR, RMi Q-system and GSI in the development of design and construction properties is an added benefit during the initial feasibility study [12].

Table 1: Rock classification systems developed throughout history based on form and type

Classification/Characterization system	Main Applications	Form/ Type	References
Terzaghi rock load classification system	Design of steel support in tunnels	D, B, F	[13]
Lauffer's standup time classification	Tunneling design	D, G	[14]
New Australian Tunneling Method (NATM)	Excavation and design in incompetent (overstressed) grounds	D, B, T	[15]
Rock classification for rock mechanical Purposes	Input in rock mechanics	D, G	[16]
A unified classification of soils and rocks	Based on particles and blocks for Communication	D, G	[17]
Rock Quality Designation (RQD)	Based on core logging; used in other classification systems	N, G	[18]
Rock Structure Rating (RSR)	Design of (steel) support in tunnels	N, F	[19]
Rock Mass Rating (RMR)	Design of tunnels, mines, and Foundations	N, F	[20]
Q- system	Design of support in underground Excavations	N, F	[21]
Mining Rock Mass Rating (MRMR)	Mining	N, F	[22]
Size-strength classification	Based on rock strength and block diameter, used mainly in the mining	N, F	[23]
Typological classification	Use in communication	N, F	[24]
Unified Rock Classification System (URCS)	Use in communication	N, F	[25]
Basic Geotechnical Description (BGD)	General applications	N, F	[26]
Rock Mass Strength (RMS)	Mining	N, F	[27]
Modified Basic Rock mass rating classification (MBR)	Mining	N, F	[28]
Surface Rock Classification (SRC)	Design of support in underground excavations in weak rocks affected by high horizontal tectonic stress	N, F	[29]
Slope Mass Rating (SMR)	Slopes	N, F	[30]

Simplified rock mass rating (SRMR)	Mines and Tunnels	N, F	[31]
Ramamurthy / Arora	For intact and jointed rocks	N, F	[32]
Geological Strength Index (GSI)	Design of support in underground Excavations	N, F	[33]
Rock Mass Number (QN)	Design of support in underground Excavations	N, F	[34]
Rock Condition Rating (RCR)	Design of tunnels, mines, and Foundations	N, F	[2]
Rock Mass index (RMi)	General characterization, design of support, TMB progress	N, F	[35]
Modified Rock mass rating classification (MRMR)	Mining, For weak, stratified, anisotropic, and clay-bearing rock masses.	N, F	[36]
Rock tunneling quality index by Tunnel Boring Machine excavation (QTBM)	Tunnel Boring Machine tunnels	N, F	[37]
Continuous Rock Mass Rating (CRMR)	General applications	N, F	[38]
Rock Mass Excitability (RME)	TBM tunnels	N, F	[39]
Experience-based RMR system	Tunneling and general applications	N, F	[40]
Rock Mass Quality Rating (RMQR)	General applications	N, F	[41]
Rock Bolt Supporting Factor (RSF)	Tunneling and underground excavations	N, F	[42]
Anisotropic Rock Mass Rating (ARMR)	Tunneling and general applications	N, F	[43]

Uniaxial Compression Strength (UCS) is an important component during the classification of rock in part due to the physical nature of its determination (laboratory testing). Rock mass quality is accessed by taking the average values of UCS as the variation of UCS values can be quite substantial along the alignment of an engineering project. The average value of UCS can give a rough idea of the strength of intact rock to an extent, but for practice to be acceptable the sampling and testing should be performed accurately and effectively [44]. A limitation of using UCS as an indicator of rock mass quality is the relatively time-consuming and expensive nature of sample extraction. Even if the factor of time and cost is ignored complications due to the inability to extract a suitable representative sample for some rock types. Inevitably this means that rock mass quality cannot be directly classified from field investigation alone [45]**.** Rock engineering and civil projects also serve the purpose of indexing the cave-ins, susceptibility to dredge, hardness, ease of excavation, and rock rip ability [46, 47]. In several cases, Rock classification/characterization are based on the various parametric study of the internal structure and texture i.e., cohesion, friction angle, modulus of deformation, allowable bearing pressure, compressive strength, pressure due to support, rock mass shear strength [48] as shown in Table 2. The attractiveness of quantitative classification of rock mass stems from the fact that it provides a better link between geologists and engineers, relating different classification systems by use of existing correlation for a higher degree of accuracy while providing support following excavation, collocate proficiency about the rock mass properties and facilitating practice for engineers [2].

At present RMR [49], Q-system [50], RMi [35] happen to be the most widely used methods for classification of the rock, while GSI (Geological Strength Index) [51] is mostly utilized for characterization index of rock masses.

Table 2: Various classifications systems and the parameters used during their quantification

Parameter	RQD	RSR	RMR	RMR Basic	Q	QN	MRMR	RMS	MBR	SRMR	SMR	GSI	RCR	RMi
Block size	-	-	-	-	-	-	-	-	✓	-	-	-	-	✓
Joint orientation	-	✓	✓	-	-	-	-	-	✓	-	-	-	-	✓
Number of joint sets	-	-	-	-	✓	✓	-	✓	-	-	-	-	✓	✓
Joint length	-	-	-	-	-	-	-	-	-	-	-	-	-	✓
Joint Spacing	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Joint strength	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Rock type	-	✓	-	-	-	-	-	-	-	-	-	-	-	-
Stress Reduction Factor	-	-	-	-	✓	-	✓	-	✓	-	-	-	-	-
Groundwater condition	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	-
Uniaxial Compressive strength	-	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓

Utilization of more than one classification in rock engineering and excavation projects where rock mass is encountered becomes a necessity in place of both support requirements and economical design consideration. For this purpose, various researchers have developed correlations between different classification systems. The conceptual idea behind this practice is to determine the value of one classification when an already known value of the classification system is the input parameter for an empirical relation. It is uncommon to find an intact rock mass with consistent engineering properties in the regions under consideration. Variations in rock types, lithology, characteristics, and properties are prevalent in both ongoing and completed projects. Conducting in situ tests in these situations is often challenging, time-consuming, and expensive. Therefore, it is more appropriate and practical to employ average design values obtained from multiple empirical equations instead of relying solely on in situ measurements. This approach is better suited and realistic for the Himalayan rock mass context [52].

The relations are still being refined and verified in various geological conditions (i.e., Type of rock, in situ stresses, condition of joints and tectonic stresses, etc.) [1]. The discussion regarding which parameter is more detrimental during the development of an empirical relation has been ignored to some extent. Modification of RMR to develop RCR (Rock Condition rating) and Q to obtain QN (Rock Mass Number) and consequently put forward its correlation with RMR_{89} from RMR for a better relationship with GSI [34] is an interesting idea which needs to further be expanded to other classification systems.

Rock mass classification systems provide a practical framework for geotechnical assessments but are subject to uncertainties due to subjectivity, measurement limitations, and site-specific variability. Key sources of error include inconsistencies in parameter selection, stress reduction factor estimation, joint orientation characterization, and scale effects. The SRF values in the Q-system are empirically derived and highly dependent on stress conditions (e.g., high-stress squeezing vs. low-stress relaxation). Choosing an inappropriate SRF due to limited stress data can lead to over- or underestimation of tunnel stability. The influence of joint orientation on stability (e.g., favorable vs. unfavorable dips) depends on excavation direction, but this is often estimated based on limited field measurements. Variability in rock mass anisotropy can result in different engineers assigning different ratings for the same joint set.

The main aim of this research is to evaluate five classification systems (i.e., RMR, Q, GSI, RCR and QN) under various geological formations i.e., sedimentary, metamorphic, and igneous rocks and furthermore to develop correlations between above-mentioned classification systems as well as its comparison with the existing correlations. The motivation behind this study is to examine and verify the above-mentioned classification systems and compare the results obtained from field and laboratory tests with the existing correlations, identify the best correlation that can be used for tunneling/underground excavation projects in the region listed in Table 3, and also to identify the parameters that might weaken the correlation between classification systems if any. The study is carried out along the full project area of the Gulpur Hydropower Project, where sedimentary and metamorphic rocks were predominantly encountered.

Table 3: Correlations developed between various classification systems during tunneling/underground excavation

Correlation	Estimated Parameter	Reference(s)
RMR from *Q*	$RMR=5.37\ln Q+40.48$	[53]
RMR from *RMi*	$RMR = 7.5\ln RMi+36.8$	
RMR from *RMi*	$RMR=36.40.3RMi^{0.2705}$	
RMi from *Q*	$RMi=1.082Q^{0.4945}$	
RCR from QN	$RCR=6\ln QN+33.84$	
GSI from RMR	$GSI=0.692RMR_{89}+22.32$	
GSI from GSI (cai)	$GSI=0.917GSI_{(cai)}+3.18$	
RMR from *Q*	$RMR=8.15\ln Q+44.88$	[54]
RMR from *Q*	$RMR=42.87Q^{0.162}$	
RMR from *Q*	$RMR=6.3\ln Q+43$	[55]
RMR from *Q*	$RMR=8.09\ln Q+43.08$	[56]
GSI from RMR	$GSI=1.35RMR-16.4$	[57]
RMR from Q	$RMR=5.7\ln Q+43.65$	[58]
GSI from RMR	$GSI=0.73RMR-4.38$	[59]
RMR from Q	$RMR=2.87\ln Q+48.71$	[60]
GSI from RMR	$GSI=0.99RMR - 4.9$	
RMR from *Q*	$RMR=4.52\ln Q+43.635$	[61]
GSI from RMR	$GSI=1.21RMR-18.61$	[62]

2. BACKGROUND

2.1. Site Geology

The Gulpur Hydropower Project site is located approximately 10.5 km south of Kotli at 34°26’ latitude and 72°52’ longitude in AJK (Azad Jammu Kashmir) province. The weir is installed 6km downstream from the confluence of Poonch River and Bann Nullah. The area is mainly composed of mountains and has small farms and dwellings along the rivers.

The weir site has an area of approximately 3,658 km^2 and the Poonch River flows through a narrow gully with an inclination ratio of 1V: 200H. The area and structures that need to be constructed are shown in Fig. 1. It is located approximately 10.5 km south of Kotli on the Poonch River which is a tributary of the Jhelum River. The site is approximately 166.5 km away from Islamabad and 283.5 km from Lahore and is directly accessible from Islamabad and Lahore by a two-lane (and partially paved) mountainous road. The project/study area and structures to be developed are shown in Fig. 1.

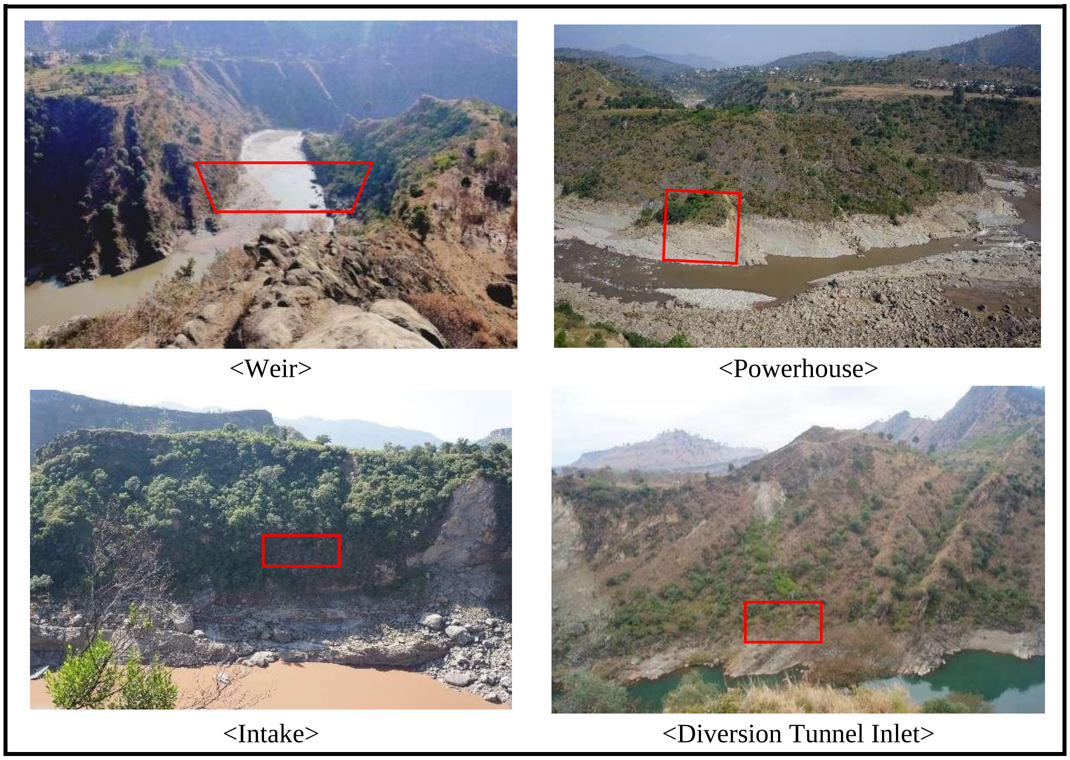


Fig. 1: Location and view of structures

The bedrock of the project area is composed of the Siwaliks Formation which mainly consists of sandstone, siltstone, mudstone and conglomerates of Miocene to Pliocene age. The 5,000 m thick Siwaliks Formation is distributed along the Main Boundary Fault which separates the Siwaliks Formation from the relatively older Murree Formation [63].

