

# Granite Rock Mass Characterization using GSI and Q-System: A Case Study for Keno-Kouh, Western Iran

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**Abstract:** The accurate classification of rock masses plays a critical role in the design and safety of geotechnical and tunneling projects. Among the most widely used systems for rock mass characterization are the Geological Strength Index (GSI) and the Rock Mass Quality index (Q-system), both of which integrate various structural and geomechanical parameters. This study focuses on evaluating the empirical relationship between GSI and Q-system in granitic rock masses of the Keno-Kouh region, situated in western Iran. Field investigations were conducted at multiple granite exposures, where joint conditions, discontinuity spacing, roughness, alteration, and rock strength were systematically measured. GSI values were derived from both direct field assessments and estimation charts, while Q-values were calculated using Barton's classification system. A statistical correlation analysis was performed between GSI and Q-values to identify a mathematical relationship relevant to this specific lithological setting. The findings demonstrate a strong linear correlation ( $R^2 > 0.85$ ) between the two classification systems within the granitic units, highlighting the isotropic and relatively homogeneous nature of the Keno-Kouh granites. The regression equations developed in this study provide a practical tool for estimating one index based on the other, which can be especially useful in data-limited engineering scenarios.

**Keywords:** Rock mass, Geological strength index, Q-System, Granite, Keno-Kouh region.

## I. INTRODUCTION

The classification of rock masses forms a cornerstone in the field of engineering geology and rock mechanics (Lin et al., 2017a). Unlike intact rock, which can be reliably tested in the laboratory, rock masses in their natural state are composed of discontinuities such as joints, faults, and bedding planes that significantly influence their mechanical behavior (Babendererde et al., 2004). These heterogeneities make the prediction of rock mass response to excavation and loading inherently complex (Villeneuve et al., 2018). Rock mass classification systems were

developed to address this complexity by providing structured frameworks to evaluate and categorize the mechanical quality of rock masses in situ (Bagde et al., 2002). Accurate rock mass classification is essential for the safe and economical design of civil and mining infrastructure, including tunnels, slopes, dams, foundations, and underground caverns (Somodi et al., 2021). It enables engineers and geologists to estimate important parameters such as rock mass strength, deformability, and stability under different stress conditions (Abad et al., 2015). This, in turn, aids in selecting appropriate excavation methods, ground support systems, and risk mitigation strategies (Salmanfarsi & Awang, 2025).

Inadequate or incorrect classification may lead to unsafe designs, cost overruns, and even structural failures, particularly in challenging geological settings (Renani & Cai, 2022). One of the key advantages of rock mass classification systems lies in their ability to provide engineers with practical, standardized methods to make informed decisions during both the preliminary and detailed stages of infrastructure projects (Ma et al., 2023). These systems reduce uncertainty by translating complex geological conditions into actionable engineering data (Cai et al., 2004). For example, they help determine tunnel support requirements, slope reinforcement needs, and foundation treatments (Agliardi et al., 2016). In large-scale projects, this translates into enhanced safety, optimized construction timelines, and reduced project costs (Hashemi et al., 2010).

Over the past decades, several rock mass classification systems have been introduced, each with a unique approach to capturing the geological and mechanical characteristics of rock masses (Zhang et al., 2018). These classification systems were developed in response to the growing need for practical, field-based methods to evaluate the behavior of rock masses during excavation and construction (Pepe et al., 2015). Traditional laboratory tests often fail to capture the large-scale mechanical behavior of fractured rock masses (Zhang et al., 2019). As a result, empirical classification systems emerged to bridge this gap, allowing engineers to relate geological observations to engineering design parameters (Cai et al., 2007). Each system was formulated with specific goals and applications in mind,

reflecting different philosophies and field conditions. Among the most commonly used are the Rock Mass Rating (RMR), Q-system, Geological Strength Index (GSI), and Rock Mass Index (RMI). These systems integrate field observations such as joint spacing, roughness, orientation, and strength parameters into numerical or qualitative scores that guide design decisions (Somodi et al., 2021). The continued evolution of these systems reflects the growing understanding of rock behavior and the need for more adaptable tools in diverse geological environments (Azarafza et al., 2017).

The RMR system, introduced by Bieniawski in the 1970s, was one of the earliest comprehensive frameworks for rock mass evaluation. It integrates several key parameters, such as uniaxial compressive strength (UCS) of intact rock, rock quality designation (RQD), joint spacing, joint condition, groundwater conditions, and joint orientation, to provide a numerical score representing rock mass quality. RMR is widely used for tunnel design, slope stability analysis, and foundation assessments (Qazi & Singh, 2023). It is especially valuable for preliminary site investigations and provides recommendations for support systems based on the rating (Rehman et al., 2018). Its simplicity, reproducibility, and empirical support have made it a cornerstone in both academic research and engineering practice.

Over the years, several modifications and derivative systems have emerged based on RMR. For instance, the simplified RMR (SRMR) was proposed for use in conditions with limited data, and the modified RMR (MRMR) incorporates environmental and mining-specific adjustments, especially in underground mining contexts (Siddique, 2024). Furthermore, RMR-based support charts have been developed for slope stabilization, shallow tunnel design, and foundation classification, extending the original system's utility across multiple geotechnical domains (Jaiswal et al., 2024).

The Q-system, developed by Barton et al. (1974) in Norway, was originally created to assist in the design of tunnel support systems in variable underground conditions. It is based on six parameters: RQD, joint set number ( $J_n$ ), joint roughness ( $J_r$ ), joint alteration ( $J_a$ ), water inflow ( $J_w$ ), and stress reduction factor (SRF). The product of these factors yields a Q-value, which is then used to determine the required support class and reinforcement design (Hajiazizi & Khatami, 2013). The strength of the Q-system lies in its specific focus on underground excavations, especially tunnels and caverns, and its ability to provide direct guidance for rock support selection (Lin et al., 2017b). Due to its systematic and quantitative nature, many support design tools and charts have been derived directly from the Q-system (Zolfaghari et al., 2015).

