

Empirical Geomechanical Classifications of Rock Mass in the Kashmir Valley Using RMR, SMR and Q Systems

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Abstract: This study presents a comprehensive geotechnical characterization of rock mass conditions across diverse litho-tectonic domains of the Kashmir Valley using the Rock Mass Rating (RMR), Slope Mass Rating (SMR), and Barton's Q-system. Detailed field investigations were carried out at multiple locations in the Kashmir Valley covering sedimentary, metamorphic, and igneous formations using established empirical correlations. The results indicate that a large proportion of the investigated rock masses fall within the very poor to poor quality classes, with Q-values generally less than 1.0 across most sites, reflecting intensely jointed, weathered, and tectonically disturbed rock conditions. Slightly improved rock quality, ranging from fair to good, is observed locally in massive basaltic and andesitic units where Q-values exceed 5.0. SMR analysis reveals predominantly unstable to partially stable slope conditions, particularly in phyllite, slate, limestone, and volcanoclastic sequences, emphasizing high susceptibility to planar, wedge, and toppling failures along major transportation corridors. From an engineering perspective, the integrated RMR–SMR–Q assessment underscores the necessity of robust design measures in civil infrastructure projects, including highways, tunnels, slopes, and foundations. The findings provide a region-specific geomechanical database that can serve as a critical input for preliminary design, hazard zonation, and risk-informed planning of infrastructure development in the seismically active and geologically complex terrain of the Kashmir Himalaya.

Keywords: Kashmir Valley, Rock mass rating, Slope mass rating, Q-system, Civil infrastructure.

I. INTRODUCTION

Sustainable infrastructure development in mountainous terrains is intrinsically linked to accurate understanding of rock mass behavior, particularly in regions characterized by complex geological conditions, active tectonic settings, and extreme climatic variability (Ahad & Bukhari, 2025; Singh et al., 2025). The Himalayan belt in India represents one of the most

challenging environments for the planning, design, and long-term performance of civil infrastructure such as highways, tunnels, hydropower projects, urban slope developments, and strategic transport corridors (Siddique et al., 2017). Recurrent slope failures, tunnel instabilities, excessive deformation, and high maintenance costs in this region have repeatedly demonstrated that infrastructure sustainability is governed not only by engineering design but also by the quality and response of the in-situ rock mass (Niu et al., 2024). Over the past several decades, empirical rock mass classification approaches have emerged as practical tools that bridge between geological characterization and engineering decision-making (Saadati et al., 2025).

In the Indian Himalayan context, these classification-based frameworks have played a decisive role in improving project sustainability by enabling rational selection of alignment, optimization of excavation methods, reduction in over-design, and minimization of environmental disturbance (Chauhan et al., 2025). Large-scale projects such as the Jammu–Srinagar National Highway (NH-44), Chenani–Nashri and Banihal tunnels, Zojila Tunnel, Atal Tunnel (Rohtang), and multiple hydropower schemes in Uttarakhand and Himachal Pradesh have demonstrated that early-stage geomechanical appraisal using rock mass indices significantly enhances construction efficiency while reducing long-term geohazard risks (Pandey, 2022). In slope engineering, particularly along Himalayan highways, rock mass classification-based slope stability assessments have contributed to more sustainable cut-slope geometries and support systems (Jaiswal et al., 2025). Application of slope-specific classification frameworks has allowed engineers to identify structurally controlled failure modes and accordingly adopt controlled blasting, bench optimization, rock bolting, and bio-engineering measures. Such approaches have proven effective along vulnerable road sections of NH-44 (Jammu–Srinagar), Mughal Road, Manali–Leh axis, and Char Dham connectivity corridors, where conventional empirical slope design has previously resulted in repeated failures and ecological degradation (Basahel & Mitri, 2017).

In underground construction, classification-guided design has facilitated adaptive tunnel support strategies that minimize

excessive lining thickness and material consumption while ensuring safety (Koothathongsumrit & Meethom, 2024). Experiences from Himalayan tunnelling projects indicate that the integration of rock mass quality indices during design and construction stages has reduced unforeseen ground conditions, construction delays, and cost overruns (Yousuf & Bukhari, 2019). These practices align with sustainability principles by optimizing resource utilization, reducing carbon-intensive support measures, and enhancing operational safety throughout the infrastructure lifecycle (Panthi, 2006). The locally enhanced rock mass quality in basaltic and andesitic units is predominantly controlled by their intrinsic lithological and structural attributes. These volcanic units exhibit higher intact rock strength values, lower discontinuity frequency, and more favorable joint orientations relative to surrounding lithologies. Furthermore, the prevalence of massive, coherent flow structures and limited weathering enhances block stability and reduces fragmentation. These factors collectively yield higher RMR and Q values, reflecting superior geomechanical behavior and improved rock mass quality in these volcanic formations.

Furthermore, in the seismically active Himalayan terrain, rock mass classification-based zonation has emerged as a critical input for infrastructure resilience planning. By correlating rock mass quality with deformation behavior and failure susceptibility, engineers have been able to prioritize stabilization interventions and maintenance planning, thereby extending service life and reducing post-construction remedial works (Abbas et al., 2024). This approach is particularly relevant in regions such as the Kashmir Valley, where infrastructure development must balance rapid connectivity expansion with environmental sensitivity and disaster risk reduction. In this context, the present study contributes to sustainable infrastructure planning in the Kashmir Valley by providing a region-wide evaluation of rock mass conditions derived from extensive field investigations. The outcomes offer a geomechanical basis for informed decision-making in slope stabilization, tunnel design, foundation assessment, and alignment planning, thereby supporting the development of safer, cost-effective, and environmentally responsible civil infrastructure in one of the most geologically complex Himalayan regions of India.

The rock mass classification results provide quantitative guidance for preliminary support design by linking empirically derived indices to engineering recommendations. RMR and Q values inform the selection and sizing of support systems for tunnels and foundations, including rock bolt spacing, shotcrete thickness, and reinforcement types, while SMR outcomes guide the slope geometry optimization and stabilization measures such as anchoring, drainage, and protective structures. By integrating these complementary classifications, the results enable site-specific, evidence-based preliminary design decisions, ensuring that support measures are proportionate to the underlying geomechanical conditions.

II. GEOMECHANICAL CLASSIFICATION OF ROCKS

Empirical rock mass classification systems form the backbone of applied rock engineering, particularly in tectonically complex mountain belts such as the Kashmir Valley (Niu et al., 2024). The Rock Mass Rating (RMR), Slope Mass Rating

(SMR), and Q-system represent three widely accepted empirical frameworks that translate field-based geological and geotechnical observations into engineering-relevant indices (Aksoy, 2008). Although developed independently, these systems are linked through empirical correlations that allow comparative assessment of rock mass quality and facilitate cross-validation of engineering interpretations (Azarafza et al., 2020a). In the Himalayan context, where the spatial variability of lithology, discontinuity characteristics, and stress conditions are pronounced, such empirical relationships provide a robust basis for regional geomechanical zonation and infrastructure planning (Kainthola et al., 2025).

Empirical rock mass classification systems, while effective for first-order assessment, have inherent limitations in highly heterogeneous and tectonically active Himalayan terrains. Intense fracturing, complex structural fabrics, variable lithologies, and localized seismic effects can produce pronounced spatial variability over short distances, challenging the assumptions of RMR, SMR, and Q. Subjective parameters, including joint conditions and groundwater influence, are particularly sensitive in such settings, potentially affecting classification reliability. So, application of these systems requires careful field calibration, cross-validation with observed failures, and, where feasible, integration with site-specific kinematic or numerical analyses to ensure robust geomechanical interpretations. The RMR system serves as the fundamental rock mass quality index, incorporating intact rock strength, rock quality designation (RQD), discontinuity spacing and condition, groundwater influence, and joint orientation adjustment (Rehman et al., 2018). In the Kashmir Valley, RMR values derived from diverse lithological units, ranging from limestones and quartzites to phyllites, slates, volcanics, and granites reflect the combined influence of intense tectonic deformation, weathering, and hydrogeological activity. These RMR values provide the baseline input for slope-specific modifications through the SMR system and allow conversion to Q-values using established empirical relations.