The project site consists of the Nagri Formation in the Siwaliks group. The geological formation and rock description of the project area are shown in Table 4. The Himalaya is an active mountain belt that terminates at both ends in nearly transverse syntaxes, i.e. areas where orogenic structures turn sharply about a vertical axis [64]. The western Himalayas in northern Pakistan consists of two northward-projecting loops or reentrants: the larger Hazara-Kashmir syntaxis and the smaller Indus syntaxis connected by a broad arcuate belt (the western arc). The dominant tectonic feature in the project area is the seismically active Hazara-Kashmir Syntaxis (HKS), based on the recent October 8, 2005, Hazara-Kashmir earthquake. The overall syntaxis is a sequence of Precambrian to Quarternary rocks that are deformed during the pre-Himalayan and Himalayan orogenesis [65]. HKS is a NNW trending regional scale antiform that folds the lesser and Sub Himalayas and some extent the Higher Himalayas. Tectonically, it is a complex tectonic zone and difficult to define its outer limit, though its axial zone is well defined by a stack of thrust faults that form a loop around its axis.

Chinji Formation: Claystone and sandstone are two types of rock. Intercalated with sandstone, the claystone is brick red, friable, firm, and intercalated. The sandstone is dark grey to brownish grey, soft, and cross-bedded, with a medium to thick-bedding texture. The thickness varies between 880 and 1,165 meters. The Nagri Formation's upper contact is conformable. The base was dated at 14.3 Ma by fission-track dating of volcanic ash at the type locality [66].

Nagri Formation: Sandstone, Claystone, and conglomerate are all types of sandstone. The sandstone is grey, greenish grey, and brownish grey, with a salt-and-pepper surface, determined by magnetite and ilmenite. It is medium to coarse-grained, thick-bedded, cross-bedded, and calcareous. The claystone is sandy or silty and is brown, reddish grey, and orange in color. The thickness varies from 500 to 900 meters. The Dhok Pathan Formation, which lies above it, is conformable. The base was dated at around 10.8 Ma by fission-track dating of volcanic ash near the type site [66].

Dhok Pathan Formation: Sandstone and claystone with conglomerate lenses in the top portion. Light grey, fine to medium grained, medium bedded, and cross-bedded sandstone. The claystone is firm and compact, with an orange red and chocolate brown coloration. The thickness ranges from 500 to 825 meters. The Soan Formation is interbedded due to the formation of the above layer. The base was dated at around 8.5 Ma by fission-track dating near the type locality [66].

Soan Formation: Sandstone, siltstone, and claystone conglomerate and subordinate interbed. The conglomerate clasts, which range in size from pebbles to boulders, are made up of around 80% rounded quartzite, 10% fine-grained volcanic trap rock, and 10% Siwalik Group metamorphic and sedimentary rocks. In a calcareous sandy matrix, clasts are cemented. The sandstone is soft, greenish-grey, and coarse-grained. The claystone is soft and orange, brown, and pale pink in color. The thickness of the exposed layer is 200–300 m. The upper contact between the Lei Conglomerate and younger layers is an older than 1.6±0.18 Ma unconformity [67]. Locally, the base rests on an anticline dated at 1.9±0.4 Ma by fission-track dating of volcanic ash [68].

Table 4: Detail of formation and rock description

Era	**Formation**		**Rock description**
Holocene	Surficial Deposits		gravel, sand, and silt
		Unconformity	
Pleistocene		Mirpur Conglomerate	Mainly conglomerates
Early Pleistocene to Pliocene	Siwalik Group	Soan Formation	Claystone, Silt Stone with subordinate conglomerates
Early Pliocene to Late Miocene		Dhok Pathan Formation	Sandstone with alternate dull red silty clay and conglomerates
Late Miocene		Nagri Formation	Massive Sandstone with mudstone and conglomerate
Late to Middle Miocene		Chinji Formation	Claystone with sandstone and conglomerate
Early Miocene	Rawalpindi Group	Murree Formation	Dark red sandstone and siltstone with lenses of conglomerate

2.2. Bed Rock Classification

During the field investigation, lithological properties of the bedrock are classified as three rock units described here:

Hard Competent Sandstone (HCS): It is a massive and blocky sandstone and forms linear cliffs which are quite prominent in the area [69]. It is greenish-grey and medium to coarse-grained. A hanging bridge is developed on this sandstone.

Soft Sandstone (SS): Soft sandstone has developed with a gradational contact with HCS. It is distinguished in the field with its grey shining color and medium to the fine-grained texture of the rock. It is not blocky as it shows a fine layered bedding structure. These beds are mostly located in the gullies with higher weathering as compared to HCS. On hammering, there is no bouncing back unlike HCS. This sandstone also shows ex-foliation.

Silty Sandstone with Mud/Clay Beds (SSM): These beds are quite prominent in gullies and riverbeds and are highly weathered. Silty beds are light greenish-grey and are medium to fine-grained. Mud/clay beds within silty sandstone are identified from their light pink color, and highly weathered and fractured surface [69]. In general, mudstone beds are highly weathered and fractured and some layers are hard and compact. Its color is slightly reddish mud.

2.3. Rock Mass Classification

The rock mass classification for the project was carried out through five systems: RMR, Q-system, QN, RCR and GSI for underground structures. The weathering grade system is based on the weathering grades of weak and weathered rock modified from [70]. This classification system was used for the foundation of the weir system and slope stability analysis. The parameters for the rock mass classification were obtained during the surface geological and borehole investigations. The rock mass class or rock mass quality is grouped into five classes based on RMR, Q and GSI values, since RCR and QN are derivate of RMR and Q and use the same classes as their parent system. The system in place for categorizing the rock based on their quality is shown in Table 4.

2.4. Fracture Condition

The linear hard cliffs show a general trend of N40W. The area is a part of Gulpur's asymmetrical syncline which lies NW (north-west) to SE (south-east) direction. The dam site is on its northern flank. Data regarding the dip and strike of various beds are provided in Fig. 2, which represents the entire study area.

Slope angles for SS and SSM range from 50° to 60°. Hard Competent sandstone (HCS) shows relatively steep slopes. As most of the terraces are filled with soil and thick pushes, no recognizable lineament such as a large shear zone is observed.

2.5. Hard Competent Sandstone (HCS)

Fractures are well developed. There are two to three master joints. Joints are open to healing. Width of the aperture varies from less than 1mm to more than 3cm which is mostly clean. Joint surfaces are slightly smooth to slightly rough. Healing by siliceous material has also been seen along some joints and fracturing is less common in this layer. Most fractures are along with bedding plans.

Massive sandstone develops a weaker zone at contact with SSM and is less common with SS due to gradational contact. Regional weaker zones along massive sandstone usually disintegrate on large scale.

2.6. Weak Soft Sandstone (SS)

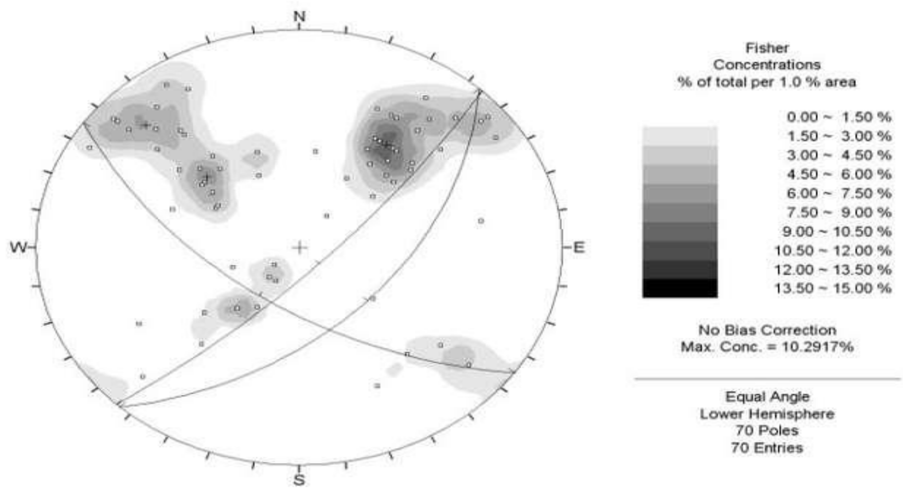
Bedding planes and fractures are plotted in Fig. 2 (a) and (b). Joints are developed perpendicular to the bedding (strike NE with dipping to SE/NW). The fracture data show two major sets of bedding joints and anti-dipping joints. Joints perpendicular to the bedding in the mapping area were measured in a few places and not considered a major joint set. The fractures developed in the mapping area are characterized as a simple joint system related to the bedding compared to other fracture data. This result is ascribed to the characteristics of the mapping area. A relatively small area of mapping - the mapping along the bedding direction.

2.7. Silty Sandstone with Mudstone/ Claystone (SSM)

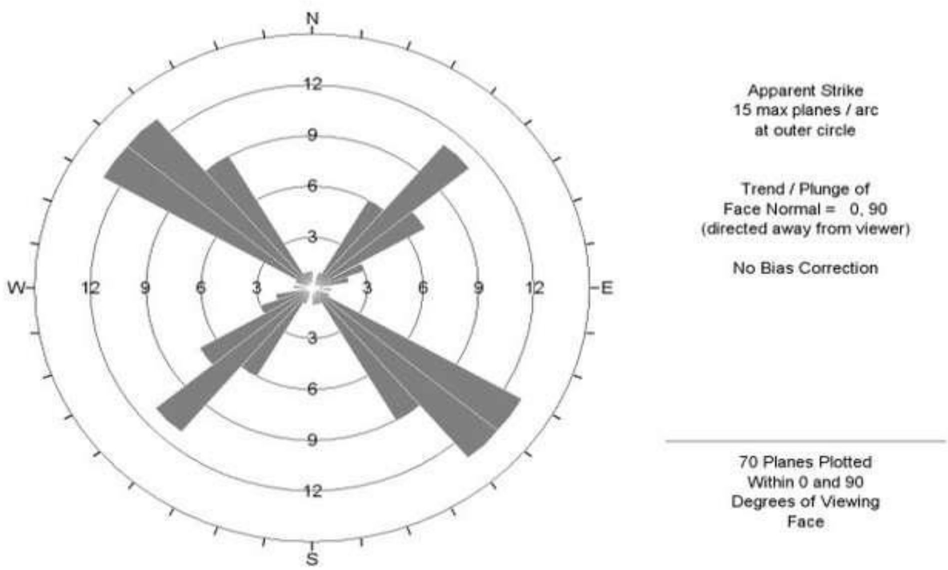
Joints and bedding planes follow the regional pattern as part of the Nagri Formation noted for the other two formations. The orientations of fractures and beddings in the project area are plotted in Fig. 2 (a) and (b). The NE (north-east) trending fractures seem to be a joint set in SS. During the detailed design stage, an additional fracture mapping was carried out from the diversion outlet to the powerhouse area in the vicinity of the final powerhouse site, as shown in Fig. 3 (a) and (b). Three types of fractures were identified during the fracture mapping as follows:-

- Bedding joint: Joints are developed along the bedding strike NW (north-west), dipping to SW (south-west).
- Joint along with the bedding: Joints are developed parallel to the bedding and dip against the bedding plane (strike NW with dipping NE).
- Joint perpendicular to the bedding: Joints are developed perpendicular to bedding (strike NE with dipping to SE/NW).