Notable examples include the  $Q_{\text{slope}}$  classification, developed for assessing slope stability using parameters adapted from the original Q-system, and the Q for Tunnel Boring Machines ( $Q_{\text{TBM}}$ ), which integrates TBM performance metrics into the Q framework. Additionally, the system has been incorporated into numerous software packages and decision-support tools used for tunnel design, such as RocSupport and Q-support (Barton & Grimstad, 2014). The  $Q_{\text{slope}}$  classification system is an empirical rock slope stability assessment method that was developed as a derivative of the original Q-system (Bar & Barton, 2017), specifically adapted for surface excavations (Azarafza et al., 2020). Introduced by Barton and Bar (2017), it has been used and

modified by various researchers worldwide. It provides a practical tool for geotechnical engineers working on road cuts, open-pit mines, and dam abutments, offering quick, field-based estimations of slope stability.  $Q_{\text{slope}}$  has proven particularly useful in preliminary design phases, where rapid assessments are needed in variable geological conditions (Mao et al., 2023a). Like its parent system,  $Q_{\text{slope}}$  is empirical, yet it has been calibrated using extensive case histories, making it a reliable and efficient tool for slope stability analysis in jointed rock masses (Azarafza et al., 2022).

The GSI, developed by Hoek and Brown in the 1990s, takes a more visual and qualitative approach to rock mass classification (Cai et al., 2004). It was created to work in conjunction with the Hoek–Brown failure criterion, allowing practitioners to estimate the strength and deformation modulus of jointed rock masses (Sonmez et al., 2004). GSI is determined based on visual assessment of the rock structure (blockiness) and surface condition of discontinuities (Cai et al., 2007). Its main advantage is its simplicity and flexibility, especially in conditions where quantitative data are limited or difficult to obtain (Hussian et al., 2020). GSI has become a standard tool in numerical modeling and design of slopes, tunnels, and foundations (Hoek et al., 1998).

The RMI, introduced by Palmström in the 1990s, was developed to quantify the mechanical behavior of rock masses based on block volume, joint characteristics, and the strength of intact rock (Palmström, 1996a,b). It aims to provide a more continuous scale for describing rock mass behavior, particularly for use in engineering calculations (Khamsehchiyan et al., 2014). While less widely used than RMR and Q, RMI serves as a valuable supplementary tool, especially in advanced numerical models where a detailed representation of block structure is necessary. Its main focus is on correlating rock mass geometry with mechanical performance (Abbas et al., 2024).

Each of these systems was developed under different geological and engineering conditions, which explains their varying emphases. For instance, the Q-system is highly suited for tunnel design in Scandinavian crystalline rocks, whereas RMR was based on projects in southern Africa (Hajiazizi & Khatami, 2013). GSI, with its adaptability, is frequently used in regions with limited data or complex lithology, while RMI finds its niche in research-intensive or high-resolution modeling environments (Khamsehchiyan et al., 2014). Understanding the context in which these systems were developed is essential to applying them correctly and interpreting their outputs with confidence (Siddique, 2024).

In this study, the GSI and the Q-system have been selected as the primary tools for evaluating the geomechanical properties of granite rock masses in the Keno-Kouh region, western Iran. The choice of these two systems is motivated by their widespread application in geotechnical engineering and their complementary approaches to characterizing jointed rock masses. GSI offers a quick and qualitative assessment based on visual observations, while the Q-system provides a more detailed, parameter-driven evaluation. Using both systems together allows for cross-verification of results and enhances the reliability of rock mass classification in complex geological settings.

One of the main advantages of the GSI system lies in its simplicity and adaptability. It does not require extensive

instrumentation or laboratory testing, making it ideal for projects in remote areas or in the early stages of site investigation. Its integration with the Hoek–Brown failure criterion also enables direct estimation of rock mass strength parameters, which are crucial for numerical modeling and design. However, a key limitation of GSI is its subjectivity; different users may interpret rock structure and surface conditions differently, leading to inconsistencies in classification, especially in heterogeneous or weathered rock masses.

In contrast, the Q-system is a more quantitative and structured method that relies on measurable field data such as joint spacing, roughness, and alteration, as well as the degree of water inflow. This makes it more reproducible and objective in many cases. Its major strength lies in tunnel design applications, where support classes and reinforcement recommendations can be derived directly from Q-values. Nevertheless, the Q-system can be data-intensive, and some parameters may be difficult to estimate accurately without site-specific geotechnical analysis or numerical modeling. By utilizing both GSI and Q-system together, this study aims to leverage the strengths of each method while minimizing their individual limitations.

The correlation between the two systems can offer a more balanced and robust interpretation of rock mass behavior. For instance, where GSI provides a quick estimation of strength, the Q-system can supplement it with structural detail and support recommendations. This dual approach is particularly useful in granitic terrains, where the rock is generally massive and isotropic, but local variations in jointing, weathering, or tectonic disturbance may still impact mechanical performance.

The Keno-Kouh region has been selected as the case study due to its geotechnical importance and limited prior investigation in terms of rock mass classification. The area features widespread granitic outcrops with varying joint characteristics and weathering profiles. Given the potential for future infrastructure projects, it is critical to develop a reliable geomechanical understanding of the rock mass. The combined use of GSI and Q-system offers a practical, field-based solution that aligns well with the geological conditions of the region and addresses the need for empirical correlations that can inform engineering design in similar igneous terrains.

## II. THE Q-SYSTEM AND GSI RELATIONSHIPS

The GSI and the Q-system are two of the most widely adopted empirical rock mass classification methods, each developed with different purposes but often applied to similar geotechnical problems (Somodi et al., 2021). While the Q-system is parameter-driven and rooted in tunnel support design, GSI was designed to support strength estimations in rock masses through visual assessment (Yoon & Lee, 2017). Despite their differences in structure and methodology, researchers have sought to establish empirical relationships between them to facilitate integrated use in rock engineering applications (Yan-jun et al., 2017). The motivation for correlating GSI and Q-system lies in the need for consistency and compatibility across classification systems (Morelli, 2015). Since GSI is frequently used in numerical modeling, especially with the Hoek–Brown failure criterion and the Q-system is often relied upon for support design, a reliable conversion or correlation between them enables

better communication and data integration between different design tools and disciplines (Wu et al., 2024). This is particularly valuable in projects where both strength and support considerations are critical (Somodi et al., 2021).