The SMR extends the applicability of RMR to rock slopes by explicitly accounting for the geometric relationship between discontinuities and slope orientation, as well as the method of excavation (Bieniawski, 1984). Empirical correction factors (F_1 , F_2 , F_3 , and F_4) applied to basic RMR values adjust rock mass quality to reflect realistic slope stability conditions (Fereidooni et al., 2015). In the Kashmir Valley, SMR values systematically indicate lower stability classes compared to corresponding RMR values, particularly along road cut slopes and mountain corridors. This reduction is primarily attributed to unfavorable joint-slope kinematics and mechanically induced damage from blasting in infrastructure projects. Empirical comparison between RMR and SMR highlights the necessity of slope-specific evaluation rather than direct reliance on rock mass quality indices (Jaiswal et al., 2024).

The Q-system provides an alternative yet complementary empirical framework by emphasizing block size (RQD/J_n), inter-block shear strength (J_r/J_a), and environmental conditions (J_w/SRF). Empirical relationships between RMR and Q, commonly expressed in logarithmic form (e.g., $RMR \approx a \ln(Q) + b$), allow mutual conversion and cross-checking of classification results (Palmstrom & Broch, 2006). Application of these

correlations in the Kashmir Valley demonstrates broad consistency between low RMR and low Q-values, confirming predominantly poor to very poor rock mass conditions across most lithological domains. However, local deviations observed in massive igneous and well-cemented carbonate formations underscore the sensitivity of the Q-system to stress and joint alteration parameters, which are particularly relevant in high-relief Himalayan terrain.

The combined use of RMR, SMR, and Q systems through empirical correlations enables a multi-dimensional understanding of rock mass behavior (Palmstrom, 2009). In the Kashmir Valley, this integrated classification approach facilitates identification of critical geomechanical domains where slope instability, tunnel support demand, and foundation vulnerability are highest (Ahad & Bukhari, 2024). Empirical interrelationships among these systems also support rational selection of support measures, excavation techniques, and stabilization strategies tailored to specific rock mass conditions. Importantly, such classification-based frameworks provide a pragmatic and scalable methodology for regional geomechanical assessment in data-constrained mountainous environments. Mainly, empirical geomechanical classification using RMR, SMR, and Q systems supported by established inter-system correlations offers a scientifically defensible and operationally efficient approach for evaluating rock mass conditions in the Kashmir Valley (Sayeed & Khanna, 2015). These empirical relations not only enhance confidence in engineering design decisions but also contribute to sustainable infrastructure development by minimizing uncertainty, optimizing resource use, and reducing the likelihood of geotechnical failures in one of the most geodynamically active regions of the Himalaya (Nyame & Adesanmi, 2024). Various authors have developed empirical approaches to calculate the SMR, RMR and Q values. Some of these methods are outlined in Table 1.

The derived rock mass classifications were systematically translated into engineering design and support recommendations by adopting the empirical support guidelines intrinsic to the RMR, SMR, and Q classification frameworks. RMR and Q indices were used to characterize intrinsic rock mass quality and to define appropriate support categories, including reinforcement type, bolt length and spacing, and shotcrete thickness. SMR outcomes were specifically employed to evaluate slope stability conditions and to inform slope geometry, reinforcement strategies, and stabilization measures such as anchoring and drainage. The integrated use of these classification systems

enables the development of design-relevant, site-specific support recommendations, thereby ensuring the practical applicability of the results to infrastructure planning and hazard mitigation along transportation corridors.

III. KASHMIR VALLEY

The Kashmir Valley, located in the northwestern part of the Indian Himalayas, is one of the most geologically dynamic and structurally complex regions in the Indian subcontinent. Bounded by the Pir Panjal Range to the southwest and the Greater Himalayas to the northeast, the valley represents a classic intermontane basin formed as a result of ongoing tectonic processes between the Indian and Eurasian plates (Irfan et al., 2025). Geographically, it lies between 33°N to 35°N latitude and 73°E to 75°E longitude, covering an area of approximately 15,000 km² (Ahad & Bukhari, 2023). The region exhibits significant topographic variation, with elevations ranging from about 1,500 m in the valley floor to over 5,000 m in the surrounding mountains. Geologically, the Kashmir Valley is underlain by a diverse assemblage of rock types ranging from the Precambrian to the Quaternary (Sinha & Upadhyay, 1995). The lithological framework includes sedimentary, metamorphic, and igneous rocks, including slates, phyllites, schists, quartzites, limestones, and volcanics (Srikantia & Bhargava, 1983). This complex geological setup is further dissected by major regional fault systems, including the Main Boundary Thrust (MBT), the Main Central Thrust (MCT), and several local shear zones and faults that contribute to the region's high seismicity (Srivastava et al., 2015). These structural features not only influence regional tectonics but also play a critical role in determining the engineering behavior of rock masses.

The field investigation dataset was structured to provide representative coverage of the dominant lithological groups in the Kashmir Valley, encompassing sedimentary, metamorphic, and igneous formations. Site selection was informed by regional geological maps and proportional targeted sampling based on areal distribution and engineering significance along transportation corridors. Consequently, sedimentary units are the most extensively represented, consistent with their regional prevalence, while metamorphic and igneous formations are sufficiently sampled to capture their distinct structural and geomechanical characteristics.

Table 1 Empirical relationships for converting geomechanical classifications index values

Author(s)	Relationship	Host rock	Location	R ² value
Bieniawski (1984)	$RMR = 9 \ln(Q) + 44$	Limestone	-	-
Rutledge & Preston (1978)	$RMR = 5.9 \ln(Q) + 43$	Various rock	New Zealand	-
Moreno (1980)	$RMR = 5.4 \ln(Q) + 55.2$	Various rock	-	-
Hashemi et al. (2010)	$RMR = 5.37 \ln(Q) + 40.48$	Limestone, Marl and dolomitic limestone	Iran	0.53
Laderian & Abaspoor (2012)	$RMR = 44.67 + 8.88 \ln(Q)$	Various rock	Iran	0.63
Zakaria et al. (2015)	$SMR = 8.2348 RMR + 0.4932$	Volcanic and sedimentary rocks	Indonesia	0.97
Soufi et al. (2018)	$RMR = 1.4906 Q + 45.73$	volcano-sedimentary rocks	Morocco	0.29
Azarafza et al. (2020b)	$SMR = 11.89 \ln(Q_{slope}) + 71.92$	Sedimentary rocks	Iran	0.75
Sadeghi et al. (2020)	$RMR = 12.34 \ln(Q) + 26.02$	Various rock	Iran	0.76
Azarafza et al. (2022)	$SMR = 6.699 \ln(Q_{slope}) + 58.99$	Various rock	Iran	0.62
Park et al. (2025)	$RMR = 2.2 \ln(Q) + 22.4$ (faulted)	Faulted rocks	South Korea	0.65
Park et al. (2025)	$RMR = 4.5 \ln(Q) + 40.9$ (weak)	weak rocks	South Korea	0.48