Bedding and Joint



(a)

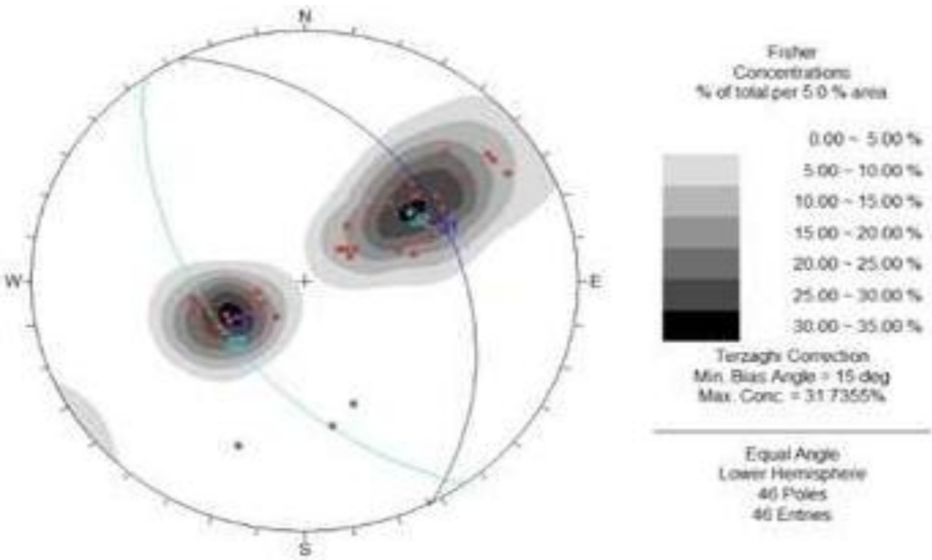


(b)

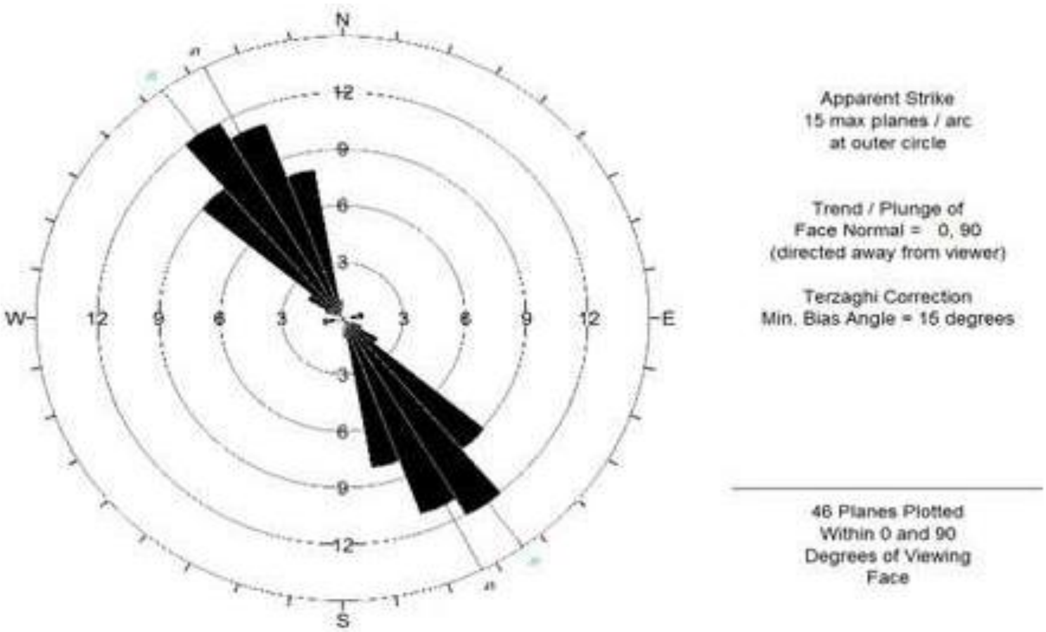
N55W/60SW(215/60) Bedding, N43E/51SE(133/51), N44E/78SE(134/78)

Fig. 2: (a) and (b) Orientation of bedding and fracture in study area

Bedding and Joint



(a)



(b)

N36W/51SW(234/51), N27W/32NE(63/32)

Fig. 3: (a) and (b) Orientation of bedding and fractures from the fracture mapping in the vicinity of the powerhouse

2.8. Discontinuity Condition

The study of evaluating the condition of discontinuity along the study area is an important feature for rock engineering projects. These studies were conducted along the strata of selected alignments of rock mass by using borehole logs [71]. The discontinuities that were intersecting each other were recorded by the use of measuring tapes of 5-15 m. These parameters were measured by the use of guidelines mentioned by the International Society of Rock Mechanics [72]. For the determination of the discontinuity condition, the orientation, joint, set, aperture, persistence, groundwater condition, infilling, roughness, and spacing were recorded for 240 sampling sites along the study area.

Discernment of the structural features and discontinuities will affect the rock properties and its use in tunneling, where strata are predominantly composed of rock. After the discontinuity study, RQD (Rock Quality Designation) was recorded and the values of UCS were obtained from laboratory testing. Stereographic projections for drawing contours diagrams were performed on Dip 5.1 computer software for the study area as shown in Fig. 2 (a-b) and Fig. 3 (a-b).

2.9. Location of Sample Collection

Fig. 4 shows the geological map and investigation plan for the study area (Gulpur Hydropower Project). Based on the structure proposed in the individual sections, the sampling sites were distributed in 7 sections. There were 240 sampling sites in total. Table 5 shows the mean rating of classification systems in these sections.

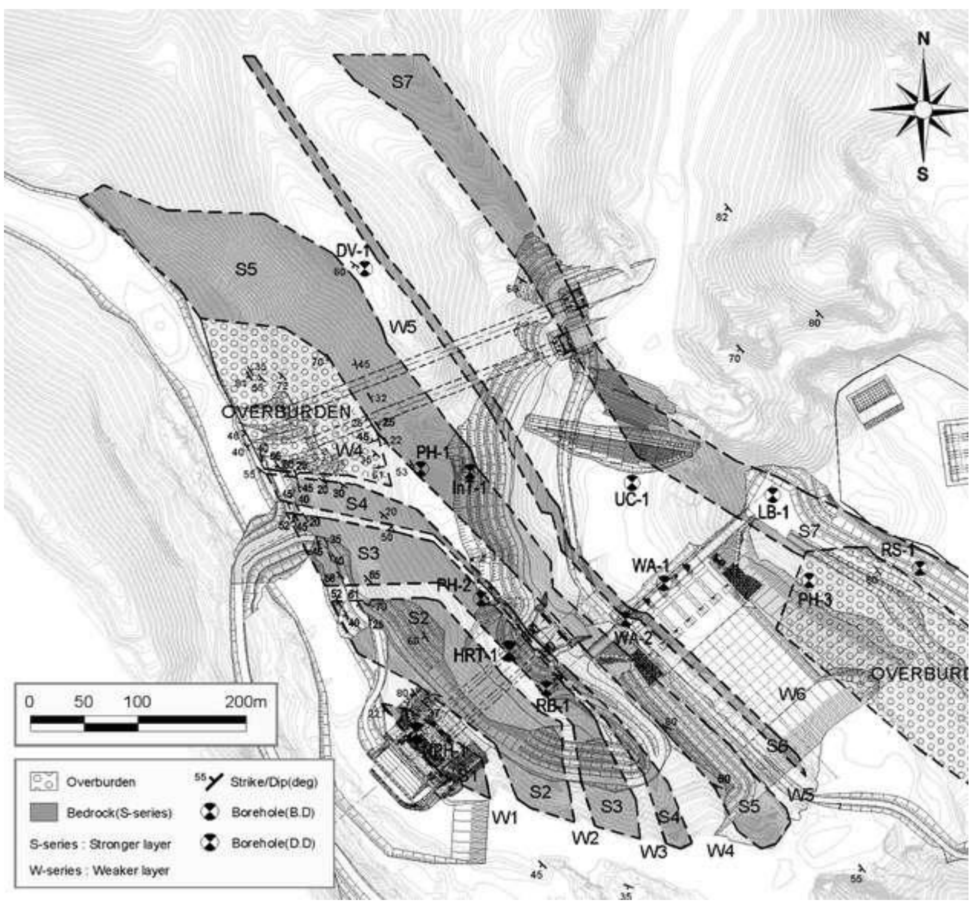


Fig. 4: Geological map and investigation plan of Gulpur Hydropower Project/Study Area

Table 5: Summary of rock mass classification rating along with Project/Study Area

Geological Unit	Borehole No.	Rock Type	Mean Rating Value		
			RMR	**Q**	**GSI**
W4	PH-2	MS and Siltstone (SSM)	43.37	15.84	46.35
S5	InT-1	Sandstone (HCS)	47.43	13.45	49.34
	PH-1	Sandstone (HCS)	44.04	14.8	46.8
	PH-2	Sandstone (HCS)	45.24	15.12	49.2
W5	InT-1	MS and Siltstone (SSM)	47.1	13.24	48.7
	PH-1	MS and Siltstone (SSM)	45	15	48
	DV-1	MS and Siltstone (SSM)	43.74	9.38	46.45
	WA-2	MS and Siltstone (SSM)	42.45	10	47
S6	DV-1	Sandstone (HCS))	44.12	10.5	47.5
	WA-2	Sandstone (SS)	43.12	10.4	47.5
W6	WA-1	MS and Siltstone (SSM)	27.72	2.02	31.6
	WA-2	MS and Siltstone (SSM)	42.45	10	47
	UC-1	MS and Siltstone (SSM)	32.2	2.4	36.5
	DV-1	MS and Siltstone (SSM)	43	10	47
	PH-3	MS and Siltstone (SSM)	35.8	3.84	38.72
S7	LB-1	Sandstone (SS)	41.5	8.69	45
	PH-3	Sandstone (HCS)	37.5	5.2	41.4
	RS-1	Sandstone (HCS)	33.8	2.55	35.8
W7	LB-1	MS and Siltstone (SSM)	42.12	9.5	47.5
	RS-1	MS and Siltstone (SSM)	34	3.12	36.2

3. METHODOLOGY

3.1. Overview of investigations

The activities of the geological investigation and geotechnical evaluation carried out during the basic and detailed design stages are summarized in Tables 6 and 7 as follows:

Table 6: Work scopes of the geological and geotechnical evaluation during the basic design stage

	Surface investigation		
Satellite image analysis	- Major deformation zone analysis in the area	Lump-sum	Project area
Surface geological Investigation	- Geological maps and Geological sections at the major facility sites	Lump-sum	Project area
Seismic Refraction survey	- Distribution of geological structures and anomaly zones - Data for the overburden thickness	1,294m	
Electrical Resistivity survey	- Distribution of geological structures and anomaly zones	1,400m	
	Sub-surface Investigation		
Borehole Investigation - Core drilling	-Distribution of overburden and bedrock in the major facility sites -Sampling of intact rock material for laboratory investigations	13 drilling holes	Major structure sites
	Laboratory Investigation		

Physical Properties of intact rock	- Specific gravity and unit weight - Basic properties of core samples	49 times 49 times	Pakistan
Point load test	- Strength index on core samples	6 times	Pakistan
Strength index properties	- Young's modulus, - Poisson's ratio - Uniaxial compressive strength - Indirect tensile strength - AE/DRA	49 times 65 times 11 times 2 times	Pakistan
Shear strength on intact rock and joint	- Triaxial compressive test - Joint shear test	12 times 4 times	Pakistan
Lithology of rock	- Petrographic Analysis	2 times	Pakistan

Table 7: Scope of geological and geotechnical evaluation in the detailed design stage

Surface investigation			
Surface geological Investigation	- Geological and fracture survey	Lump-sum	Access roads Powerhouse, etc.
Laboratory Investigation for Rock			
Physical Properties of intact rock	- Specific gravity and unit weight - Basic properties of core samples	12 times 12 times	Pakistan
Wave Velocity Test	- Vp, Vs	12 times	Pakistan
Strength index properties	- Young's modulus, - Poisson's ratio - Uniaxial compressive strength - Indirect tensile strength	12 times 15 times 10 times	Pakistan
Shear strength on intact rock	- Triaxial compressive test - Direct shear strength - Joint shear test	17 times 8 times 1 time	Pakistan

3.2. Methodology of Site Investigations

The methodology of the site investigation has been described in detail in the geological and geotechnical investigation of the Basic Design Report. In this report, it is briefly summarized.

The major investigations are included:

- Lineament analysis
- Scan line survey
- Rock mass classification
- Borehole investigation and in-situ tests
- Ground geophysical survey
- Laboratory tests

3.2.1. Lineament identification

Topography, geology, and satellite images were constructed into the spatial database. Digital elevation, slope, aspect, curvature, and hill shade of topography were calculated from the topographic database, and lithology was imported from the geological database. The lineaments were interpreted from the mosaicked-false color composite image of the recent Landsat-8 OLI and form four computerized-shaded relief images of DEM (Digital Elevation Model) illuminated from the west, N45W, north and N45E, respectively.

DEM, unlike Landsat images, represents the true projections with no distortion; tonal variations are entirely identified with relief, the sun position can be placed anywhere above the terrain surface and DEM or image has better resolution than satellite images.

3.2.2. Scan line survey

The fracture measurements during the scan line survey were carried out as the following process:

- The orientation of scan lines follows along the strike or maximum dip direction of the outcrop investigated.
- The location and orientation of fractures, with a truncation length of 50cm, were recorded during this scan line mapping.
- Orientation is expressed by degrees as the dip direction and dip angle of the discontinuity measured at the point of intersection with the scan line.
- Roughness was measured by taking an impression or profile of the surface as shown in Fig. 5 and the results from scan line survey are provided in Table 8.
- The maximum trace length of fractures is dependent on the areal size of the outcrop.
- Size, orientation, surface geometry, and other clues may together indicate whether the discontinuity is a fault, joint, bedding plane, cleavage, or other features.