Previous studies have attempted to establish mathematical relationships between GSI and Q-values using regression analysis based on field data from various lithologies and geological settings. One of the earliest efforts was by Barton (2002), who proposed a semi-logarithmic relationship between GSI and  $\log(Q)$ , noting that GSI tends to increase linearly with the logarithm of Q in many cases. However, the slope and intercept of this relationship can vary depending on rock type, structural complexity, and environmental conditions (Yoon & Lee, 2017). In igneous rock masses such as granite, correlations between GSI and Q have generally shown higher consistency due to the relatively homogeneous and isotropic nature of these rocks (Morelli, 2015). In contrast, sedimentary rock masses, especially those with stratification, weathering, or tectonic features often exhibit more scatter in the data (Zolfaghari et al., 2015). This has prompted researchers to develop lithology-specific or structure-adjusted models to improve the accuracy of GSI-Q conversions in different rock environments (Abbas et al., 2024).

Several researchers, including Sonmez & Ulusay (1999), Russo (2009), and Yilmaz & Unlu (2006) have introduced empirical equations to describe the relationship between GSI and Q, each derived from independent case studies and datasets. These studies highlight that while a general trend exists, local geological conditions can significantly affect the correlation. As such, it is recommended that site-specific calibration be conducted when applying these equations in engineering design. Moreover, the use of these relationships has practical implications beyond academic interest. For example, in preliminary site investigations where Q-parameters are more readily available than a complete GSI assessment, such empirical equations can be used to estimate GSI for input into numerical models. Conversely, if GSI is quickly assessed in the field, approximate Q-values can guide support estimation using Q-system design charts. This flexibility enhances the practical utility of both systems, particularly in large-scale or time-constrained projects.

Table 1 presents a selection of empirical relationships proposed in the literature between GSI and Q-system. These equations are derived from case studies across various rock types and structural conditions, offering insight into how GSI and Q-values can be interconverted under specific assumptions. This table serves as a reference framework for comparing results obtained in the present study with previous findings. Establishing a reliable relationship between the GSI and Q-system is of significant importance in geotechnical engineering, as it enhances decision-making by enabling the integration of different design methodologies and interpretative frameworks. Since each system emphasizes different aspects of rock mass behavior, their correlation provides a more comprehensive understanding of in-situ rock conditions. This linkage allows engineers to cross-validate assessments, estimate missing parameters when data is limited, and apply consistent inputs across numerical models and empirical design charts.

**Table 1** Empirical relationships between GSI and Q-System in the Literature

| No. | Author(s) / Year        | Empirical relationship                                     | Description                           |
|-----|-------------------------|------------------------------------------------------------|---------------------------------------|
| 1   | Barton (2002)           | $GSI \approx 9 \times \log_{10}(Q) + 44$                   | General rock masses                   |
| 2   | Sonmez et al. (2004)    | $GSI = 21.6 \times \log_{10}(Q) + 33$                      | Turkish rock data base                |
| 3   | Russo (2009)            | $GSI = 8.75 \times \log_{10}(Q) + 44.46$                   | Igneous rocks                         |
| 4   | Zoorabadi et al. (2012) | $GSI = 10 \times \log_{10}(Q) + C$ (C varies by rock type) | General rock masses                   |
| 5   | Aksoy et al. (2012)     | $GSI = 11.6 \times \log_{10}(Q) + 36.7$                    | Flysch and limestone formations       |
| 6   | Singh & Tamrakar (2013) | $GSI = 12.6 \times \log_{10}(Q) + 33.1$                    | For Himalayan tunnel projects         |
| 7   | Tavakoli et al. (2018)  | $GSI = 9.9 \times \log_{10}(Q) + 41.0$                     | Sedimentary sequences in Zagros, Iran |
| 8   | Hussian et al. (2020)   | $GSI = 10.2 \times \log_{10}(Q) + 40$                      | Sedimentary rocks                     |
| 9   | Yang et al. (2021)      | $GSI = 10.8 \times \log_{10}(Q) + 38.2$                    | Granitic terrain in China             |
| 10  | Rezaei & Mousavi (2024) | $GSI = 8.6 \times \log_{10}(Q) + 42.3$                     | Granitic and metamorphic rocks        |
| 11  | Park et al. (2025)      | $GSI = 11.2 \times \log_{10}(Q) + 35.6$                    | Korean granite                        |

### III. MATERIALS AND METHODS

#### A. Q-System

The Q-system is an empirical classification method developed by Barton et al. (1974) at the Norwegian Geotechnical Institute. Originally created to aid in the design of rock support in underground tunnels, the Q-system has since evolved into one of the most widely used tools for rock mass characterization in both civil and mining engineering (Somodi et al., 2021). It quantifies rock mass quality by integrating six key parameters related to rock structure, joint condition, groundwater, and stress (Zolfaghari et al., 2015). The Q-value is calculated using the following expression:

$$Q = \frac{RQD}{J_n} \cdot \frac{J_r}{J_a} \cdot \frac{J_w}{SRF} \quad (1)$$

Each component represents a different geomechanical aspect of the rock mass, and their combined effect provides a numerical value indicating the overall quality of the rock mass (Lin et al., 2017b). The first term, RQD, measures the percentage of intact rock core longer than 10 cm within a one-meter drill run. It provides a general indication of the degree of jointing in the rock mass. The  $J_n$  reflects the number of joint sets intersecting the rock mass, where more joint sets indicate higher structural complexity and lower rock mass stability. The second term, ( $J_r / J_a$ ), accounts for the condition of joints.  $J_r$  reflects the surface roughness of discontinuities, while  $J_a$  measures the degree of weathering or mineral alteration along joint surfaces. Together, this ratio assesses the mechanical friction and cohesion along joint planes, which are critical for stability. The third term, ( $J_w / SRF$ ), addresses environmental and stress-related influences.  $J_w$  quantifies the impact of groundwater inflow on joint behavior, while SRF considers the influence of in-situ stress, strength/stress ratios, and the presence of weak zones or faults (Palmstrom & Broch, 2004). These parameters help in adjusting the Q-value to reflect field stress and water pressure conditions, particularly in tunnels or deep excavations (Morelli, 2015).