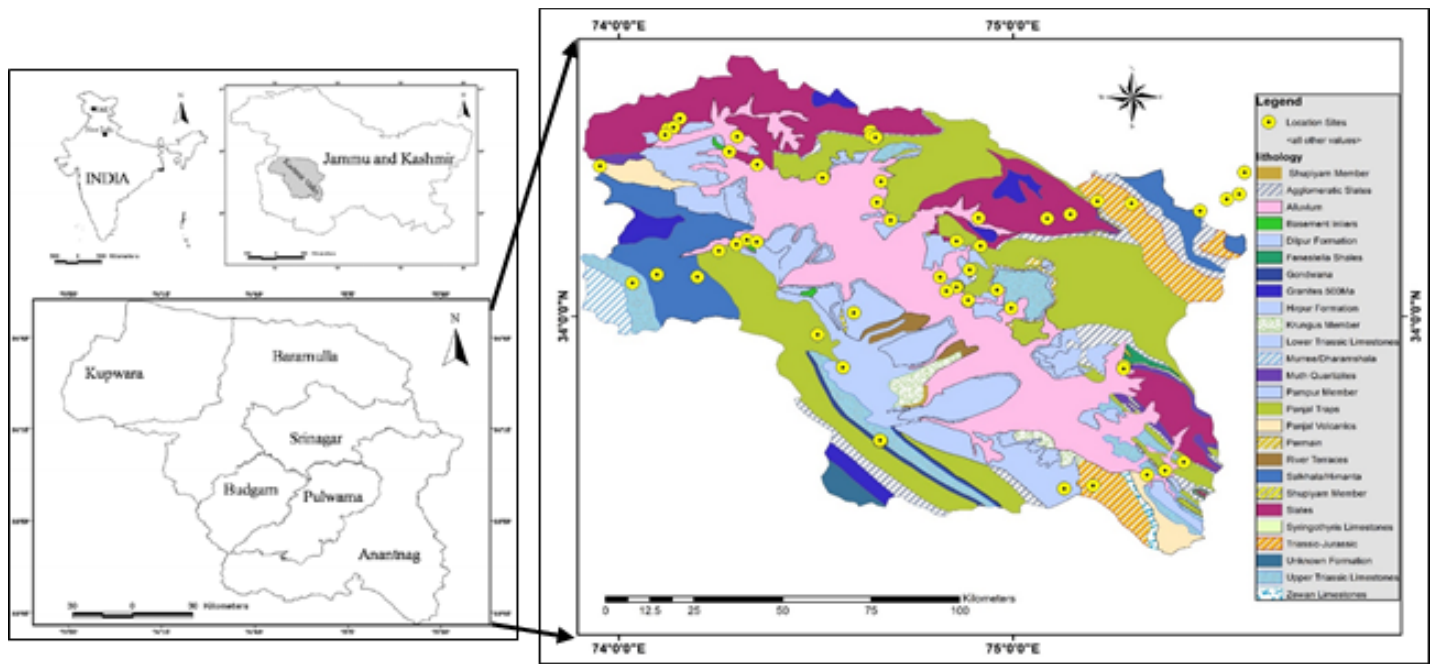


Fig. 1 Location and geological map of the studied area

This distribution ensures that the dataset faithfully reflects the lithological diversity and associated variability in rock mass behavior across the study area. The valley is particularly significant for engineering geological investigations due to its high vulnerability to landslides, slope failures, and earthquake-induced hazards, especially in areas where infrastructure development, such as roads, tunnels, and hydropower projects are expanding (Shah et al., 2021). So, an empirical assessment of rock mass quality using classification systems such as RMR, SMR, and Q is crucial to understanding the geomechanical behavior of these rocks, which directly impacts the design and safety of engineering structures in this tectonically active Himalayan terrain.

The effects of active tectonics and regional seismicity in the Kashmir Himalaya are directly reflected in the rock mass classification results through variations in discontinuity density, orientation, and condition, as well as fragmentation and block size. Zones subject to elevated tectonic strain and seismic activity exhibit systematically lower RMR and Q values, indicative of reduced rock mass quality, while SMR analyses reveal heightened slope instability potential where structural orientations favor kinematically feasible failures. Collectively, these outcomes capture the spatial imprint of ongoing deformation and seismic loading, enabling a realistic, geomechanically informed assessment of rock mass behavior under both static and dynamic conditions. Figure 1 illustrates the location of the study region. RMR, SMR, and Q were selected because they are well-established, empirically validated rock mass classification frameworks that provide complementary insights directly relevant to the geological and engineering conditions of the study area.

The lack of proper geomechanical characterization can lead to inaccurate design parameters, increasing the risk of slope failures, tunnel collapses, and construction delays. In particular, slope instability and seismic vulnerability are major concerns in this region. So, a systematic application of rock mass

classification systems is critical to ensure the safety, cost-effectiveness, and sustainability of infrastructure projects in the Kashmir Valley. Investigation sites were selected using an integrated litho-tectonic and geomechanical framework to ensure representative coverage of the Kashmir Valley. Site selection was guided by regional geological and structural maps and targeted locations where comprehensive field data permit robust evaluation of rock mass conditions using the RMR, SMR, and Q classification systems. The selected sites span a wide range of lithologies, structural configurations, and deformation intensities, encompassing poor to very good rock mass classes. This strategy ensured that the dataset captures the inherent geomechanical variability across the major litho-tectonic domains of the valley and supports regionally representative interpretations. This study addresses this need by evaluating rock mass conditions across representative sites using these well-established empirical methods.

IV. MATERIALS AND METHODS

The methodological framework adopted in this study follows a multistage approach integrating desk-based analysis, remote sensing, field investigations, laboratory testing, and empirical rock mass classification to evaluate geomechanical conditions across the Kashmir Valley. The workflow begins with a proper desk study, involving a review of regional geology, tectonic framework, previous engineering geological studies, and compilation of historical landslide inventory data from secondary sources. This stage facilitated identification of lithologically and structurally critical zones and guided the selection of representative field sites. The remote sensing and GIS-based terrain analysis was conducted using satellite imagery and digital elevation models to delineate slope morphology, lineaments, drainage patterns, and geomorphic indicators of instability. Potential landslide-prone areas, road cuttings, tunnel portals, and

structurally controlled slopes were identified to refine field investigation locations. Detailed field investigations, including engineering geological mapping and discontinuity surveys at selected sites, were conducted. Discontinuity parameters such as joint orientation, spacing, persistence, surface condition, infilling, and weathering were measured following ISRM standards. Scanline and window mapping techniques were employed to quantify joint frequency, while slope geometry and excavation characteristics were recorded. Selected active and dormant landslides were investigated to identify failure mechanisms and correlate them with rock mass conditions.

Rock sampling and laboratory testing were carried out, where representative samples were collected for uniaxial compressive strength determination and index property evaluation. Figure 2 shows the Uniaxial Compressive Strength (UCS) apparatus and Schmidt hammer used for testing, respectively. In areas with limited sample recovery, in-situ Schmidt hammer tests and empirical correlations were used to estimate strength parameters. Data integration and analysis were carried out through processing field and laboratory data to compute RMR, SMR, and Q for each site. The classification outputs were spatially analyzed and interpreted in relation to lithology, structure, slope geometry, and historical landslide data. The results were used to assess rock mass behavior, slope stability, and excavation performance, forming the basis for engineering recommendations for hazard-resilient infrastructure development in the Valley.

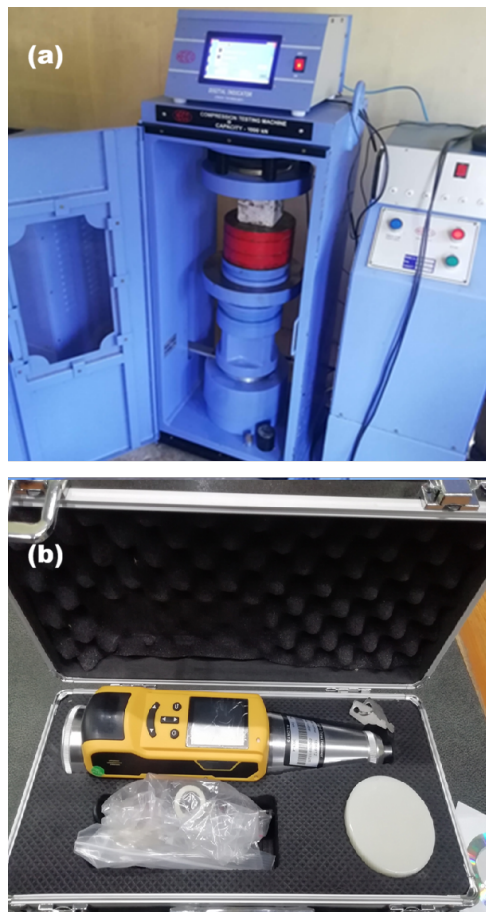


Fig. 2 Used experiments in this study to investigate rock mass index properties: (a) UCS, (b) Schmidt rebound

V. ENGINEERING GEOLOGY OF STUDIED SITES

A. RMR Classification

The RMR values obtained from different locations across the Kashmir Valley reflect significant spatial variability in rock mass characteristics, controlled primarily by lithology, structural fabric, degree of weathering, groundwater conditions, and the tectonic history of the region.