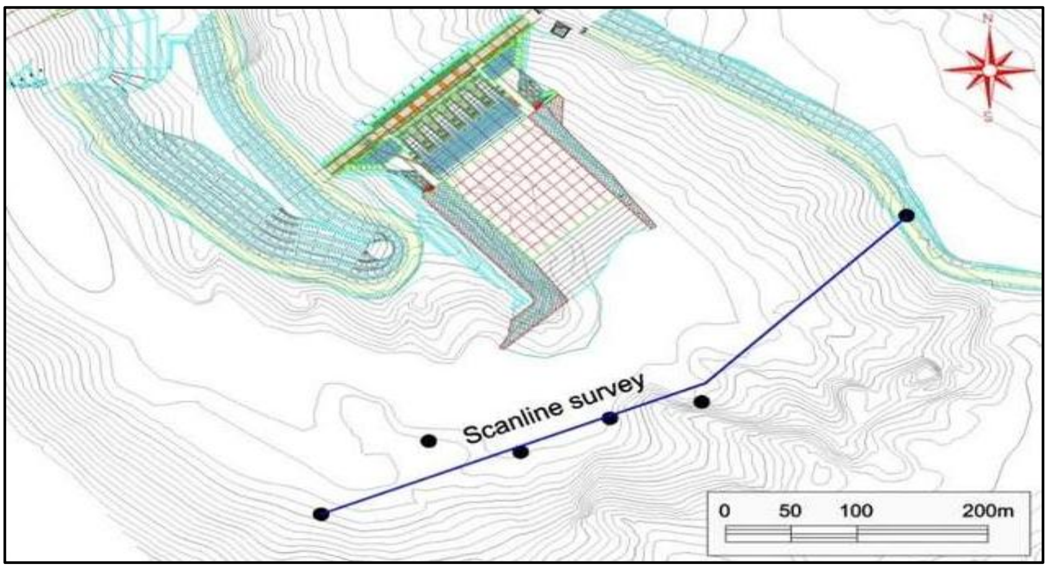


Fig. 5: Scan-line survey conducted opposite the Kamili Ridge tongue

Table 8: Joint and bedding data from scan line survey

Set	Type	Dip direction/Dip	Spacing (mm)	Persistence (m)	Joint filling
1	Joint/Bedding	215/51	398.6	6.9	Inactive clay
2	Joint	39/24	512.5	2.0	Non cohesive /Inactive clay
3	Joint	131/83	400.0	4.7	Inactive clay

3.2.3. Rock mass Classification

The rock mass classification for the project was carried out through two systems: Weathering grade system for near-surface structures and RMR/Q-system for underground structures. The weathering grade system is based on the weathering grades of weak and weathered rock modified from [70] as shown in Table 9. This classification system was used for the foundation of the weir system and slope stability analysis. Since the weathering grade system is somewhat qualitative, the system is enhanced by quantification of the RMR/Q-system. Meanwhile, RMR/Q-system is applied mainly for underground structures such as tunnels for waterways and diversion.

Table 9: Weathering grades of weak and weathered rock modified from [70, 73]

Classification	General Description	Specific Description	
		Weathered Material(1)	**Weak Rock Material(2)**
Grade I (Fresh)	100 percent rock; no discoloration, decomposition, or other change.	Unchanged from the original state.	-
Grade II (Slightly decomposed)	100 percent rock; discontinuity surfaces or rock material may be discolored.	Slight discoloration and slight weakening.	-
Grade III (Moderately decomposed)	Up to 50 percent soil from the decomposition of the rock mass.	Considerably weakened, penetrative discoloring; large pieces cannot be broken by hand.	Un-weathered. Original strength, color, and fracture spacing.
Grade IV (Highly decomposed)	50-100 percent soil from the decomposition of the rock mass.	Large pieces can be broken by hand; does not readily slake when a dry sample is immersed in water.	Partially or distinctly weathered. Weakened, close fracture spacing, weathering penetrating in from fractures, brown oxidation.
Grade V (Completely decomposed)	The rock is changed to the soil in which the original rock texture is (mainly) preserved.	Considerably weakened, slakes, and the original texture is apparent.	De-structured. Greatly weakened, mottled, ordered *lithorelicts* in matrix becoming weakened and disordered, bedding disturbed.
Grade VI (Residual soil)	The rock is completely changed to soil in which the original rock texture has been destroyed.	Soil is derived by in situ weathering but retains none of the original texture or fabric.	Residual or reworked. Matrix with occasional altered random or “apparent” *lithorelicts*, bedding destroyed.

: Uniform weathered materials such as igneous and metamorphic rocks, which may show weakening and susceptibility to slaking on weathering.

: Materials that incorporate both matrix and mass features; weathering is enhanced along with fractures, but most weathering occurs near the ground surface. Includes over-consolidated clays, shales, and mudstones.

The parameters for the rock mass classification were obtained during the surface geological and borehole investigations. The rock mass class or rock mass quality is grouped into five classes based on RMR and Q values. This class will be a guideline for excavation and support systems for tunneling. Rock mass is qualified based on five descriptions i.e, very good rock (RMR 81-100 Q index > 40), good rock (RMR 61-80 Q index 10-39), fair rock (RMR 41-60 Q index 4-9), poor (RMR 21-40 Q index 1-3) and very poor rock (RMR < 20 Q index < 1).

3.2.4. Borehole Investigation-Core drilling

The objectives of borehole investigation with core drilling are to determine subsurface characteristics of overburden thickness, geological condition of bedrocks, and fracture zones.

For boreholes located in the flat areas, the drilling rig was secured by the additional load on both skids to minimize movement and vibration during drilling. If the drilling site was not flat, the area was flattened before the drilling rig was emplaced and the same manner was applied to secure for the drilling rig.

Core samples obtained were laid in standard 1.0m long core boxes. The site geologist logged and photographed the core boxes before transporting the core specimen for laboratory testing. The sub-contractor prepared the geological logs of each borehole simultaneously with drilling in a standard format and the Consultant personnel confirmed the core logging data.

3.2.5. Seismic survey

In the basic design stage, a 24-channel signal enhancement seismograph "GEODE" of Geometrics, USA was used in the field for the recording of the arrival time of seismic waves. For 230 meters long profile, 24 geophones were planted on the ground surface in an almost straight line at an interval of 10 meters along with the seismic profile. The following equipment was used for seismic data acquisition:

- Seismograph: GEODE with 24 Channels
- Geophones: 10Hz, 125mm spike length
- Seismic Cables: Seismic cables have 12 takeouts at 10 meters spacing
- Triggering device: High-frequency geophone
- Laptop: Vipor
- Software: Geometrics Seismodule Controller

The geophysical data were processed by computer-aided software SeisImager (Pickwin and Plotrefa Modules) of Geometrics, the USA to correlate it with manual interpretation and confirmation of manually interpreted layers. The interpretation of observed seismic wave velocities in terms of lithology was based on a generalized correlation keeping in view the observed geology of the project area and the available data of the boreholes.

The interpretation of seismic refraction data in terms of velocity of subsurface layers had shown that the top near-surface layer representing overburden material consisting of sandy silt on terraces displayed seismic wave velocity less than 1,000m/sec. The top layer along profiles taken in the river bed showed velocity ranging between 1,000 to 1,500m/sec, representing dense overburden with gravel, cobbles, and boulders embedded in a silty sand matrix. The seismic wave velocity of more than 1,500m/sec was interpreted to represent bedrock. The difference in seismic wave velocity of rocks was interpreted in related mainly to the degree of jointing/fracturing and compactness/strength of the rocks.

For this study, the methods for classification of rock were selected based on their level of use in other engineering projects and accuracy for a safe and economical design. Rock Mass Rating (RMR), Rock Mass Number (QN), Quality system (Q), Geological Strength Index (GSI), and Rock Condition Rating (RCR) were used throughout the study area as mentioned in Table 5 from W4-W7. The choice of RCR and QN as classification systems is justified by their specific strengths and suitability for different applications. RCR is ideal for assessing weak to moderately strong rock masses, particularly in civil engineering projects where stability and deformability are critical. In contrast, QN is better suited for high-stress environments and large-scale excavations, such as those encountered in mining or deep tunneling as shown in Table 10.

Table 10 Comparison and use of RCR and QN classification system

Aspect	RCR	QN
Primary Use	Weak to moderately strong rock masses; stability and deformability.	High-stress environments; deep excavations; mining.
Key Parameters	Intact rock strength, joint conditions, groundwater.	Stress reduction factor (SRF), joint conditions, excavation dimensions
Reliability	High for weak rock masses; lower for very strong or massive rocks.	High for high-stress conditions; lower for shallow or low-stress environments.

Practical Usability	Easy to use in the field; relies on qualitative judgments.	Requires detailed input; less user-friendly for quick assessments.
Strengths	Comprehensive assessment of rock mass behavior; suitable for weak rocks.	Explicitly accounts for stress and scale effects; widely used in mining.
Limitations	Subjective assessments; less suitable for very strong rocks.	Complex parameter estimation; less useful in low-stress environments.

The oldest and most widely used RMR system was introduced by [20]**.** This system was dependent on the parametric study of Uniaxial Compressive Strength (UCS), discontinuity spacing, groundwater condition, condition of discontinuity, rock quality designation (RQD) and orientation of discontinuities. The latest iteration of this system [74] has been utilized in this study. The joint orientation has been adjusted in the basic rating of RMR to use the latest version. The study indicates that the difference in rating for old and new system is about (±3), which is negligible when in case of designing a support systems or determining the type and quality of rock.

A relatively new system Geological Strength Index was proposed by [75] for the characterization of rocks by the qualitative method. The system indexes rock based on its appearance and texture. A distinct relationship between the quality of rock mass and GSI does exist.

A modified version of Quality-system (Q) was proposed by [34]. In this modified version the parameter that contributed to stress reduction was taken as constant with a value of 1 from the original equation. The modified version was named Rock Mass Number (QN).

$$Q = \left(\frac{RQD}{J_n}\right)\left(\frac{J_r}{J_a}\right)(J_w) \tag{1}$$

Rock condition rating (RCR) was introduced [76] by dropping the ratings for UCS and joint orientation from the RMR formulation as follows [1]:

RCR=RMR- (Rating for ‘c’ and joint orientation)

4. RESULTS AND DISCUSSION

The study area was divided into 7 sections as shown in Fig. 4 where construction of various structures was proposed i.e., weir, diversion tunnel, powerhouse, storage unit, etc. the initial geological investigation indicated the presence of both hard compacted and soft sandstone, silt and mudstone with the occasional occurrence of conglomerates. The classification of rock in all the investigation sections was performed by making use of 5 classification systems i.e., RMR (Latest Iteration), Quality System (Q), QN, GSI, and RCR. For exploration and investigation boreholes and logs at the various length of sections were performed through drilling and outcrop identification. The sample was then tested in the laboratory for evaluation of uniaxial compressive strength with the help of a compression testing machine. Afterward, individual ratings of all the parameters was performed as per the standards mentioned in ISRM. The results indicate the presence of very weak to good rocks for RMR. Hard sandstone contained a high quantity of ferrous material and sulfate which was evident from its brownish to a black color and was found in the Nagri formation. The weaker quality rocks were extracted from Chinji formation with a greenish-grey discoloration and presence of siliceous layer stratification. These rocks underneath diagonal dykes and were found to be on top of hard sandstone which exposed these rocks to weathering action from rain and high-velocity winds. During the evaluation of Q system ratings high/very good quality rock were recorded further investigation reveals the presence of a sandstones mixed with conglomerates with a high quantity of calcareous minerals in the Mirpur formation.

After the rating of all the classification systems statistical approach was utilized to form a correlation between RMR-Q, GSI-Q, GSI-RMR, RCR-Q, RCR-QN, RCR-RMR, and GSI-RCR. The relationship was checked for all the available trends i.e., logarithmic, linear, polynomial, exponential and power. The trend line which provided the best correlation coefficient was selected as the relationship between the two classification systems.

The results were also checked with existing correlations to evaluate the best possible method that can be utilized for the type of rock encountered in the area and whether that equation can be used if a different type of rock is available, if not what could be a possible parameter that weakens the correlation.

4.1. Development of Correlation

The use of statistical analysis for developing correlation gives 5 different trends as shown in Fig. 5 the best possible correlation between RMR-Q is obtained through the use best fit curve by power method (R^2 = 0.89).

It is evident from Fig. 5 that most of the data calculated from the Q-system is scattered around 1-20 which shows rock of poor to fair/good quality. The data scatter for Q rating will be in most cases higher (high standard deviation) because the total range in this system categorizes rocks from 0.001 to 1000. As can be observed in Fig. 6 some of the rock also falls in the range of very good quality which shows the presence of competent sandstones and conglomerates.