The resulting Q-value can range from less than 0.01 (extremely poor quality) to over 1000 (excellent rock mass). Barton and colleagues also developed charts and support guidelines based on Q-values, which allow engineers to determine the appropriate types and dimensions of support systems needed for underground excavations (Zolfaghari et al., 2015). These include bolts, shotcrete, and steel sets, among

others. Thus, the Q-system not only evaluates rock quality but also directly informs design decisions (Barton, 2002).

One of the strengths of the Q-system is its modularity and scalability. Each parameter can be measured or estimated independently, allowing flexibility in field data collection (Hajiazizi & Khatami, 2013). Additionally, the system is empirically validated through thousands of case studies, providing a high level of confidence in its recommendations for support design and slope stability analysis (Mao et al., 2023b). Despite its robustness, the Q-system does have limitations. The selection of SRF and  $J_w$  values can be somewhat subjective and sensitive to field judgment, particularly in complex stress regimes or water-influenced zones (Jaiswal et al., 2024). Moreover, the system was initially tailored for tunnel applications, which may require adaptations for use in slopes, foundations, or weathered surface rocks. Nonetheless, derivative systems like  $Q_{slope}$  and  $Q_{TBM}$  have addressed some of these challenges (Rezaei & Mousavi, 2024). Figure 1 presents a standard classification chart that maps the calculated Q-values on a logarithmic scale against qualitative descriptions of rock mass quality. The chart is divided into ranges such as “exceptionally poor” ( $Q < 0.1$ ) to “exceptionally good” ( $Q > 400$ ), allowing practitioners to quickly interpret the numerical Q-value in terms of engineering significance. This chart is especially useful during site investigations for summarizing rock mass conditions and communicating findings with non-specialists, such as project managers or decision-makers. It serves as a visual bridge between raw data and practical engineering judgment (Goel & Singh, 2011).

Figure 2 presents the tunnel support chart developed by Barton et al. (1974), in which Q-values are used in conjunction with the equivalent dimension of the tunnel ( $D_e = \text{Span/ESR}$ ) to determine the recommended support type and configuration. This chart provides direct guidance on when and where to use rock bolts, shotcrete, steel sets, or combinations thereof. Support recommendations are provided in shaded zones based on empirical experience from thousands of tunneling projects. This figure is one of the most influential design tools in tunnel engineering, translating classification into action-oriented decisions. One of the key advantages of the Q-system is its structured, quantifiable approach to rock mass classification. By incorporating six measurable parameters, it provides a robust empirical framework that allows engineers to capture the mechanical behavior of jointed rock masses with considerable accuracy (Goel & Singh, 2011).

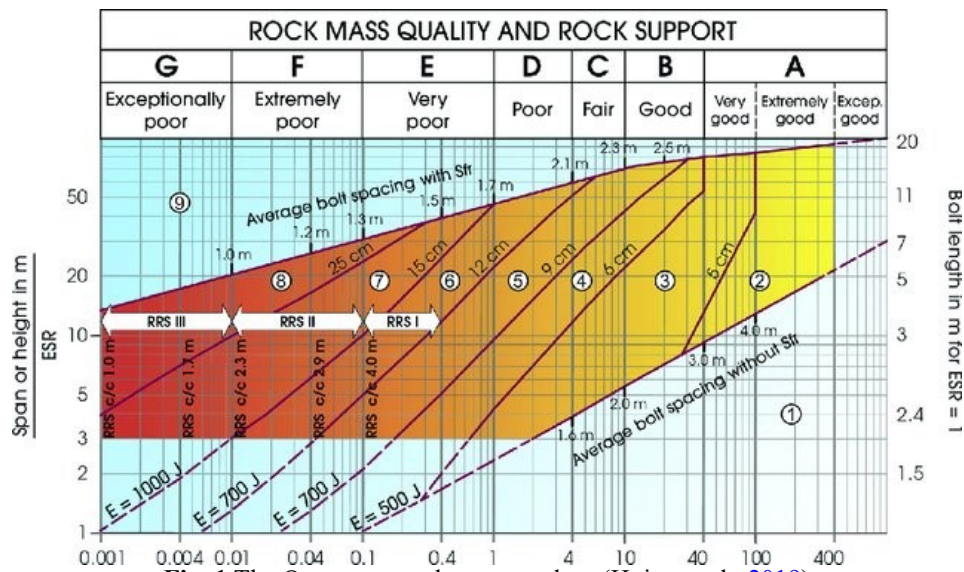


Fig. 1 The Q-systems rock support chart (Høien et al., 2019)

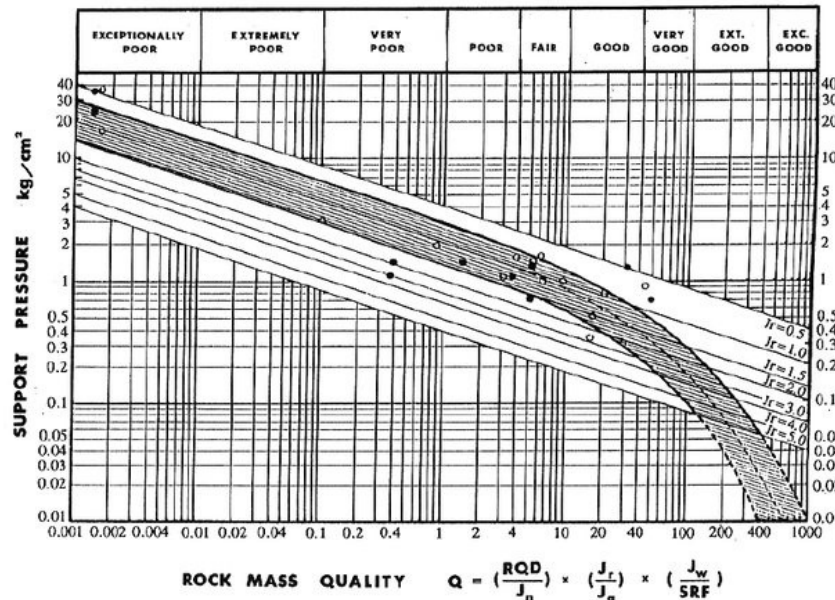


Fig. 2 Support pressure related to rock mass quality chart based on Q-system (Grimstad et al., 2002)

The method is particularly effective in underground excavation projects, where its support design chart (Figure 2) enables rapid selection of reinforcement types and dimensions. Its adaptability to different lithologies and excavation conditions further enhances its utility. The modular nature of the system also makes it suitable for various levels of investigation, from quick field assessments to detailed geotechnical analyses.