Kupwara District: The Kupwara region exhibits predominantly fair to poor rock mass quality, with RMR values ranging from 30.5 to 51. Lithologies such as siltstone, greywacke, arenite, limestone, slate, sandstone, basalt, and marble were evaluated. Limestone units at Shumnag and Nutnus show relatively higher RMR values (43.5–51), indicating moderately jointed but competent rock masses with favorable groundwater conditions. These rock masses are suitable for moderate-scale civil infrastructure such as building foundations, retaining walls, and low-height cut slopes with minimal support. In contrast, slate-dominated areas such as Kralpora and Sagipora exhibit poor RMR values (30.5–32.5), reflecting closely spaced joints, weak joint surfaces, and susceptibility to weathering. These rock masses are prone to instability when excavated and would require systematic slope stabilization measures, including rock bolting, shotcrete, and proper drainage for road construction or slope cutting projects.

Baramulla District: The Baramulla District shows a mix of poor to fair rock mass conditions, with RMR values generally between 35.5 and 48.5. Phyllite and slate formations dominate the majority of the area, particularly around Mohra, Uri, and Khanpora, where poor RMR values indicate highly foliated, anisotropic rock masses. Such rocks are structurally weak and sensitive to excavation-induced stress relief, making them unsuitable for unsupported cuts. Granite exposures at Qazinag display relatively higher RMR values (~48.5), reflecting massive rock fabric and higher intact rock strength. These zones are favorable for tunnelling, bridge abutments, and heavy structural foundations, provided that joint orientations are properly accounted for during design. Figure 3 presents field photographs of selected locations captured during the geological fieldwork.

Bandipora District: The Bandipora region presents considerable variability in rock mass quality due to alternating limestone and phyllite lithologies. Fair RMR values (40–48.5) are observed at Watlab, Mansbal, and Saderkote indicate moderately competent rock masses with acceptable joint spacing and favorable groundwater conditions. These areas are suitable for infrastructure development such as highways, residential structures, and shallow tunnels with light to moderate support systems. However, sections along the Gurez Road exhibit poor RMR values (26.5–33), highlighting structurally disturbed and weathered rock masses. These poor-quality zones are critical from a geotechnical standpoint and demand careful alignment selection, reinforced cut slopes, and comprehensive drainage control to prevent landslides and slope failures. Figure 4 presents field photographs of selected locations captured during the geological fieldwork.

Ganderbal and Sonmarg Region: Granite-dominated zones such as Kangan Wangat and Kulan Sonmarg show fair RMR values (44.5–45.5), indicating relatively competent rock masses suitable for tunnels and deep foundations. Conversely, mixed

lithologies of limestone, phyllite, and slate around Gund and Gagangir show poor RMR values (38–39), reflecting tectonic deformation and unfavorable joint conditions. These zones pose challenges for tunnelling and slope stabilization and require systematic rock reinforcement measures such as rock bolts, wire mesh, and shotcrete lining. Figure 5 presents field photographs of selected locations captured during the geological fieldwork.

Zojila Pass to Kargil Corridor: The Zojila Pass region is dominated by phyllite, slate, limestone, and granite. Poor RMR values (28–35) dominate the pass and tunnel zones, highlighting weak, sheared, and moisture-sensitive rock masses. These conditions explain the frequent slope failures and maintenance challenges faced along this corridor. Granitic rocks near Drass, Bhimbat, and Kargil show fair RMR values (43.5–49.5), indicating better rock mass stability and higher load-bearing capacity. These areas are suitable for heavy civil structures such as bridges, tunnel portals, and military infrastructure, provided proper excavation techniques are employed. Figure 6 presents field photographs of selected locations captured during the geological fieldwork.

Srinagar and Budgam Areas: The Srinagar region shows a mix of fair and poor RMR values, reflecting urban geological complexity. Basalt and Agglomeratic slate formations exhibit moderate RMR values (~37–42.5), while sandstone units show poorer ratings due to higher weathering and groundwater

influence. These conditions necessitate careful foundation design, especially for multistorey buildings and urban infrastructure. Budgam district largely exhibits poor RMR values (31–38.5), particularly in basalt and limestone formations affected by weathering and jointing. Infrastructure development in this area should prioritize shallow foundations, slope stabilization, and controlled excavation practices. Figure 7 presents field photographs of selected locations captured during the geological fieldwork.

Anantnag, Shopian, and Pulwama Regions: Southern Kashmir regions such as Anantnag and Shopian predominantly exhibit poor RMR values (26–37.5), especially in volcanic and sedimentary rocks, including Panjal Volcanics, shale, slate, and limestone. These rock masses are highly fractured and weathered, making them unsuitable for unsupported excavations. However, the Khanmoh–Khrew–Panthachowk area in Pulwama exhibits the best rock mass conditions in the study area. RMR values up to 61 (Good Rock) were recorded in basalt and andesite formations, indicating massive, strong, and well-interlocked rock masses. These zones are ideal for heavy infrastructure such as tunnels, bridges, industrial foundations, and large underground excavations with minimal support requirements. Figure 8 presents field photographs of selected locations captured during the geological fieldwork.



Fig. 3 Field photos from the Baramulla-Uri Road survey showing rock formations and landslides caused by poor rock mass conditions



Fig. 4 Field photos from the geological survey along Bandipora-Gurez road, highlighting diverse rock formations



Fig. 5 Field photos from the Ganderbal Sonmarg Road survey showing rock formations and landslides caused by poor rock mass conditions



Fig. 6 Field photos captured during geological survey along the Zojila Pass road, showcasing the diverse rock formations



Fig. 7 Field photos captured during geological survey Beerwah Budgam, showcasing the diverse rock formations



Fig. 8 Field photos from the Kulgam and Anantnag Districts survey showing rock formations and landslides caused by poor rock mass conditions

The RMR values obtained in this study provide a critical input for the planning and designing civil infrastructure across the Kashmir Valley. Areas with good to fair rock mass quality ($RMR > 40$) are generally suitable for major infrastructure projects, including tunnels, highways, bridges, hydropower projects, and urban development, with conventional support systems. In contrast, regions with poor rock mass quality ($RMR < 35$) require detailed site investigations, careful alignment selection, and robust stabilization measures. These include rock bolting, shotcrete, retaining structures, controlled blasting, and effective drainage systems. RMR-based zoning can significantly reduce construction risks, cost overruns, and long-term maintenance issues. The RMR-based evaluation across Kashmir Valley clearly demonstrates the strong control of lithology, structure, and groundwater on rock mass behavior. The spatial variability in RMR values underscores the necessity of site-specific geotechnical investigations for infrastructure development in this tectonically active region. The results serve as a valuable decision-making tool for engineers, planners, and policymakers, enabling safer, more economical, and sustainable development of civil infrastructure across Kashmir.

B. SMR Classification

The SMR values derived for different locations across the Kashmir Valley demonstrate pronounced spatial variability in slope stability conditions, reflecting the combined influence of lithology, structural discontinuities, tectonic deformation,

geomorphology, and excavation practices. The results presented demonstrate that SMR values across the region range from very poor (~ 18) to good (~ 61), indicating that slope stability conditions vary significantly over short distances in this tectonically active Himalayan terrain. Different slope failure modes are distinguished within the SMR framework by systematically evaluating the geometric and structural relationships between slope orientation and discontinuity sets, as prescribed in the SMR methodology. Planar, wedge, and toppling failure potentials were inferred based on the angular relationships, spacing, persistence, and condition of discontinuities relative to the slope face, without requiring detailed numerical kinematic modeling. This approach leverages the empirical, kinematics-informed scoring inherent to SMR, enabling rapid, field-based identification of dominant failure mechanisms while maintaining consistency with observed slope behaviors along the investigated corridors. In general, slopes developed in massive igneous rocks such as basalt, andesite, and granite exhibit higher SMR values, whereas slopes in phyllite, slate, shale, limestone with karstification, and volcano-sedimentary sequences commonly display low to very low SMR values. This variability has direct implications for the planning, design, and maintenance of civil infrastructure such as highways, tunnels, rail corridors, urban cut slopes, and hydropower projects in the Kashmir Valley. SMR-based slope instability interpretations were rigorously validated through integrated field verification and independent kinematic analyses along major transportation corridors.

Observed slope failures were systematically inventoried and classified according to failure mechanism and structural control and subsequently compared with SMR-derived stability classes and predicted modes of instability. Kinematic analyses, based on measured discontinuity sets and slope orientations, were conducted to independently evaluate the feasibility of planar, wedge, and toppling failures. The strong correspondence between SMR predictions, kinematic outcomes, and documented failure occurrences demonstrates the robustness and predictive reliability of the SMR-based slope instability assessment.