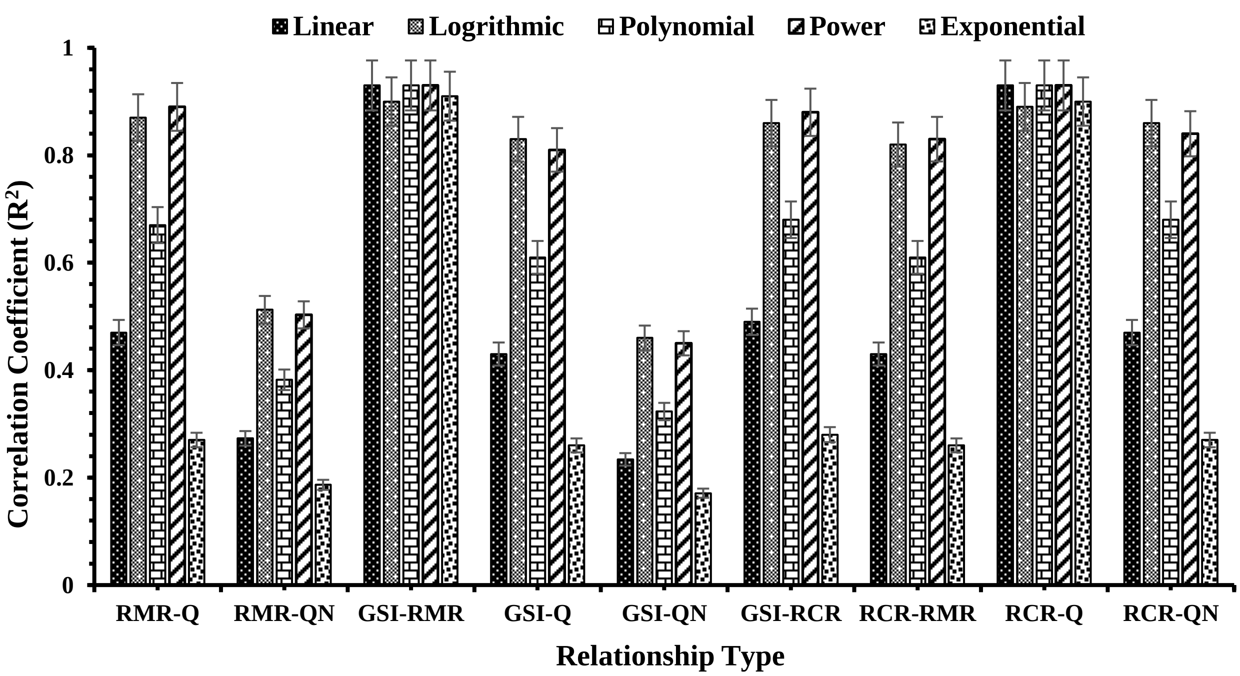


Fig. 6: Result of statistical analysis by using (i) Linear (ii) Logarithmic (iii) Polynomial (iv) Power and (v) Exponential Curves

The relationship developed for GSI-RMR showed an equal value of correlation coefficient (R^2) for linear and power curves. So, both these trends are suitable in this case shown in Figure. The relationship between GSI-Q logarithmic and power trend shows the best available correlation coefficient (R^2>0.8).

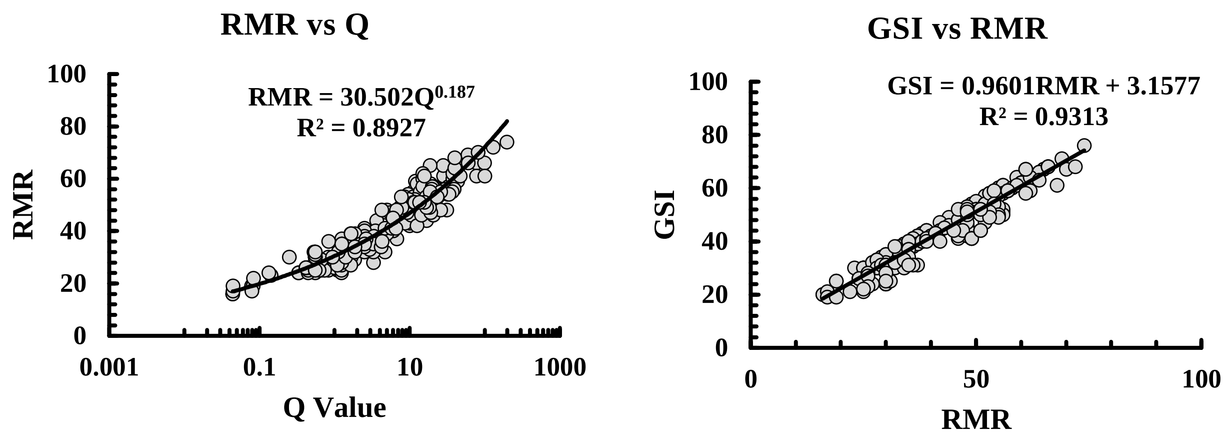
In the same manner, all possible correlations between 5 classifications were checked with the help of a statistical approach and relationship with the highest value of R^2 was chosen as the result of studies conducted for the study area. Fig. 6(a-b), Fig. 7(a-b), Fig. 8(a-b) and Fig. 9(a-b) shows the results of borehole log, laboratory testing and standard guidelines by [77] for assigning discontinuity ratings. All the relationships and their corresponding correlation coefficient (R^2) are given below in Table 11.

From Table 11 it was observed that the strongest correlations are between GSI and RMR (R^2=0.93) and between RMR and Q (R^2 =0.89). These high R^2 values indicate that these relationships are robust and can be reliably used for conversion between systems. The strong correlation between RCR and Q (R 2 =0.86) is also noteworthy, as it provides a reliable link between these two systems. Correlations involving QN (e.g., RMR-QN, GSI-QN, RCR-QN) generally have lower R 2 values, indicating greater variability and less reliability. This is likely due to the additional normalization step in QN, which introduces uncertainty. The quadratic correlation between RCR and RMR (R^2 =0.604) is also relatively weak, suggesting that a simple linear relationship may not adequately capture the relationship between these variables. It is recommended to prioritize using correlations with high R^2 values (e.g., GSI-RMR, RMR-Q) for reliable conversions between classification systems. Correlations with lower R^2 values (e.g., GSI-QN, RCR-RMR) should be used with caution and supplemented with additional data or site-specific calibrations.

Table 11: Proposed correlations based on geological data

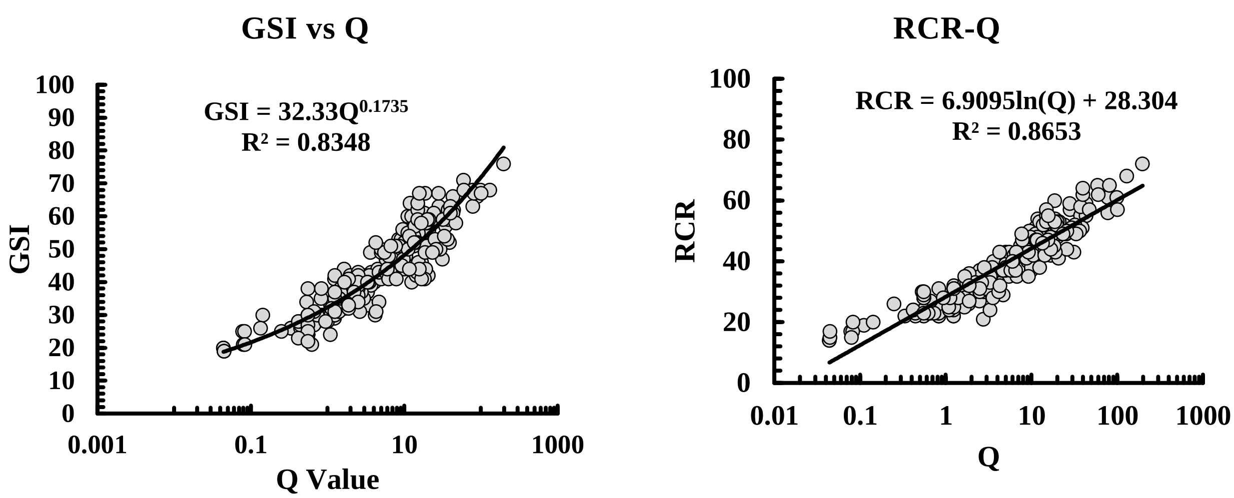
Proposed correlations	**Correlations coefficients (R^2)**
$RMR = 30.502\ Q^{0.187}$	0.89
$RMR = 32.205\ QN^{0.146}$	0.52
$GSI = 0.9601RMR + 3.157$	0.93
$GSI = 7.04\ \ln(Q) + 33.32$	0.82
$GSI = 5.33\ \ln(QN) + 35.66$	0.47
$GSI = 0.702RCR + 7.98$	0.55
$RCR = 6.91\ \ln(Q) + 28.30$	0.86
$RCR = -0.0016RMR^2 + 0.8686RMR + 5.0579$	0.604
$RCR = 27.39QN^{0.1938}$	0.89

The graphical representation of the above-mentioned equations is shown in Fig. 7 (a-b), Fig. 8 (a-b), Fig. 9 (a-b) and Fig. 10 (a-b) it is evident from the developed correlations that the best estimation of one classification from one another is strongest when comparing RMR-Q, GSI-RMR, GSI-Q, RCR-Q and RCR-QN. The parameters that are most critical from the results obtained are joint orientation, and stress reduction factor, since the confidence level in the relationship between RMR-QN, GSI-QN, GSI-RCR and RCR-RMR is less than 60 % in all the cases. As we know that RCR and QN are relatively new systems and are developed by modifying the existing RMR and Q classifications so the use of these systems should be (i) limited to certain types of rocks i.e., where the orientation of dip and strike are in either favorable or very favorable in tunnel, mines and foundations and very favorable in sloping ground excavations (ii) the stress reduction factor should only be excluded if the rocks are competent with low to medium amount of shear under favorable stress conditions. The relationship between RCR-QN is showing a confidence level of R^2=0.89 from which it can be concluded that if the classification used are both devoid of joint orientation and stress reduction factor then the use of these systems is applicable but due to less-than-ideal research on these systems, their use in actual construction projects is nonexistent.



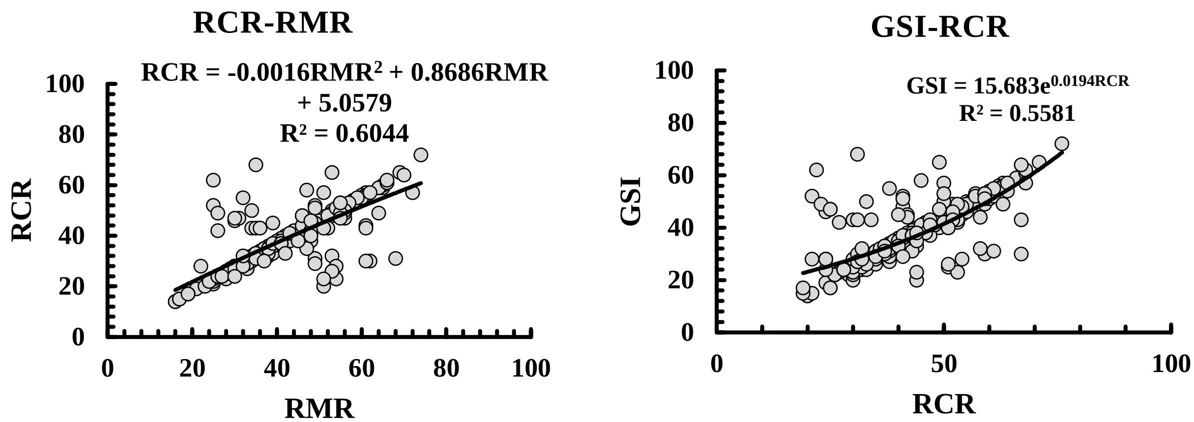
(a) (b)

Fig. 7: Result of correlation developed for the study area (a) RMR-Q (b) GSI-RMR



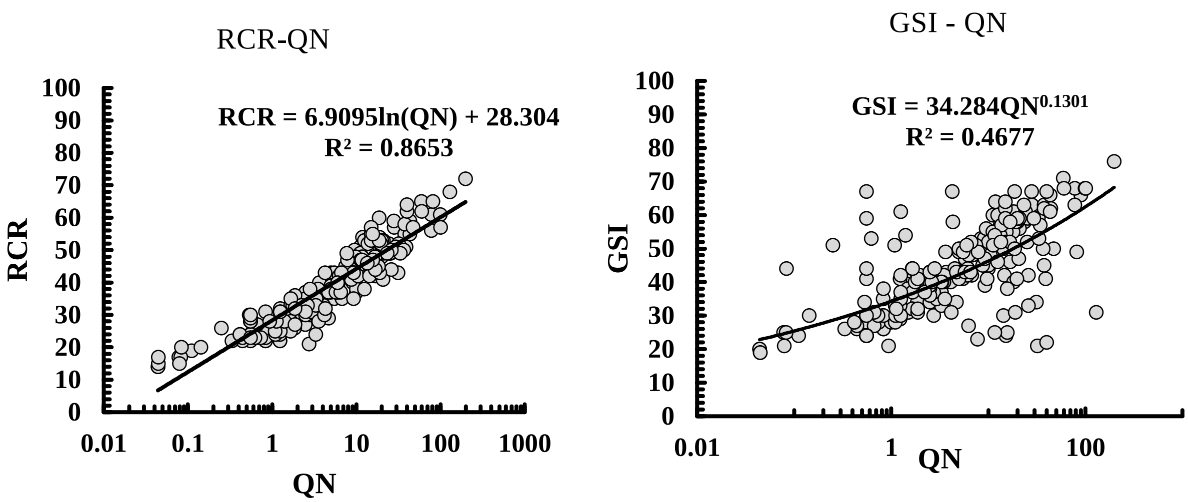
(a) (b)