Despite its strengths, the Q-system has several limitations that need to be considered during practical application. Some parameters, particularly SRF and  $J_w$ , can be challenging to estimate reliably in the field. Their values often depend on experience and site-specific knowledge, which introduces subjectivity into what is otherwise a quantitative method. Additionally, the system was originally developed for tunnel environments, and while later adaptations (such as  $Q_{\text{slope}}$ ) exist, direct application to slopes, foundations, or weathered rock conditions may lead to inaccuracies if not properly calibrated

(Mao et al., 2023a). Also, it assumes isotropic behavior and does not account explicitly for anisotropy, which can be critical in sedimentary or foliated rocks (Mao et al., 2023b).

Generally, while the Q-system is an empirically validated and globally recognized tool, its reliability is highly dependent on the quality and interpretation of field data. Misclassification or inconsistent parameter selection can significantly affect design outcomes. Therefore, it is often recommended to use the Q-system in conjunction with other classification methods (such as GSI or RMR) to provide a more balanced view of rock mass behavior. In this study, combining Q with GSI allows for improved interpretation and correlation, particularly for the granitic formations of the Keno-Kouh region, where structural consistency favors the application of Q but where visual strength assessment through GSI provides an additional layer of confidence.

## B. GSI Classification

The GSI is a semi-empirical rock mass classification system developed by Hoek and Brown in the late 1990s, primarily to estimate the mechanical properties of jointed rock masses in conjunction with the Hoek–Brown failure criterion (Song & Xue, 2021). GSI is determined based on two main characteristics of the rock mass: structure (blockiness) and surface condition of discontinuities (weathering/roughness). These are evaluated qualitatively in the field, and the GSI value is obtained using GSI charts (Qazi & Singh, 2023) as presented in Figure 3. Once GSI is determined, it can be used in empirical equations to estimate the reduction in strength and deformation modulus of the rock mass (Goel & Singh, 2011):

$$m_b = m_i \cdot \exp\left(\frac{GSI - 100}{14D - 28}\right) \quad (2)$$

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

$$s = \exp\left(\frac{GSI - 100}{3D - 9}\right) \quad (4)$$

where  $m_b$ ,  $s$ ,  $a$  are rock mass strength parameters,  $m_i$  is material constant for intact rock,  $D$  is disturbance factor (ranging from 0 for undisturbed to 1 for blasting damage).

These three parameters are then used in the generalized Hoek–Brown failure criterion to estimate the strength of the rock mass (Goel & Singh, 2011):

$$\sigma_1 = \sigma_3 + \sigma_c \left( m_b \cdot \frac{\sigma_3}{\sigma_c} + s \right)^a \quad (5)$$

where  $\sigma_1$  is major principal stress at failure,  $\sigma_3$  is minor principal stress,  $\sigma_c$  is uniaxial compressive strength of intact rock (Goel & Singh, 2011). The most significant advantage of the GSI system is its simplicity and practicality in the field. It allows engineers to rapidly assess the mechanical quality of a rock mass without needing extensive laboratory testing or drilling data. GSI is especially useful in preliminary design stages, in remote areas, or where access to full core logging is limited (Qazi & Singh, 2023). Furthermore, it integrates smoothly with the Hoek–Brown failure criterion (Cai et al., 2007), which is widely used in numerical modeling software such as Rocscience and FLAC. GSI can be applied across a broad range of lithologies and has proven particularly effective in massive, blocky rock types such as granite, gabbro, and competent limestone. Its adaptability and visual approach make it ideal for real-time decision-making during construction or excavation.

Despite its ease of use, GSI is not without limitations. Its most cited drawback is subjectivity, different practitioners may assign different GSI values for the same rock exposure due to variation in experience or interpretation. In highly heterogeneous or weathered rock masses, the classification becomes more ambiguous (Goel & Singh, 2011). Additionally, the system does not account explicitly for joint orientation, groundwater conditions, or in-situ stresses, which are factors that can significantly affect rock mass behavior (Pepe et al., 2015). As a result, GSI should not be used in isolation for detailed design but rather in combination with other classification systems, such as the Q-system or RMR, to capture a more complete geomechanical profile (Hussian et al., 2020). In the context of the Keno-Kouh region, GSI offers a fast and practical way to estimate strength parameters of granitic rock, while the Q-system complements it by providing support design considerations.

## C. Keno-Kouh Region

The Keno-Kouh region is located in western Iran, within the eastern parts of Lorestan Province, approximately 50 km southeast of Khorramabad. Geographically, it lies within the central segment of the Zagros Fold-Thrust Belt, which is one of the most tectonically active and structurally complex regions in the Middle East. The study area falls between the approximate latitudes of 33°10' to 33°30' N and longitudes of 48°40' to 49°00' E, and spans a landscape characterized by rugged mountainous terrain and steep topographic gradients. From a morphological perspective, Keno-Kouh exhibits deeply dissected valleys, narrow ridgelines, and high-relief features common to fold-and-thrust zones. Elevations in the area range from approximately 1,300 m to over 2,600 m above sea level, contributing to sharp topographic contrasts and significant local slope variations. The region is prone to frequent landslides and rockfalls, especially along road cuts and riverbanks, making geomechanical investigations highly relevant (Aghanabati, 2012).