Kupwara Region: The Kupwara district exhibits SMR values ranging from 20.05 to 51.06, reflecting predominantly poor to fair slope stability conditions. Limestone slopes at Shumnag and Nutnus show relatively high SMR values (>43), attributable to moderate joint dip relationships and favorable excavation methods. These slopes can generally remain stable under controlled excavation, provided that adequate drainage and local reinforcement are implemented. In contrast, slate and marble slopes at Kralpora and Zirhama record very low SMR values ($\sim 20\text{--}25$), indicating high susceptibility to planar or wedge failures. The unfavorable angular relationships between joint sets and slope faces, combined with mechanical excavation effects, significantly reduce slope stability. Such slopes require systematic stabilization measures, including rock bolting, anchored shotcrete, and benching, particularly along road corridors and settlement expansions.

Baramulla District: The Baramulla region presents SMR values mostly within the moderate stability range ($\sim 35\text{--}49$). Granite slopes at Qazinag exhibit relatively high SMR values (~ 48.7), suggesting stable slope conditions suitable for major infrastructure such as highways, tunnel portals, and bridge abutments. These slopes are characterized by favorable joint orientations and minimal adverse effects of excavation. However, phyllite and slate slopes at Mohra, Uri, and Khanpora show lower SMR values ($\sim 35\text{--}38$), indicating potential instability under heavy rainfall or seismic loading. These slopes are particularly vulnerable to toppling and planar failures, necessitating slope flattening, controlled blasting, and surface drainage provisions in road-cut and urban development projects.

Bandipora and Gurez Road Corridor: The Bandipora district and Gurez Road sections represent some of the most geotechnically sensitive areas in the study. SMR values in this region vary widely from 18.80 to 40.74. Several Gurez Road sites exhibit very low SMR values (<25), reflecting highly unfavorable joint-slope relationships and excavation-induced instability. These slopes are prone to frequent rockfalls and debris slides, posing significant risks to road users and maintenance operations. Conversely, slopes at Saderkote Bala and Payeen exhibit moderately stable conditions (SMR ~ 40), indicating better rock mass behavior due to comparatively favorable structural orientations. Infrastructure development in this corridor must therefore rely on SMR-based zoning to identify critical sections requiring heavy stabilization, such as rockfall barriers, reinforced retaining structures, and realignment of road sections where feasible.

Ganderbal-Sonmarg Sector: The region shows SMR values ranging from 26.18 to 44.54, reflecting mixed stability conditions. Granite slopes at Kangan Wangat exhibit relatively stable conditions suitable for tunnel portals and highway cuts

with minimal reinforcement. In contrast, slopes composed of limestone, phyllite, and slate around Gund, Gagangir, and Sonmarg exhibit poor SMR values (<32), indicating structurally controlled instability. These low SMR values explain the frequent slope failures observed along the Srinagar-Sonmarg highway, especially during snowmelt and monsoon periods. Engineering interventions in this region must integrate systematic rock reinforcement, improved drainage systems, and controlled excavation techniques to mitigate failure risks.

Zojila Pass to Kargil Corridor: The Zojila Pass and adjoining sections exhibit predominantly poor slope stability, with SMR values mostly between 28 and 35 in phyllite and slate formations. These lithologies are intensely foliated and tectonically disturbed, resulting in highly unfavorable discontinuity orientations relative to steep natural slopes. This condition accounts for the chronic instability issues along the Zojila corridor, including frequent landslides and road closures. In contrast, granite slopes near Drass, Bhimbat, and Kargil show higher SMR values ($\sim 44\text{--}50$), indicating comparatively stable slope conditions. These areas are more suitable for infrastructure development, including tunnel alignments and military installations, although seismic considerations must still be incorporated into design.

Srinagar Urban Area: The Srinagar region exhibits a wide range of SMR values ranging from 22.54 to 51.78, reflecting the geological heterogeneity of the urban setting. Basalt and agglomeratic slate slopes show poor to moderate stability, while sandstone slopes at Hariparbat display high SMR values (>50), indicating stable conditions favorable for urban development and heritage conservation. However, low SMR values along certain road cuts (e.g., Gupkar Road sites) highlight the need for slope-specific engineering interventions in urban planning to ensure long-term safety and sustainability.

Budgam, Anantnag, Shopian, and Pulwama: Southern Kashmir generally exhibits poor to moderate slope stability, with SMR values commonly below 40 in limestone, basalt, slate, and volcanic formations. Shopian and Anantnag regions show particularly low SMR values (<30), indicating high landslide susceptibility along road corridors such as the Mughal Road. In contrast, the Pulwama region, particularly Panthachowk and Athwajan, records the highest SMR values (>61), reflecting excellent slope stability in massive basalt and andesite formations. These slopes are ideal for large-scale infrastructure projects such as tunnels, industrial zones, and transportation hubs with minimal stabilization requirements.

The SMR results provide a robust empirical basis for slope stability assessment and infrastructure planning across the Kashmir Valley. Areas with SMR > 45 are generally stable and suitable for steep cut slopes with minimal support, while areas with SMR < 30 require extensive stabilization, careful excavation sequencing, and continuous monitoring. Incorporation of SMR-based zoning into infrastructure planning can significantly reduce construction risks, optimize design costs, and improve long-term slope performance. The SMR framework is particularly valuable for road and tunnel projects in mountainous terrain, where slope orientation and excavation method play a critical role in stability.

The SMR-based evaluation across the Kashmir Valley highlights the strong control of structural geology and excavation practices on slope stability. The results underscore the necessity

of site-specific geotechnical investigations and SMR-based design approaches for sustainable and safe civil infrastructure development in this seismically active Himalayan region. The findings provide a valuable reference for engineers, planners, and policymakers.

C. Q Classification

The Q-values derived from different lithological units across the Kashmir Valley reveal predominantly very poor to poor quality of rock mass, with a limited number of sites exhibiting fair rock mass conditions. These results provide critical insights into the engineering challenges associated with infrastructure development in this tectonically active Himalayan region. Across the study area, Q-values ranging from 0.025 to a maximum of 5.379, indicating that most rock masses fall within the very poor rock category ($Q < 1$). Such low Q-values are characteristic of intensely fractured, sheared, weathered, and groundwater-affected rock masses, conditions that are common in the Kashmir Valley due to its complex geological evolution, proximity to major thrust systems, and active seismicity. The dominance of very poor Q-values underscores the inherent geotechnical vulnerability of the region and highlights the necessity of adopting conservative design approaches for both surface and underground civil engineering projects.

Kupwara and Baramulla: In the Kupwara district, Q-values range between 0.050 and 0.845, indicating uniformly very poor rock mass quality across diverse lithologies including siltstone, greywacke, arenite, slate, limestone, basalt, and marble. Despite relatively competent intact rock strength in limestone and basalt units, the low Q-values suggest that the rock masses are severely downgraded by closely spaced joints, unfavorable joint surface conditions, and groundwater ingress. Slate and marble formations at Kralpora and Zirhama show particularly low Q-values (< 0.1), reflecting pronounced anisotropy, foliation-controlled weakness, and susceptibility to weathering. These conditions make such rock masses highly unsuitable for unsupported excavations and necessitate heavy support measures for tunnels, cut slopes, and underground utilities. Similarly, the Baramulla district exhibits Q-values mostly below 0.4, even in comparatively strong lithologies such as schistose quartzite and granite. The granite at Qazinag, despite its high intact strength, yields a Q-value of 0.794, illustrating that structural discontinuities and groundwater conditions exert greater control on rock mass behavior than lithology alone. For civil infrastructure projects in these regions, the Q-system results imply the need for systematic rock reinforcement, including rock bolts, fiber-reinforced shotcrete, steel ribs, and effective drainage systems.

Bandipora and Gurez Road Corridor: The Bandipora district, particularly along the Gurez Road corridor, displays some of the lowest Q-values recorded in the study, with values as low as 0.027. Limestone–phyllite assemblages dominate the region, and the very poor Q-values reflect intense tectonic deformation, closely spaced discontinuities, and adverse groundwater conditions. Such rock masses are prone to squeezing behavior and frequent instability under excavation. These results are highly significant for infrastructure development along the strategically important Gurez corridor. Road cuts, tunnels, and

slope excavations in this area are expected to experience persistent stability issues unless comprehensive ground improvement measures are implemented. The Q-system results strongly advocate for the use of flexible support systems, staged excavation, reduced span designs, and continuous monitoring to mitigate the risk of collapse and long-term deformation.