Fig. 8: Result of correlation developed for the study area (a) GSI-Q (b) RCR-Q



(a) (b)

Fig. 9: Result of correlation developed for the study area (a) RCR-RMR (b) GSI-RCR



(a) (b)

Fig. 10: Result of correlation developed for the study area (a) RCR-QN and (b) GSI-QN

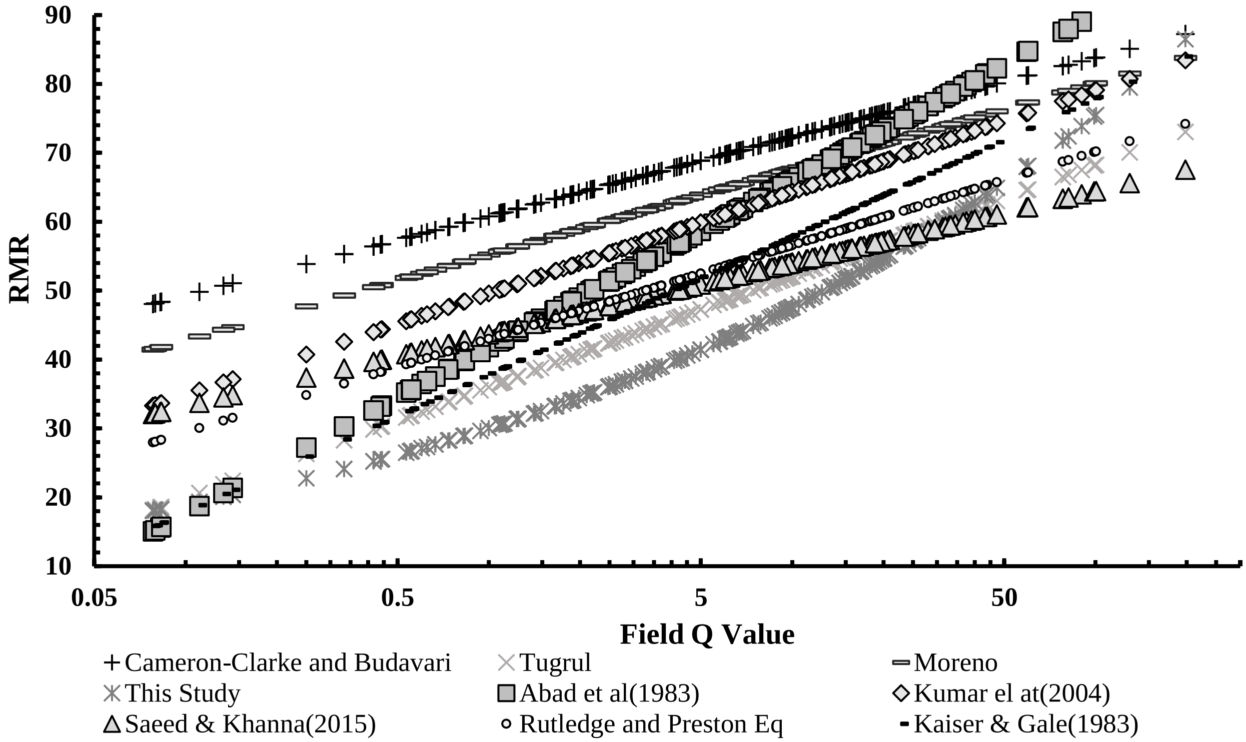


Fig. 11: Comparison of existing correlation developed for RMR-Q

In Fig. 11 the existing correlations between RMR-Q are evaluated for the Gulpur Hydropower area which consists of both competent and weak sandstones and mudstones with occasional occurrence of conglomerates. As can be observed from the Fig. 11 the best correlation that fit the study area is represented by [78]. These correlations were developed for sedimentary rocks i.e., shale and breccia. The slightly higher values of estimation are due to these correlations being developed for more component rock but the difference between field value and estimated value is 4-9 which is negligible and is also beneficial in design considerations. The correlation developed by [79] should only be used for very poor rock masses (Q<0.04) as the Fig. 10 shows that as the Q rating increases the difference between field RMR and estimated RMR also increases. Using the correlation presented by [80] to estimate the values of RMR shows overestimation compared to the values obtained from field investigation, as can be observed in Fig. 11 for the rock of very poor to good quality the difference between empirical and field value is more than 30-40 ratings. This means [80] should only be incorporated into calculation when sedimentary rocks of very good quality are encountered.

For comparison between RCR-RMR, only one empirical correlation exists developed by [74]. Since RCR is an altered form of RMR a slight deviation from rating is calculated on the ground as it does not take into consideration the uniaxial compressive strength and joint orientation. So, taking this into account the trend observed in the Fig. 12 shows a slight overestimation of 5-10 and in some cases a difference of 15 can be seen but this variation in values can be attributed to human error in identifying the various parameters based on ISRM standard, then this empirical relationship can be used only in tunneling and mining operations. The application of this correlation should only be agreed upon if the identification and calculation of parameters is performed by an experienced geologist or rock specialist.

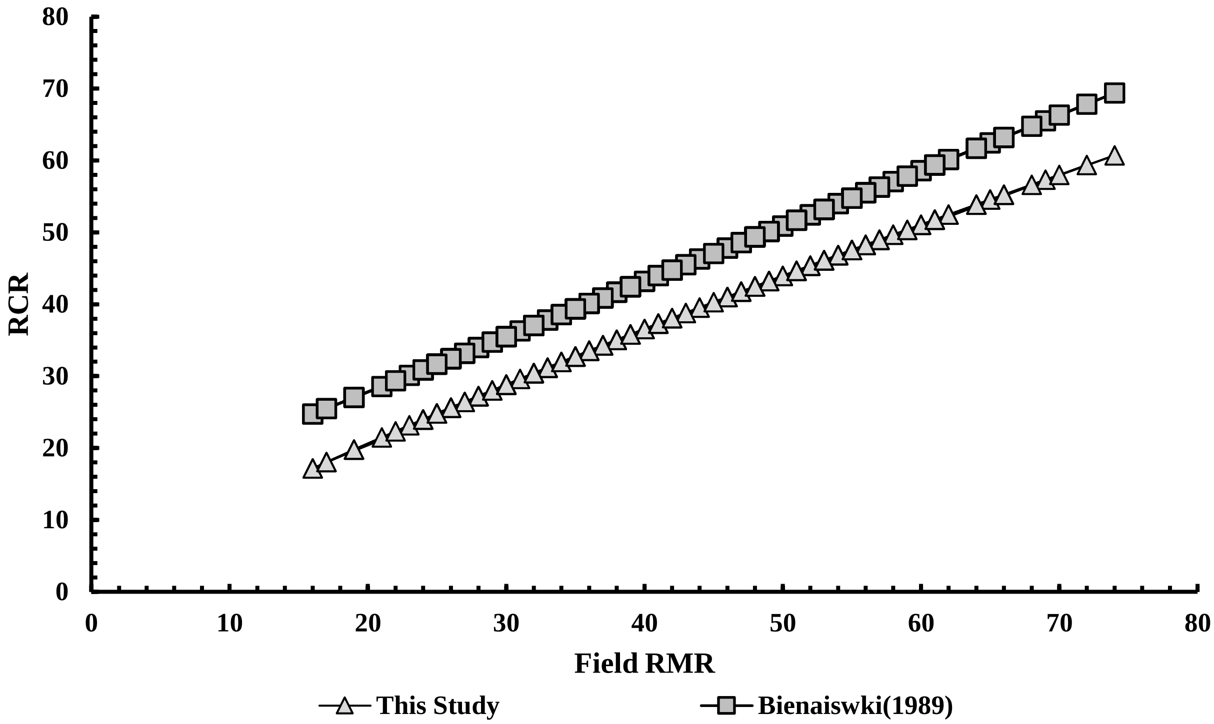


Fig. 12: Comparison of existing correlation developed for RCR-RMR

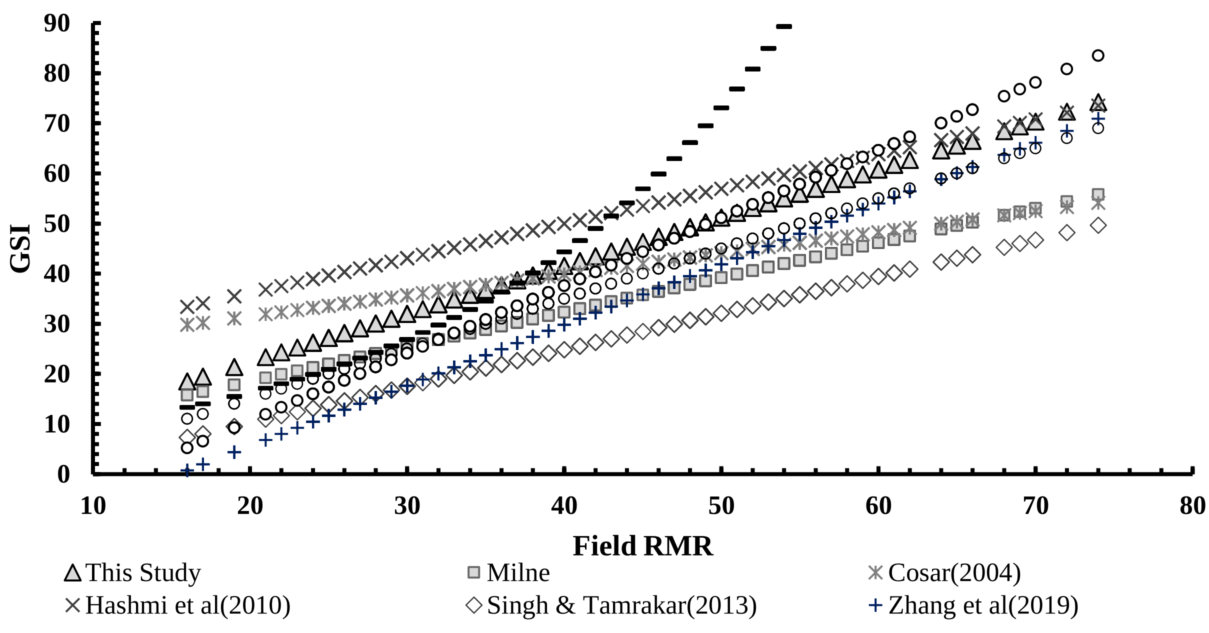


Fig. 13: Comparison of existing correlation developed for GSI-RMR

For the relationship between RMR and GSI (Fig. 13), The Hoek's relationship is based on data from rocks whose GSI value is greater than 25 which means medium to good quality rocks [81]. The Fig. 13 shows a comparison of GSI values estimated and the expressions developed by [82, 83]. The trend observed shows that [84] estimate better GSI values for RMR >50 whereas it underestimates the GSI values for values RMR<50. On the contrary [83] expression overestimates the GSI values for RMR>60. The difference in estimated GSI and [83] expression becomes insignificant for RMR<40.

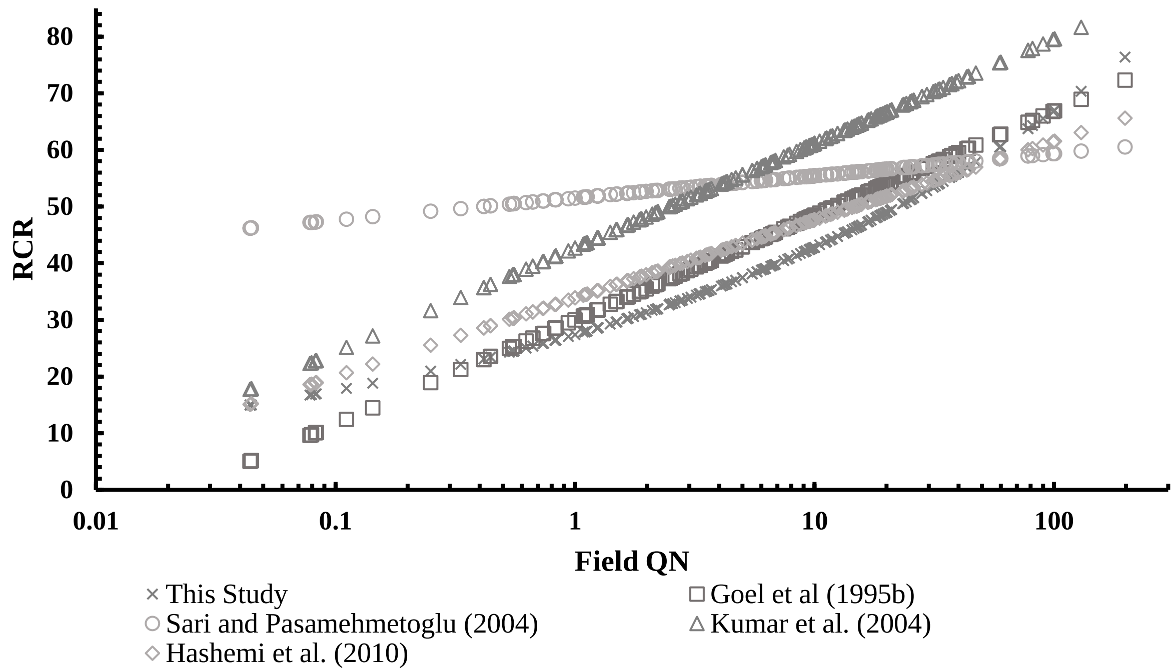


Fig. 14: Comparison of existing correlation developed for RCR-QN

The strength of correlation between RCR-QN for existing studies is shown in Fig. 14 which is best estimated by [53] but considering that the former relationship was developed for metamorphic rocks of very poor to fair quality it means that this correlation can even be applied to rocks of different type but during investigation, its quality should be on the lower scale of rating spectrum (i.e., very poor to fair quality). This can be further corroborated by observation of the trend for [85] as it was proposed for sedimentary rocks but in Fig. 14 deviation from field, rating is more than 10-15, since their quality was on the higher scale of rating spectrum.