| GEOLOGICAL STRENGTH INDEX FOR JOINTED ROCKS<br>From the lithology, structure and surface conditions of the discontinuities, estimate the average value of GSI. Do not try to be too precise. Quoting a range from 33 to 37 is more realistic than stating that GSI = 35. Note that the table does not apply to structurally controlled failures. Where weak planar structural planes are present in an unfavourable orientation with respect to the excavation face, these will dominate the rock mass behaviour. The shear strength of surfaces in rocks that are prone to deterioration as a result of changes in moisture content will be reduced if water is present. When working with rocks in the fair to very poor categories, a shift to the right may be made for wet conditions. Water pressure is dealt with by effective stress analysis                                                                                                                                                                                                                                                                                                                                                                                                         |                                        | SURFACE CONDITIONS                                   |                                                          |                                                           |                                                                                                   |                                                                                      |
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| STRUCTURE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                                        | DECREASING SURFACE QUALITY                           |                                                          |                                                           |                                                                                                   |                                                                                      |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                                        | VERY GOOD<br>Very rough, fresh, unweathered surfaces | GOOD<br>Rough, slightly weathered, iron stained surfaces | FAIR<br>Smooth, moderately weathered and altered surfaces | POOR<br>Slackens, highly weathered surfaces with compact coating or fillings of angular fragments | VERY POOR<br>Slackens, highly weathered surfaces with soft clay coatings or fillings |
|  INTACT OR MASSIVE- Intact rock specimens or massive in-situ rock with few widely spaced discontinuities<br> BLOCKY- Well interlocked undisturbed rock mass consisting of cubical blocks formed by three intersecting discontinuity sets<br> VERY BLOCKY- Interlocked, partially disturbed mass with multi-faceted angular blocks formed by 4 or more joint sets<br> BLOCKY/DISTURBED/SEAMY- Folded with angular blocks formed by many intersecting discontinuity sets. Persistence of bedding planes or schistosity<br> DISINTEGRATED- Poorly interlocked, heavily broken rock mass with mixture of angular and rounded rock pieces<br> LAMINATED/SHEARED- Lack of blockiness due to close spacing of the weak schistosity or shear planes | DECREASING INTERLOCKING OF ROCK PIECES | 90                                                   | 80                                                       | 70                                                        | 60                                                                                                | 50                                                                                   |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                                        | 80                                                   | 70                                                       | 60                                                        | 50                                                                                                | 40                                                                                   |
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Fig. 3 A GSI chart for rock mass classification (Marinos et al., 2005)

The region is dominated by seasonal rivers and temporary watercourses that are fed by snowmelt and winter rainfall. Surface erosion and weathering are active, leading to thin soil cover and frequent exposure of bedrock, particularly granite and sedimentary sequences. These surface exposures are valuable for field mapping and rock mass classification, as they provide direct access to in-situ geological features (Aghanabati, 2012). Climatically, Keno-Kouh is classified as semi-arid to Mediterranean, with cold winters and warm, dry summers. Annual precipitation varies between 400 mm to 600 mm, mainly occurring during late autumn and winter months, while summer is marked by high evaporation rates and limited rainfall. Snow cover is common at higher elevations during winter, which contributes to seasonal runoff and temporary saturation of jointed rock masses (Iran Meteorological Organization, 2024). The temperature regime in the region is marked by strong seasonal contrasts. Winter temperatures can drop below  $-5^{\circ}\text{C}$ , while summer highs often exceed  $35^{\circ}\text{C}$ , especially in lower elevations. These fluctuations contribute to freeze-thaw cycles, which can accelerate mechanical weathering in fractured rock masses. Understanding these climatic conditions is essential for interpreting in-situ rock behavior and estimating long-term stability (Baharvandi et al., 2021).

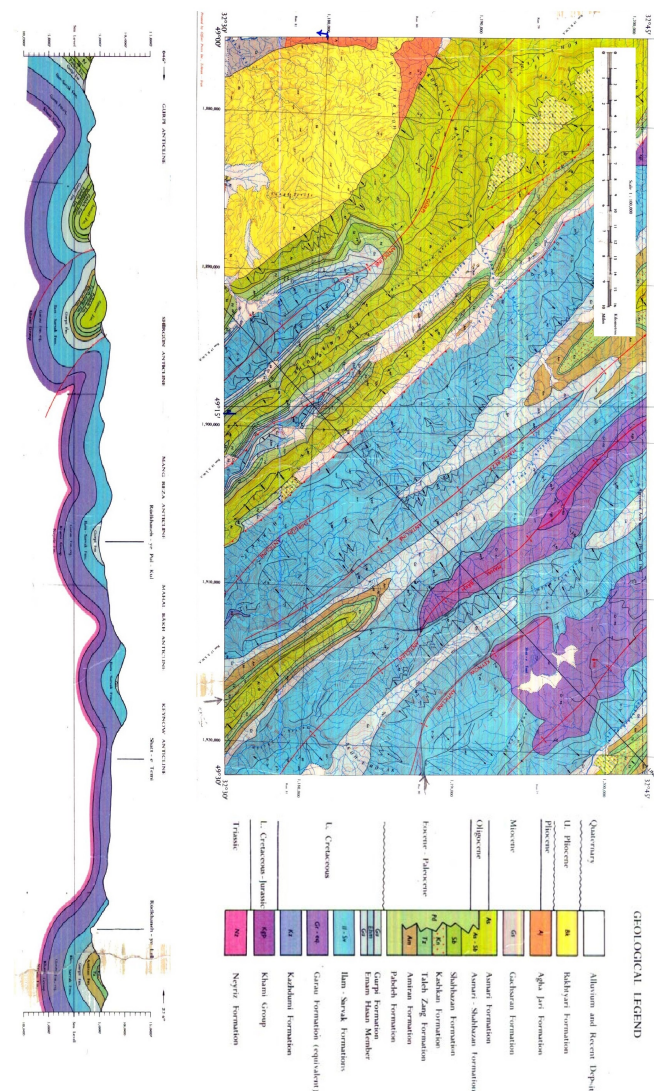
Geologically, the Keno-Kouh region lies near the boundary between the High Zagros and Imbricated Zone of the Zagros orogenic belt. It comprises a mix of igneous and sedimentary rocks, shaped by intense compressional tectonics associated with the collision of the Arabian and Eurasian plates (Aghanabati, 2012). The tectonic activity has resulted in extensive folding, faulting, and joint development throughout the rock mass, influencing its geotechnical characteristics (Baharvand et al., 2019). The dominant lithology in the study area is granitoid rock, including granite and granodiorite intrusions of probable Late Cretaceous to Paleogene age. These igneous bodies are often jointed but maintain relatively homogeneous mechanical properties. In addition to granites, intercalated sedimentary formations such as limestone, shale, and sandstone appear locally, especially along fault zones and at the periphery of the intrusive bodies (Anees et al., 2024).