Central Kashmir (Ganderbal and Srinagar): In the Ganderbal–Sonmarg sector, Q-values range from 0.158 to 0.501, indicating consistently very poor rock mass quality in limestone, phyllite, slate, and granite units. Even granitic rocks, which typically offer good engineering performance, exhibit low Q-values due to unfavorable jointing and stress conditions. These findings corroborate the frequent slope failures and tunnel maintenance challenges observed along the Srinagar–Sonmarg axis. The Srinagar urban area also exhibits predominantly very poor Q-values (< 0.4), particularly in basalt, agglomeratic slate, and sandstone formations. These results highlight the vulnerability of urban slopes, foundation excavations, and underground services to instability and groundwater-related issues. For urban infrastructure development, such as metro systems, basements, and utility tunnels, the Q-system results emphasize the necessity of robust ground support and waterproofing strategies.

Zojila Pass to Kargil Sector: The Zojila Pass and adjoining regions show extremely poor Q-values, commonly below 0.1 in phyllite and slate formations. These lithologies are highly foliated, weathered, and affected by freeze–thaw cycles, resulting in very weak rock masses. The granite units near Drass, Bhimbat, and Kargil exhibit slightly higher Q-values (up to 0.944), yet fall within the very poor category. These results explain the chronic instability issues along the Zojila corridor, including frequent tunnel collapses, slope failures, and maintenance-intensive road sections. From an engineering standpoint, the Q-system classification strongly supports the adoption of heavily reinforced tunnel linings, reduced excavation spans, and advanced support systems such as yielding supports and reinforced concrete linings for long-term stability.

Anantnag, Shopian, Kokernag, and Pulwama: Southern Kashmir regions such as Anantnag and Shopian exhibit uniformly very poor Q-values (< 0.15), particularly in volcanic and sedimentary formations like Panjal Volcanics, shale, slate, and limestone. These low values indicate extremely poor rock mass conditions, making these areas highly susceptible to landslides and slope failures, especially along critical routes such as the Mughal Road. In contrast, the Pulwama region presents a notable improvement in rock mass quality. Basalt and andesite formations at Panthachowk and Athwajan exhibit Q-values of 5.379, classifying them as fair rock masses. Limestone at Khrew also shows a higher Q-value (1.882), falling within the poor category. These relatively higher Q-values indicate more massive rock fabric, better joint conditions, and reduced groundwater influence. Such conditions are favorable for large-scale civil infrastructure, including tunnels, industrial foundations, and transportation hubs, with moderate support requirements.

The Q results provide a powerful quantitative framework for assessing the feasibility and design requirements of civil infrastructure in the Kashmir Valley. The predominance of very poor Q-values implies that most underground excavations will require systematic and heavy support systems, including closely

spaced rock bolts, thick shotcrete layers, steel ribs, and reinforced concrete linings. For surface infrastructure, such as road cuts and slope excavations, the results indicate a high likelihood of instability unless slopes are flattened, reinforced, and adequately drained.

Q-values can be directly used to optimize tunnel span, excavation method, and support class selection, thereby reducing construction risks and lifecycle costs. Integration of Q-system results with RMR and SMR classifications provides a comprehensive geotechnical characterization, enabling engineers to design safer and more resilient infrastructure in this seismically active and geologically complex region. The Q-based evaluation of rock masses across the Kashmir Valley reveals predominantly very poor rock mass conditions, reflecting the strong influence of tectonics, structural discontinuities, and groundwater. The limited occurrence of fair-quality rock masses highlights localized zones of engineering advantage that can be prioritized for major infrastructure development. Overall, the Q-system results underscore the necessity of rigorous geotechnical investigation, conservative design, and advanced support systems for sustainable infrastructure development in the Kashmir Valley.

VI. RESULTS AND DISCUSSION

The combined analysis of RMR, SMR, and Q classifications provides a coherent and mutually reinforcing interpretation of rock mass behavior across the Kashmir Valley, highlighting the strong influence of lithology, structural discontinuities, slope geometry, and hydrogeological conditions on engineering performance. The statistical distribution of Q-values (Figure 9) clearly demonstrates a pronounced dominance of very poor rock mass quality throughout the study area. Most sites exhibit Q-values well below 1.0, indicating intensely fractured, tectonically disturbed, and weathered rock masses with limited self-supporting capacity. This observation is consistent with the regional geological setting of the Kashmir Himalaya, characterized by active tectonics, multiple deformation phases, and pervasive jointing in sedimentary, metamorphic, and volcanic formations. The statistical measures, including mean, range, and variance of RMR, SMR, and Q values were computed for all investigation sites to quantitatively characterize spatial variability in rock mass quality. These metrics reveal systematic trends in rock mass conditions across different litho-tectonic domains and slope settings, providing a robust basis for identifying high- and low-quality zones. By incorporating these statistical descriptors, the study not only captures inherent heterogeneity but also supports evidence-based engineering design and risk assessment along transportation corridors.

The SMR distribution (Figure 10) complements the Q results by revealing that slope stability conditions predominantly range from poor to fair, with only a limited number of locations exhibiting comparatively stable slope conditions. While some sites record moderate RMR values, their SMR ratings are substantially reduced due to unfavorable discontinuity-slope orientations and excavation effects captured through correction factors (F_1 – F_4). This underscores the critical role of slope geometry and structural alignment in governing instabilities.

The relationship between RMR and Q (Figure 11) exhibits a positive but nonlinear trend, confirming that increases in RMR

generally correspond to higher Q-values. However, the strong clustering of data points at very low Q-values despite moderate RMR scores highlights the greater sensitivity of the Q to joint condition parameters and groundwater influence. This indicates that while RMR provides a useful overall index of rock mass, it may underrepresent the severity of adverse jointing and water conditions that critically control excavation behavior in the study area. The proposed region-specific geomechanical database is conceived as a spatially integrated, standardized repository of lithological, structural, and geomechanical information derived from systematic field investigations. It will incorporate quantitative rock mass indices (RMR, SMR, and Q), discontinuity and slope-geometry parameters, groundwater conditions, and records of observed instability. Implemented within a GIS-compatible framework, the database will enable spatial zonation of rock mass quality and slope stability and allow direct integration with infrastructure planning workflows.

The correlation between RMR and SMR (Figure 12) further demonstrates that rock mass quality alone does not necessarily translate into slope stability. Although higher RMR values tend to be associated with improved SMR ratings, significant scatter is observed due to the modifying effect of slope orientation and excavation method. This finding reinforces the necessity of SMR-based evaluation for slope-specific design, particularly in Himalayan terrain where structurally controlled failures are common.

The relationship between Q and SMR (Figure 13) reveals that sites with extremely low Q-values predominantly correspond to unstable or marginally stable slopes. A limited number of higher Q-values align with improved SMR ratings, indicating relatively competent rock masses with more favorable joint configurations. Nevertheless, the wide dispersion of data reflects the partial decoupling between subsurface rock mass quality and surface slope geometry, emphasizing that no single classification system can independently capture the full spectrum of geomechanical behavior. Potential inconsistencies and conceptual overlaps among the RMR, SMR, and Q classification systems were addressed through an integrated, multi-criteria validation approach. Each classification scheme was applied independently using a common field dataset to maintain methodological consistency and minimize parameter redundancy. The resulting classifications were systematically compared to evaluate convergence and divergence in rock mass quality assessments, with observed differences interpreted in light of the distinct theoretical emphases of each system. Specifically, RMR and Q were used to characterize the intrinsic rock mass quality, whereas SMR was prioritized for incorporating slope orientation and kinematic controls. Rather than enforcing direct numerical equivalence, the systems were synthesized to derive a coherent geomechanical interpretation tailored to the specific engineering context, thereby enhancing the robustness and reliability of the integrated assessment.