4.2. Comparison of Existing correlation

4.2.1. RMR-Q, GSI-RMR, GSI-Q and RCR-Q

The new correlation shows a nonlinear relationship between RMR and Q, whereas previous studies proposed logarithmic relationships. The R^2 value of 0.89 indicates a strong correlation, but the form of the equation differs from previous research. The new correlation has a higher R^2 value (0.93) compared to previous studies, suggesting a stronger linear relationship. The slope and intercept differ significantly from previous correlations, which may reflect differences in the dataset or methodology. The new correlation has a lower coefficient for ln(Q) compared to previous studies, indicating a less steep relationship. The R^2 value of 0.82 is strong but lower than some previous studies, possibly due to differences in dataset composition. The new correlation is consistent with previous studies in form but differs in slope and interception. The R^2 value of 0.86 suggests a strong relationship, but the discrepancies in coefficients may reflect differences in dataset composition or methodology.

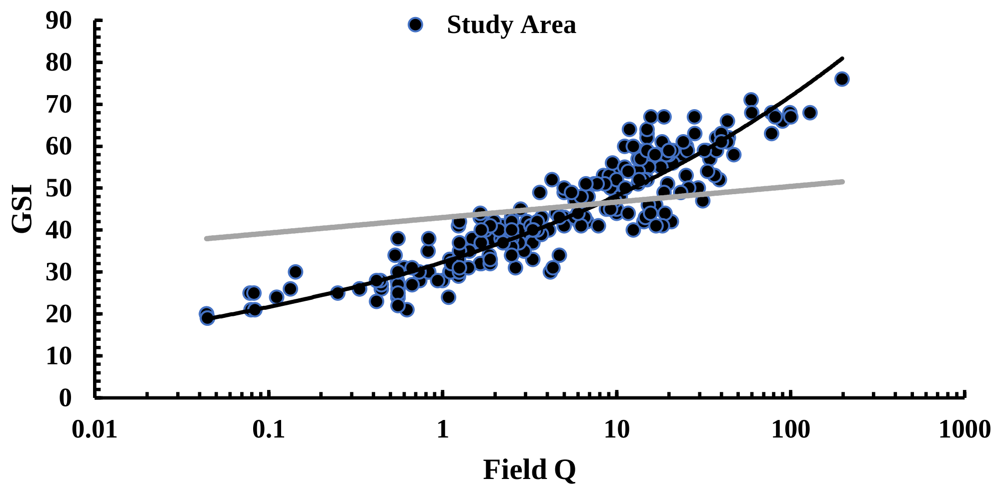


Fig. 15: Comparison of existing correlation developed for GSI-Q

The correlation developed by [86] estimating GSI values from the empirical method using Q ratings shows a high deviation from the field values when applied to the concerned study area, as shown in Fig. 15. Since GSI is a descriptive form of classification, errors in its record should make it a less desirable classification method, or there is a need for further research to make the modus operandi more streamlined.

4.3. Practical implication of developed correlations

The high R^2 values for some correlations (e.g., GSI-RMR, RMR-Q) suggest that they are broadly applicable to a wide range of rock mass conditions. However, their reliability depends on the similarity between the project conditions and the dataset used to develop the correlations. The correlations between RMR, Q, and GSI can be used to estimate rock mass properties and design appropriate support systems (e.g., rock bolts, shotcrete, steel sets). For example, if Q values are available, the correlation $RMR = 30.502\ Q^{0.187}$ can be used to estimate RMR, which can then guide support design based on RMR-based guidelines. The GSI-RMR correlation ($GSI = 0.9601\ RMR + 3.157$) can be used to estimate GSI, which is essential for numerical modeling using the Hoek-Brown failure criterion. This helps predict rock mass behavior under different stress conditions. The RCR-Q correlation ($RCR = 6.91 \ln(Q) + 28.30$) can be used to assess the rock mass condition and select appropriate excavation methods (e.g., drill and blast, TBM).

5. CONCLUSIONS

The following conclusions were deduced from this study:

- Geographical and geotechnical properties of rock units uncovered at the surface, furthermore, cut along the route of the entire length of the project area in the review zone for Gulpur Hydropower Project located in northern areas of Pakistan.
- The rock samples are collected at 240 segments taken from 7 boreholes with a total length of more than 1000m. A new set of correlations has been developed for RMR-Q, RMR-QN, GSI-Q, GSI-RMR, GSI-QN, GSI-RCR, RCR-Q, RCR-RMR, RCR-QN.

- Comparison with the existing correlations reveals that results were overestimated in most of the cases for existing correlations. It is further concluded that existing correlations show a lot of variation in results for different quality of rocks.
- Correlations presented in this paper were checked for linear, exponential, logarithmic, power and polynomial trends, and the relationship with the highest values of R^2 was selected. In all the cases where established classification systems were used the R^2 was consistently showing the accuracy of more than 0.85 but the value dropped down to less than 0.60 where the modified form of these classifications systems was incorporated.
- The parameters that were responsible for lower values of correlation coefficient were uniaxial compression strength (UCS), stress reduction factor (SRF) and the orientation of dip and strike (joint orientation) as these were omitted from the modified systems (i.e., RCR and QN).
- The relationships developed in this study show promising results and give a high correlation coefficient (R^2) which indicates that for rocks of varying quality, estimated values are very near too accurate. However, the same cannot be said for existing relationships developed by numerous researchers. The reason can be attributed to the fact that apart from the type and quality of rocks, these relationships are highly dependent on their origin, lithology, and mineralogical characteristics which vary for even the same type of rock in different parts of the world.
- It is concluded that the engineers and geologists must consider the origin of rocks and data used for the development of these relationships before using them for support design or any other tunneling, mining and underground excavation.

6. Recommendation

- The dataset's focus on mudstone, siltstone, sandstone and gneiss provides valuable insights into the relationships between rock mass classification systems for sedimentary and metamorphic rocks. However, the limited diversity of rock types may restrict the generalizability of correlations to other geological settings. To address this limitation, it is essential to acknowledge the bias in the dataset, expand the data to include other rock types, and validate the correlations using independent data

Conflict of Interest

The authors declare that there is no conflict of interest.

REFERENCES

1. Sadeghi, S., E.S. Teshnizi, and B. Ghoreishi, *Correlations between various rock mass classification/characterization systems for the Zagros tunnel-W Iran.* Journal of Mountain Science, 2020. **17**(7): p. 1790-1806.
2. Singh, B. and R.K. Goel, *Rock mass classification: a practical approach in civil engineering*. Vol. 46. 1999: Elsevier.
3. Aksoy, C., *Review of rock mass rating classification: historical developments, applications, and restrictions.* Journal of mining science, 2008. **44**(1): p. 51-63.
4. Hsiao, F., C.-L. Wang, and J. Chern, *Numerical simulation of rock deformation for support design in tunnel intersection area.* Tunnelling and underground space technology, 2009. **24**(1): p. 14-21.
5. Zarei, H.R., A. Uromeihy, and M. Sharifzadeh, *Identifying geological hazards related to tunneling in carbonate karstic rocks-Zagros, Iran.* Arabian Journal of Geosciences, 2012. **5**(3): p. 457-464.
6. Yellas, C., R. Benzaid, and M. Tekkouk, *Application of classification systems for the assessment of rock mass stability—case of national road 43, Jijel, Algeria.* Arabian Journal of Geosciences, 2021. **14**: p. 1-10.
7. Nourani, M.H., M.T. Moghadder, and M. Safari, *Classification and assessment of rock mass parameters in Choghart iron mine using P-wave velocity.* Journal of Rock Mechanics and Geotechnical Engineering, 2017. **9**(2): p. 318-328.

8. Jain, A. and S.K. Rao, *Stresses and ground response analysis of four rock types of Rohtang Tunnel in the Himalayas.* Arabian Journal of Geosciences, 2023. **16**(3): p. 1-11.
9. Cao, R.-h., et al., *An experimental and numerical study on mechanical behavior of ubiquitous-joint brittle rock-like specimens under uniaxial compression.* Rock Mechanics and Rock Engineering, 2016. **49**(11): p. 4319-4338.
10. Palmstrom, A., *Measurements of and correlations between block size and rock quality designation (RQD).* Tunnelling and Underground Space Technology, 2005. **20**(4): p. 362-377.
11. Palmstrom, A. and H. Stille, *Ground behaviour and rock engineering tools for underground excavations.* Tunnelling and Underground Space Technology, 2007. **22**(4): p. 363-376.
12. Justo, J., et al., *The use of rock mass classification systems to estimate the modulus and strength of jointed rock.* Rock mechanics and rock engineering, 2010. **43**(3): p. 287-304.
13. Terzaghi, K., *Rock defects and loads on tunnel supports.* Rock tunnelling with steel supports, 1946.
14. Lauffer, H., *Gebirgsklassifizierung für den Stollenbau: Geology Bauwesen, v. 24.* 1958.
15. Rabcewicz, L.v., *The New Austrian Tunnelling Method, Part III.* Water Power, 1965: p. 19-24.
16. Patching, T. and D. Coates, *A recommended rock classification for rock mechanics purposes.* Canadian Mining and Metallurgical Bulletin, 1968. **61**(678): p. 1195-&.
17. Deere, D.U. and R. Miller, *Engineering classification and index properties for intact rock*. 1966, Illinois Univ At Urbana Dept Of Civil Engineering.
18. Deere, D., *The rock quality designation (RQD) index in practice*, in *Rock classification systems for engineering purposes*. 1988, ASTM International.
19. Wickham, G.E., H.R. Tiedemann, and E.H. Skinner. *Support determinations based on geologic predictions*. in *N Am Rapid Excav & Tunnelling Conf Proc*. 1972.
20. Bieniawski, Z.T., *Estimating the strength of rock materials.* Journal of the Southern African Institute of Mining and Metallurgy, 1974. **74**(8): p. 312-320.
21. Barton, N., R. Lien, and J. Lunde, *Engineering classification of rock masses for the design of tunnel support.* Rock mechanics, 1974. **6**(4): p. 189-236.
22. Laubscher, D., *Geomechanics classification of jointed rock masses: mining applications.* Inst. Min. Metall., Trans., Sect. A;(United Kingdom), 1977. **86**.
23. Franklin, J.A., *Triaxial strength of rock materials.* Rock mechanics, 1971. **3**(2): p. 86-98.
24. Matula, M. and R. Holzer. *Engineering topology of rock masses*. in *Proceedings of Felsmekanik Kolloquium, Grundlagen ung Andwendung der Felsmekanik, Karls-ruhe, Germany*. 1978.
25. Williamson, D.A., *Unified rock classification system.* Bulletin of the Association of Engineering Geologists, 1984. **21**(3): p. 345-354.
26. Brown, E.T., *Rock characterization, testing & monitoring: ISRM suggested methods.* 1981.
27. Stille, H., T. Groth, and A. Fredriksson, *FEM-analysis of rock mechanical problems with JOBFEM.* Stiftelsen Bergteknisk Forskning–BeFo, Stockholm, 1982. **307**(1): p. 82.
28. Kendorski, F., et al. *Rock mass classification for block caving mine drift support*. in *5th ISRM Congress*. 1983. OnePetro.
29. de Vallejo, L.G., *SRC rock mass classification of tunnels under high tectonic stress excavated in weak rocks.* Engineering geology, 2003. **69**(3-4): p. 273-285.
30. ROMANA, M.R., *A geomechanical classification for slopes: slope mass rating*, in *Rock testing and site characterization*. 1993, Elsevier. p. 575-600.
31. Brook, N. and G. Dharmaratne, *Simplified rock mass rating system for mine tunnel support.* Transactions-Institution of Mining and Metallurgy. Section A. Mining Industry, 1985. **94**: p. 148-154.
32. Ramamurthy, T. and V. Arora. *A classification for intact and jointed rocks*. in *Geotechnical engineering of hard soils-soft rocks*. 1993.
33. Marinos, V., *Tunnel behaviour and support associated with the weak rock masses of flysch.* Journal of Rock Mechanics and Geotechnical Engineering, 2014. **6**(3): p. 227-239.
34. Goel, R., J. Jethwa, and A. Paithankar, *Indian experiences with Q and RMR systems.* Tunnelling and Underground Space Technology, 1995. **10**(1): p. 97-109.
35. Palmström, A. *Characterizing rock burst and squeezing by the rock mass index*. in *International conference in design and construction of underground structures*. 1995.
36. Unal, E., *Modified rock mass classification: M-RMR system.* Milestones in rock engineering, 1996.
37. Barton, N., *TBM perfomance estimation in rock using QTBM.* Tunnel and Tunnelling International, 1999: p. 30-34.