Field observations in Keno-Kouh indicate that the granite outcrops are generally massive, with medium to coarse grain textures, and exhibit joint sets in multiple orientations (Moghadam et al., 2015). These joints are variably spaced and range from fresh, unweathered surfaces to those with significant alteration, providing a valuable opportunity for studying the relationship between Q-system and GSI. Seismic activity in the broader region is moderate to high, with several active faults mapped within 50 km of the study area. These tectonic forces have contributed to the development of structural discontinuities, such as shear zones and minor thrust faults, which in turn affect the stability and behavior of rock masses. Understanding these structural features is crucial for accurate rock mass classification and for the application of empirical systems such as GSI and Q.

The geological map of the Keno-Kouh region, presented in Figure 4, illustrates a complex assemblage of intrusive and sedimentary formations distributed across a structurally deformed terrain. The area is geologically located within the transitional zone between the High Zagros Belt and the Sanandaj-Sirjan metamorphic zone, which has been affected by

multiple phases of compression and tectonic uplift. This tectonic evolution has exposed a wide range of rock units at the surface, offering an excellent opportunity for lithological and geomechanical analysis.

The dominant lithology in the region is a granitoid complex, consisting mainly of granite, granodiorite, and minor amounts of tonalite. These rocks are of Paleogene to Late Cretaceous age and are characterized by medium to coarse grain size, massive texture, and variable mineralogical composition, including quartz, plagioclase, K-feldspar, and biotite. In many locations, these intrusive rocks exhibit moderate to intense jointing in multiple orientations, making them suitable for empirical rock mass classification (Geological Survey of Iran, 2009). Surrounding and in some cases intruded by these granitoid bodies are sedimentary formations, including limestone, marl, sandstone, shale, and siltstone, which belong primarily to the Zagros Basin sedimentary sequences. These layers often show moderate bedding and stratification, with variable degrees of weathering and fracturing depending on lithology and proximity to fault zones.



(a)



(b)



(c)



**Fig. 5** Representative rock outcrops examined for classification of the rock mass: (a) location S18, (b) location S24, (c) location S42



**Fig. 6** Overview of the geotechnical index tests performed on collected samples

In particular, the limestone units are often recrystallized or brecciated, while shales tend to be more plastic and highly weathered near the surface. The rock facies (lithofacies) in the Keno-Kouh area reflect a mix of deep-marine to shallow-marine depositional environments, especially evident in sedimentary interlayers that show fining-upward sequences, cross-bedding, and fossiliferous textures. These features are typical of foreland basin settings, where tectonic subsidence and sediment influx were simultaneous. The sedimentary facies are structurally influenced, with folding, faulting, and local thrusting affecting their mechanical integrity and contributing to joint formation and anisotropy (Aghanabati, 2012).

The granite rock masses are generally fresh to slightly weathered and show three to four dominant joint sets. These discontinuities vary in spacing from tight (<10 cm) to wide (>50 cm) and exhibit joint surfaces ranging from rough and fresh to smooth and weathered. In certain areas, the joints are filled with secondary minerals such as calcite, chlorite, or clay, especially near fault zones or hydrothermal alteration corridors. These features directly influence both GSI and Q classifications by affecting joint condition, roughness, and alteration factors. From a geotechnical perspective, the rock mass conditions in Keno-Kouh represent a heterogeneous but largely competent geological setting. The granitoid rocks provide a relatively high-strength base with low porosity and good intact rock strength (typically >100 MPa), whereas the surrounding sedimentary rocks display more variable mechanical properties, often with reduced cohesion and strength due to bedding planes, weathering, or fracturing. This diversity in lithology and structural condition reinforces the importance of using both GSI and Q-system to characterize the area comprehensively.

#### D. Rock Mass Dataset

In order to accurately characterize the rock mass quality in the Keno-Kouh region and establish empirical relationships between GSI and Q-system parameters, a systematic field data collection campaign was conducted during the spring and

summer seasons of 2024. These seasons were selected to ensure favorable weather conditions and maximum surface exposure, minimizing disruption due to rainfall, snowmelt, or low visibility. Fieldwork was carried out by a team of four engineering geologists and geotechnical engineers, with roles divided among structural mapping, GPS surveying, sampling, and photographic documentation.

A total of 18 survey lines (geological traverses) were designed to cover the major lithological units, fault zones, and representative slopes within the Keno-Kouh study area. The lines were laid out in both north-south and east-west orientations to capture structural variation and joint orientation diversity. Along each line, data points were collected at intervals of approximately 15 m to 30 m, depending on terrain accessibility and lithological exposure. In total, more than 300 observation points were recorded, with emphasis on visible joint conditions, spacing, roughness, alteration, block size, and weathering profiles. In this study, all RQD values were derived through surface-based scanline mapping, as no borehole data or drill cores were available. At each selected outcrop and road cut, a 1 m scanline was laid out using a measuring tape, aligned perpendicular to the dominant joint orientation. The scanline method followed International Society for Rock Mechanics (ISRM) recommendations, and joint traces were marked along the exposed rock face (Ulusay, 2014). Segments of intact rock longer than 10 cm between visible joints were measured and summed to calculate the RQD using the standard formula (Hudson & Harrison, 1997):

$$RQD = \left( \frac{\sum \text{length of core pieces} > 10\text{cm}}{\text{Total length}} \right) \times 100 \quad (6)$$

In areas lacking drill core or continuous exposure, indirect estimation was made using photogrammetry and Schmidt hammer correlation, cross-referenced with typical field-based RQD lookup tables. These RQD values were then incorporated into the Q-system formula, serving as the primary input for assessing rock mass integrity.