The interpretation of RMR, SMR, and Q classifications in this study highlights the dynamic nature of rock mass behavior across the Kashmir Valley and underscores its direct influence on infrastructure planning and development strategies in mountainous terrain. Rather than viewing these indices as static descriptors of rock quality, the observed spatial variability demonstrates how geomechanical conditions evolve in response

to lithology, structural complexity, slope geometry, and anthropogenic modification through excavation. Such variability has important implications for long-term infrastructure performance, risk mitigation, and sustainability. One of the key insights from this study is the recognition that moderate rock mass quality values do not necessarily translate into stable engineering conditions. The adjustment of RMR values through slope-specific parameters in the SMR framework reveals how excavation geometry and joint-slope relationships can significantly reduce overall stability. This has direct consequences for road widening projects, tunnel portal design, and cut slope development, where seemingly competent rock masses may exhibit failure when unfavorable structural orientations are exposed. From a development perspective, this finding highlights the need to move beyond generalized geological assessments and adopt site-specific geomechanical evaluations early in the planning phase. The integrated RMR–SMR–Q assessment enhances risk-informed decision-making by providing a quantitative, site-specific evaluation of rock mass quality, slope stability, and likely failure modes, surpassing the generalized insights of conventional hazard zonation maps. Unlike traditional maps, which delineate broad risk areas, this combined empirical framework captures lithological, structural, and geomechanical heterogeneity, enabling targeted engineering judgments and prioritized mitigation measures. By linking

geomechanical characterization directly to infrastructure planning and support design, the approach facilitates evidence-based, context-specific risk management in the structurally complex Himalayan terrain.

The Q-system results further emphasize the sensitivity of excavation behavior to joint conditions and groundwater influence, factors that are particularly critical in the Himalayan environment. The predominance of low Q-values suggests that unsupported or minimally supported excavations are unlikely to remain stable over time, especially under seasonal variations in pore water pressure and freeze–thaw cycles. Incorporating Q-based support guidelines into design practices can therefore reduce over-excavation, minimize maintenance costs, and enhance the longevity of infrastructure, contributing directly to resource-efficient and sustainable development.

From a broader sustainability perspective, the empirical relationships established between RMR, SMR, and Q systems provide a robust framework for optimizing design interventions. By identifying zones where minor improvements in slope orientation, drainage control, or excavation method can yield significant gains in stability, this approach supports targeted mitigation rather than extensive structural interventions. Such optimization reduces material consumption, limits environmental disturbance, and aligns infrastructure development with ecological constraints typical of the Kashmir Valley.