38. Şen, Z. and B.H. Sadagah, *Modified rock mass classification system by continuous rating.* Engineering Geology, 2003. **67**(3-4): p. 269-280.
39. Von Preinl, Z., et al., *Rock mass excavability indicator: New way to selecting the optimum tunnel construction method.* Tunnelling and Underground Space Technology, 2006. **21**(3-4).
40. Celada, B., et al., *Actualización y mejora del RMR.* IGP–InGeoPress, 2014. **234**: p. 18-22.
41. Aydan, Ö., R. Ulusay, and N. Tokashiki, *A new rock mass quality rating system: rock mass quality rating (RMQR) and its application to the estimation of geomechanical characteristics of rock masses.* Rock mechanics and rock engineering, 2014. **47**(4): p. 1255-1276.
42. Mohammadi, M. and M.F. Hossaini, *Modification of rock mass rating system: Interbedding of strong and weak rock layers.* Journal of rock mechanics and geotechnical engineering, 2017. **9**(6): p. 1165-1170.
43. Saroglou, C., et al., *ARMR, a new classification system for the rating of anisotropic rock masses.* Bulletin of Engineering Geology and the Environment, 2019. **78**(5): p. 3611-3626.
44. Arıkan, F., R. Ulusay, and N. Aydın, *Characterization of weathered acidic volcanic rocks and a weathering classification based on a rating system.* Bulletin of Engineering Geology and the Environment, 2007. **66**(4): p. 415-430.
45. Cao, R.-h., et al., *Mechanical behavior of brittle rock-like specimens with pre-existing fissures under uniaxial loading: experimental studies and particle mechanics approach.* Rock Mechanics and Rock Engineering, 2016. **49**(3): p. 763-783.
46. Bar, N. and N. Barton, *The Q-slope method for rock slope engineering.* Rock Mechanics and Rock Engineering, 2017. **50**(12): p. 3307-3322.
47. Santos, V., P.F. Da Silva, and M.G. Brito, *Estimating RMR values for underground excavations in a rock mass.* Minerals, 2018. **8**(3): p. 78.
48. Basahel, H. and H. Mitri, *Application of rock mass classification systems to rock slope stability assessment: A case study.* Journal of rock mechanics and geotechnical engineering, 2017. **9**(6): p. 993-1009.
49. Bieniawski, Z., *Classification of rock masses for engineering: the RMR system and future trends*, in *Rock Testing and Site Characterization*. 1993, Elsevier. p. 553-573.
50. Barton, N., *Some new Q-value correlations to assist in site characterisation and tunnel design.* International journal of rock mechanics and mining sciences, 2002. **39**(2): p. 185-216.
51. Sonmez, H. and R. Ulusay, *A discussion on the Hoek-Brown failure criterion and suggested modifications to the criterion verified by slope stability case studies.* Yerbilimleri, 2002. **26**(1): p. 77-99.
52. Chaulagai, K., R.K. Dahal, and K. Panthi, *Assessment of rock mass quality and deformation modulus by empirical methods in Nepal Himalaya.* Arabian Journal of Geosciences, 2022. **15**(19): p. 1559.
53. Hashemi, M., S. Moghaddas, and R. Ajalloeian, *Application of rock mass characterization for determining the mechanical properties of rock mass: a comparative study.* Rock Mechanics and Rock Engineering, 2010. **43**(3): p. 305-320.
54. Laderian, A. and M.A. Abaspoor, *The correlation between RMR and Q systems in parts of Iran.* Tunnelling and Underground Space Technology, 2012. **27**(1): p. 149-158.
55. Ranasooriya, J. and H. Nikraz, *Reliability of the linear correlation of rock mass rating (RMR) and tunnelling quality index (Q).* Australian Geomechanics, 2009. **44**(2): p. 47-54.
56. Rafiee, R., M. Ataei, and M. Kamali, *Tunnels stability analysis using binary and multinomial logistic regression (LR).* Journal of Geology and Mining Research, 2013. **5**(4): p. 97-107.
57. Irvani, I., W. Wilopo, and D. Karnawati, *Determination of nuclear power plant site in west bangka based on rock mass rating and geological strength index.* Journal of Applied Geology, 2013. **5**(2).
58. Castro Caicedo, Á.d.J. and D.M. Pérez Pérez, *CORRELATIONS BETWEEN THE RMR AND Q GEOMECHANICAL CLASSIFICATIONS AT" LA LÍNEA" EXPLORATORY TUNNEL, COLOMBIAN CENTRAL ANDES.* Boletín de Ciencias de la Tierra, 2013(34): p. 42-50.
59. Singh, J.L. and N.K. Tamrakar, *Rock mass rating and geological strength index of rock masses of Thopal-Malekhu river areas, central Nepal lesser himalaya.* Bulletin of the Department of Geology, 2013. **16**: p. 29-42.
60. Ali, W., N. Mohammad, and M. Tahir, *Rock mass characterization for diversion tunnels at Diamer Basha Dam, Pakistan-a design perspective.* International Journal of Scientific Engineering and Technology, 2014. **3**(10): p. 1292-1296.
61. Sayeed, I. and R. Khanna. *Empirical correlation between RMR and Q systems of rock mass classification derived from Lesser Himalayan and Central crystalline rocks*. in *International Conference on "Engineering Geology in New Millennium*. 2015.
62. Zhang, Q., et al., *Quantitative assessments of the correlations between rock mass rating (RMR) and geological strength index (GSI).* Tunnelling and Underground Space Technology, 2019. **83**: p. 73-81.

63. Saif, A. and K. Ahmed Sheikh, *Design of grout curtain for temporary embankments on rock foundation.* Geomechanics and Geoengineering, 2020: p. 1-16.
64. Bossart, P., et al., *The tectonic structure of the Hazara-Kashmir syntaxis, southern Himalayas, Pakistan.* Tectonics, 1988. **7**(2): p. 273-297.
65. Sana, H. and S.K. Nath, *In and around the Hazara-Kashmir syntaxis: A Seismotectonic and seismic hazard perspective.* J. Ind. Geophys. Union, 2016. **20**: p. 496-505.
66. Johnson, N.M., et al., *Paleomagnetic chronology, fluvial processes, and tectonic implications of the Siwalik deposits near Chinji village, Pakistan.* The Journal of Geology, 1985. **93**(1): p. 27-40.
67. Johnson, N.M., et al., *Magnetic polarity stratigraphy and ages of Siwalik Group rocks of the Potwar Plateau, Pakistan.* Palaeogeography, Palaeoclimatology, Palaeoecology, 1982. **37**(1): p. 17-42.
68. RAYNOLDS, R.G.H., *The Plio-Pleistocene structural and stratigraphic evolution of the eastern Potwar Plateau, Pakistan*. 1980, Dartmouth College.
69. Sheikh, K.A., *3D Limit Equilibrium Analyses of Translational.* Journal of Geotechnical and Transportation Engineering, 2019. **5**(1): p. 1.
70. Santi, P.M., *Field methods for characterizing weak rock for engineering.* Environmental & Engineering Geoscience, 2006. **12**(1): p. 1-11.
71. Piteau, D.R., *Characterizing and extrapolating rock joint properties in engineering practice*, in *Geomechanik—Fortschritte in der Theorie und deren Auswirkungen auf die Praxis/Geomechanics—Progress in Theory and Its Effects on Practice*. 1973, Springer. p. 5-31.
72. Hatheway, A.W., *The complete ISRM suggested methods for rock characterization, testing and monitoring; 1974–2006*. 2009, Association of Environmental & Engineering Geologists.
73. Dearman, W., *Weathering classification in the characterisation of rock for engineering purposes in British practice.* Bulletin of the International Association of Engineering Geology-Bulletin de l'Association Internationale de Géologie de l'Ingénieur, 1974. **9**(1): p. 33-42.
74. Bieniawski, Z.T., *Engineering rock mass classifications: a complete manual for engineers and geologists in mining, civil, and petroleum engineering*. 1989: John Wiley & Sons.
75. Hoek, E. and E. Brown, *The Hoek–Brown failure criterion and GSI–2018 edition.* Journal of Rock Mechanics and Geotechnical Engineering, 2019. **11**(3): p. 445-463.
76. Singh, B., et al., *Support pressure assessment in arched underground openings through poor rock masses.* Engineering Geology, 1997. **48**(1-2): p. 59-81.
77. Ulusay, R. and J. Hudson, *International Society for Rock Mechanics (ISRM), The Complete ISRM Suggested Methods for Rock Characterization, Testing and Monitoring, 1974–2006*. 2007, Ankara, Pergamon, Oxford.
78. Tugrul, A., *The application of rock mass classification systems to underground excavation in weak limestone, Ataturk dam, Turkey.* Engineering geology, 1998. **50**(3-4): p. 337-345.
79. Abad, J., et al. *Application of geomechanical classification to predict the convergence of coal mine galleries and to design their supports*. in *5th ISRM Congress*. 1983. OnePetro.
80. Cameron-Clarke, I. and S. Budavari, *Correlation of rock mass classification parameters obtained from borecore and in-situ observations.* Engineering Geology, 1981. **17**(1-2): p. 19-53.
81. Zhao, X., M. Cai, and M. Cai, *Considerations of rock dilation on modeling failure and deformation of hard rocks—a case study of the mine-by test tunnel in Canada.* Journal of Rock Mechanics and Geotechnical Engineering, 2010. **2**(4): p. 338-349.
82. Milne, D., J. Hadjigeorgiou, and R. Pakalnis, *Rock mass characterization for underground hard rock mines.* Tunnelling and underground space technology, 1998. **13**(4): p. 383-391.
83. Hoek, E., P. Marinos, and M. Benissi, *Applicability of the Geological Strength Index (GSI) classification for very weak and sheared rock masses. The case of the Athens Schist Formation.* Bulletin of Engineering Geology and the Environment, 1998. **57**(2): p. 151-160.
84. Osgoui, R. and E. Unal. *Characterization of Weak Rock Masses Using GSI-Index and the Estimation of Support-Pressure*. in *Alaska Rocks 2005, The 40th US Symposium on Rock Mechanics (USRMS)*. 2005. OnePetro.
85. Kumar, N., N. Samadhiya, and R. Anbalagan, *Application of rock mass classification systems for tunneling in Himalaya, India.* International Journal of Rock Mechanics and Mining Sciences, 2004.
86. Osgoui, R. and E. Ünal, *Rock reinforcement design for unstable tunnels originally excavated in very poor rock mass.* Underground space use: Analysis of the past and lessons for the future, 2005: p. 291-296.

تقييم أداء أنظمة تصنيف الصخور المختلفة ومقارنتها بالارتباطات الحالية لدعامات الصخور

ملخص: تهدف تصنيفات الكتل الصخرية إلى توفير تقييم نوعي لها لأغراض التصميم الأولي للهياكل الصخرية. وقد طُبِّق نظام الدعم القائم على تصنيف الكتل الصخرية في تطبيقات متنوعة، مثل الأنفاق ومحطات الطاقة وتخزين النفط الخام، في باكستان وحول العالم. يُعدّ تصنيف كتلة الصخور لبيينياوسكي (RMR)، ونظام بارتون (Q)، ومؤشر القوة الجيولوجية لهوك وبراون (GSI) أشهر أنظمة تصنيف الكتل الصخرية، وقد بذل باحثون مختلفون حول العالم جهودًا لتطوير علاقات بينها. كما تم فحص أنظمة تصنيف حالة الصخور (RCR) ورقم كتلة الصخور (QN)، الأقل شهرة، لاستخدامها في قطاع البناء، نظرًا لتجاهلها بعض المعايير المستخدمة أثناء البحث الميداني. يهدف هذا البحث إلى تطوير علاقة بين تصنيفات كتلة الصخور RMR وGSI ونظام Q، باستخدام نهج إحصائي، باستخدام 240 نقطة بيانات مُسجلة من خلال سجلات جيولوجية للانجرافات الاستكشافية وسجلات الأنفاق أثناء الحفر لمشروع جولبور للطاقة الكهرومائية في باكستان. تم تطوير الارتباطات المقدمة في هذا البحث باستخدام مناهج إحصائية مختلفة (أي الخطية، واللوغاريتمية، والقوة، والأسية، والمتعددة الحدود) لتطوير الارتباط الذي لا يسمح لنا بمقارنة نتائج المناهج الإحصائية المختلفة فحسب، بل يخبرنا أيضًا أي نهج يعطي أفضل النتائج للارتباط بين نظامين لتصنيف كتلة الصخور.