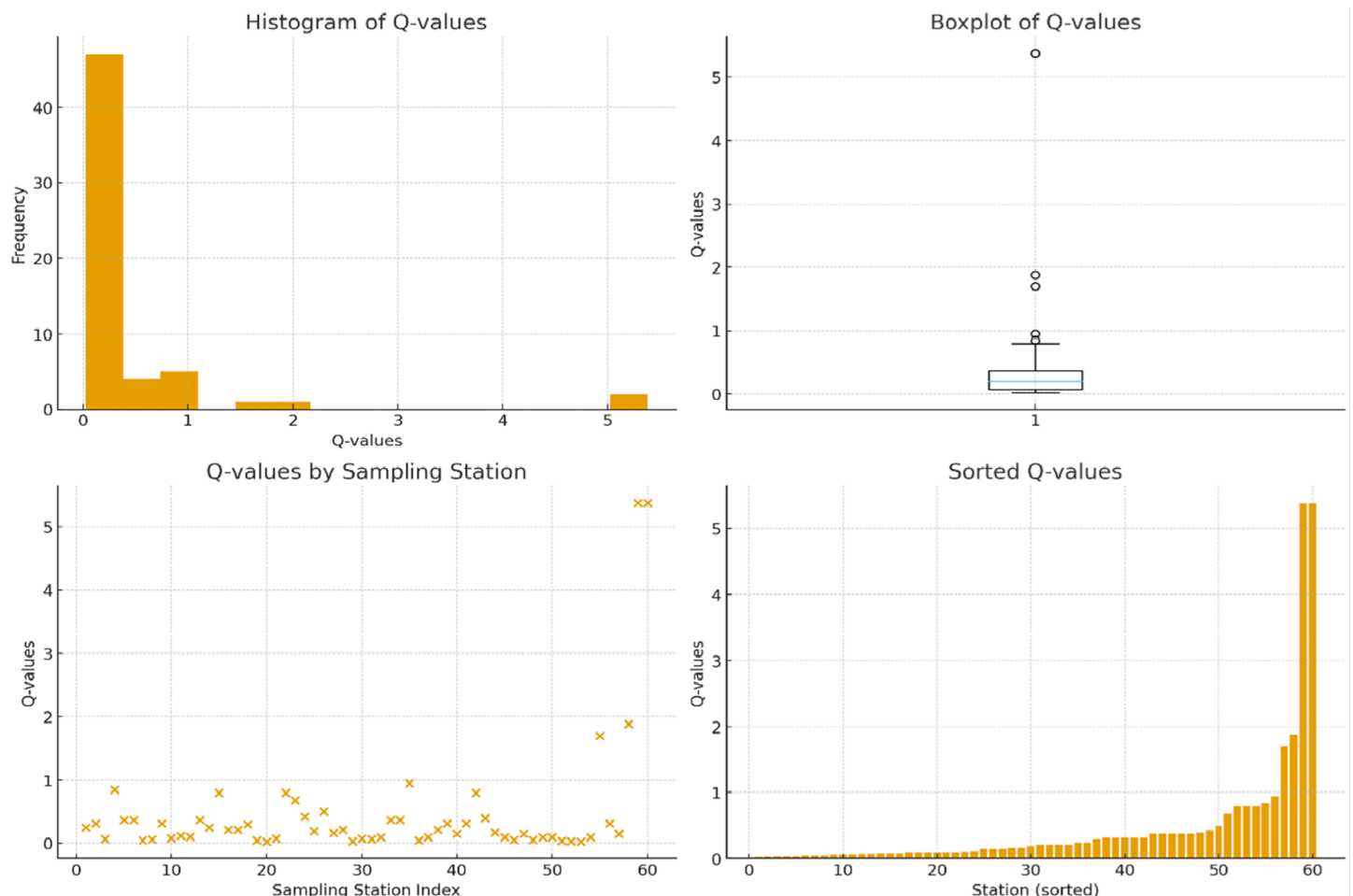


Fig. 9 Statistical summary of Q values showing across the study area

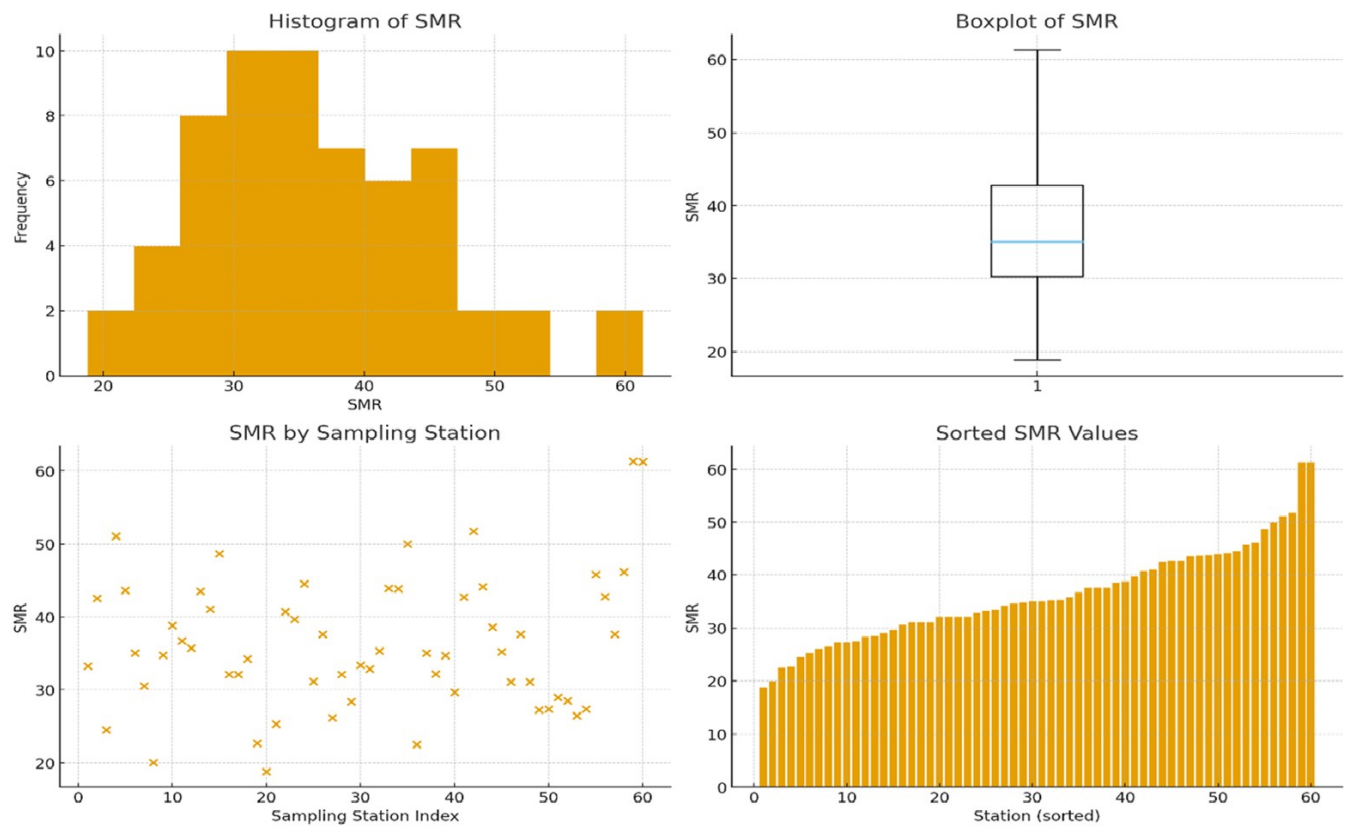


Fig. 10 Statistical summary of SMR values showing across the study area

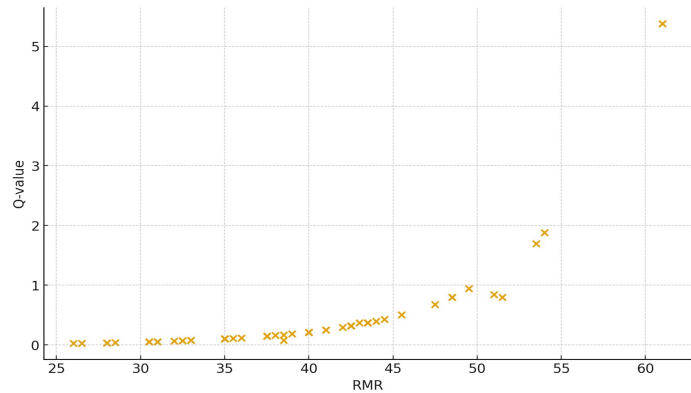


Fig. 11 Correlation between RMR and Q-value

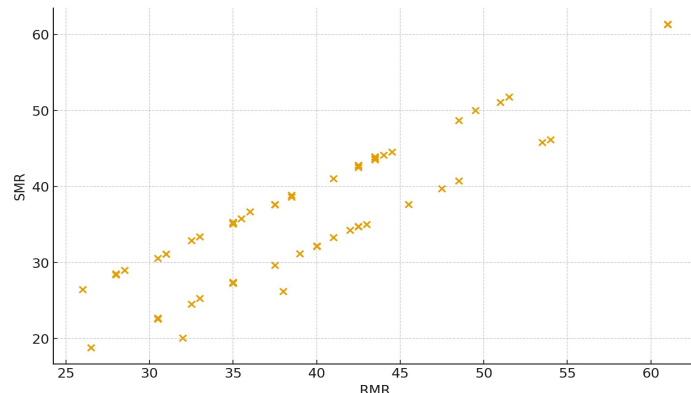


Fig. 12 Relationship between RMR and SMR

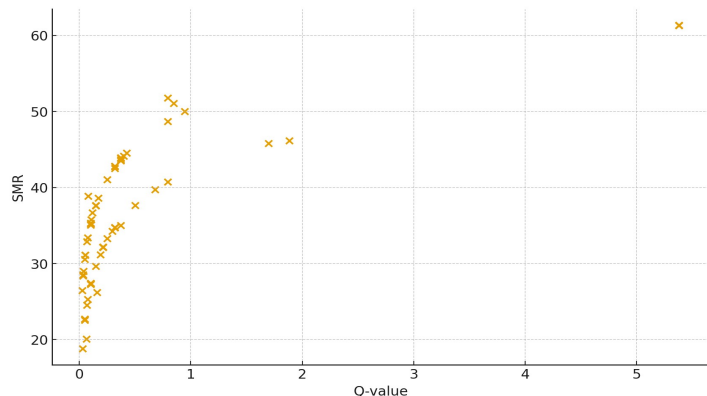


Fig. 13 Relationship between Q-value and SMR

While empirical rock mass classification systems inherently include parameters with a degree of subjectivity, such as joint conditions and groundwater state, their influence on the reported rock mass quality classes was minimized through standardized field protocols and systematic cross-checking. All subjective parameters were evaluated using established rating guidelines, supported by repeated field observations, photographic documentation, and consistency checks among the investigators. Sensitivity analyses were conducted by examining the effect of plausible rating variations on the final RMR, SMR, and Q classifications, which demonstrated that the overall rock mass quality classes remained stable within defined rating ranges. Consequently, although subjectivity cannot be eliminated, its impact on the integrated geomechanical assessment is limited and does not affect the robustness of the reported classifications.

This study also contributes to disaster risk reduction by linking geomechanical classifications with known instability-prone terrains. The ability to anticipate performance under excavation and loading conditions allows planners to avoid high-risk alignments, prioritize stabilization in critical corridors, and integrate geotechnical considerations into land-use planning. In a region where infrastructure development must coexist with fragile ecosystems and active tectonics, this predictive capability is essential for sustainable growth. Mainly, the integrated use of RMR, SMR, and Q systems demonstrated in this study offers a practical, scalable, and cost-effective decision-support tool for infrastructure development in the Kashmir Himalaya. By embedding empirical geomechanical evaluation into planning and design workflows, the approach facilitates safer construction practices, reduced lifecycle costs, and environmentally responsible development, reinforcing the role of engineering geology as a cornerstone of sustainable infrastructure in mountainous regions.

VII. CONCLUSION

This study provides a comprehensive geomechanical characterization of rock masses in the Kashmir Valley using an integrated application of the RMR, SMR, and Q classification systems. The main objective was to evaluate the engineering behavior of different lithological units in a tectonically active Himalayan environment and to assess their implications for infrastructure development, particularly in terms of slope stability, excavation performance, and long-term sustainability. To address increasing infrastructure demands under complex geological conditions, the study adopted a multi-scale methodology combining desk studies, historical landslide analysis, remote sensing, field investigations, and laboratory and in-situ testing. This approach enabled the identification of both regional trends and site-specific geomechanical controls, providing a realistic understanding of rock mass behavior. The results indicate that much of the study area consists of weak to very poor rock masses, mainly due to intense jointing, unfavorable discontinuity orientations, groundwater effects, and weathering. While RMR offers a general assessment of rock quality, SMR highlights the importance of slope geometry and excavation methods, and the Q-system emphasizes the influence of joint conditions and hydrogeological factors. The combined use of these methods shows that relying on a single classification

system may lead to incomplete or non-conservative design decisions. Mainly, the integrated RMR–SMR–Q framework provides an effective tool for identifying unstable zones, understanding failure mechanisms, and estimating support requirements. The study demonstrates that systematic empirical classification can improve the safety, efficiency, and sustainability of infrastructure development in the Kashmir Valley, offering valuable guidance for engineers and planners working in similar mountainous regions.

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DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available from the corresponding author upon reasonable request. No publicly archived dataset was generated.

ETHICS APPROVAL

This study did not involve human participants, personal data, or animal subjects. No specific ethical approval was required.

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AUTHORS' CONTRIBUTIONS

Aasif Ibni Ahad conducted the formal analysis, investigation, software development, visualization, and was responsible for writing the original draft. He also contributed to methodology, validation, conceptualization, and data curation. Syed Kaiser Bukhari, and Maqbool Yousuf performed supervision, contributed to validation, and were responsible for reviewing and editing the manuscript. All authors read and approved of the final manuscript.

CONFLICT OF INTEREST

The authors have not disclosed any competing interests.

USE OF AI

AI tools were not used in data generation, analysis, results, or decision-making.

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