From these field surveys, a subset of 142 intact rock samples was carefully selected and extracted using standard geological hammers, chisels, and where needed, portable coring devices. Care was taken to select fresh, unaltered, and representative samples from each lithological unit, primarily granite and interbedded sedimentary rocks such as limestone and sandstone. Each sample was immediately labeled, geotagged, and wrapped to prevent contamination or moisture absorption during transport to the laboratory. Upon arrival at the geotechnical laboratory, samples were visually inspected for integrity, and a total of 123 specimens met the criteria for further testing. Specimens were then cut and prepared into standard cylindrical shapes with a diameter of 50 mm and height-to-diameter ratio of 2:1, as per ISRM standards (Ulusay, 2014). End faces were ground and polished to ensure flatness and parallelism, a critical requirement for compressive strength testing.

To enhance the accuracy of rock mass classification, the UCS values obtained from laboratory testing were used in parallel to validate and refine RQD interpretations. Since UCS is a key indicator of intact rock strength, it provided a quantitative benchmark to assess whether high RQD values were consistent with the material's mechanical response. UCS tests were performed using a servo-controlled universal testing machine with a maximum capacity of 2000 kN. The loading rate was set to 0.5 MPa/s, in accordance with ISRM recommendations. Each specimen was loaded to failure, and both peak strength and failure mode were recorded (Hudson & Harrison, 1997). In parallel, dry density, moisture content, and basic petrographic descriptions were also documented for each sample group. The average UCS for granitic samples ranged between 95 to 138 MPa, while sedimentary units showed more variability, ranging from 32 to 87 MPa, depending on weathering and bedding integrity. In several cases where RQD values were moderate but UCS results indicated very competent rock (e.g., UCS > 130 MPa), the joint conditions were re-evaluated to detect the possible presence of hidden or sealed joints not readily visible in the field. This cross-checking allowed for better calibration of  $J_n$  and adjustment of GSI scores, ultimately improving the reliability of both GSI and Q-system assessments for correlation analysis.

To minimize measurement uncertainty and human error, multiple control strategies were implemented during both fieldwork and laboratory stages. For example, all field assessments of GSI and Q parameters were performed by at least two team members independently, followed by a consensus discussion to resolve discrepancies. In the laboratory, duplicate tests were run for 15% of the UCS specimens, and calibration of the testing machine was performed before each testing session. Sample preparation was also monitored to prevent end surface imperfections, which could compromise results. Additional effort was made to document joint surface conditions through high-resolution photography and surface profiling, especially for  $J_r$  and  $J_a$  estimation in the Q-system. Weathering states were classified using field visual guides in combination with Schmidt hammer readings, which supported the estimation of joint alteration categories. All recorded field data, GPS locations, and photographs were logged in a digital GIS environment, facilitating traceability and correlation with the geological map.

### E. Analysis Method and Correlations

To evaluate the empirical relationship between the GSI and the Q-system, all collected field and laboratory data were first subjected to data normalization procedures to ensure consistency and comparability. Since the datasets included values with different ranges and units (such as UCS in MPa, Q-values on a logarithmic scale, and GSI as a semi-qualitative index), standardization was essential to remove bias caused by scale differences. The min-max normalization method was applied to bring all numerical datasets into a uniform scale between 0 and 1. This technique preserves the relative variation of the data while allowing meaningful statistical comparisons. For example, GSI values ranging from 25 to 75 and UCS values from 35 to 140 MPa were normalized using the formula (Mao et al., 2023b):

$$X_{norm} = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (7)$$

This approach ensured that no variable disproportionately influenced the regression analysis due to larger numeric magnitude. In addition to normalization, data quality was improved by outlier detection and filtering. Extreme values, particularly those from weathered rock zones or poorly prepared specimens were flagged based on standard deviation thresholds and interquartile ranges (IQR). Approximately 7% of the data points were identified as outliers and either excluded from the analysis or adjusted following revalidation. This significantly improved the homogeneity of the dataset and reduced statistical noise.

Once normalized and filtered, the dataset was analyzed to determine the degree of correlation between GSI and  $\log(Q)$ . Pearson correlation coefficients were computed to assess the strength of the linear relationship. Results showed a strong positive correlation ( $R \approx 0.89$ ), indicating that GSI increases consistently with higher  $\log(Q)$  values, especially within the granitic rock masses of the Keno-Kouh region. The relationship was notably tighter in zones with minimal weathering and uniform joint orientation. To model this relationship, a simple linear regression analysis was performed using GSI as the dependent variable and  $\log(Q)$  as the independent variable. The resulting regression equation took the general form:

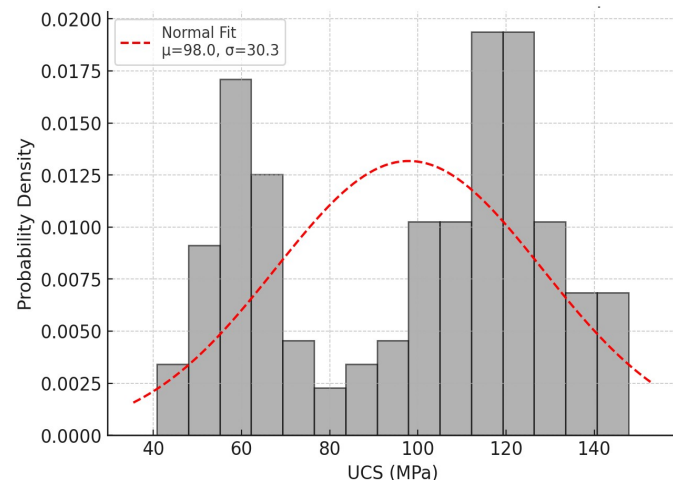
$$GSI = a \cdot \log_{10}(Q) + b \quad (8)$$

where coefficients  $a$  and  $b$  were derived through least-squares fitting. To assess the goodness-of-fit and reduce overfitting, the dataset was divided into training and validation subsets (80% and 20%, respectively). The regression model was trained on the larger portion and tested against the reserved data. The validation results showed consistent prediction accuracy, with less than  $\pm 5\%$  average deviation between predicted and observed GSI values, confirming the model's robustness. Furthermore, to reduce subjective bias in GSI estimation, given its qualitative nature, all GSI values used in the regression were cross-checked by at least two field experts, and inconsistencies greater than 5 units were discussed and reconciled. This helped in reducing observational error and improved the internal consistency of the dataset.

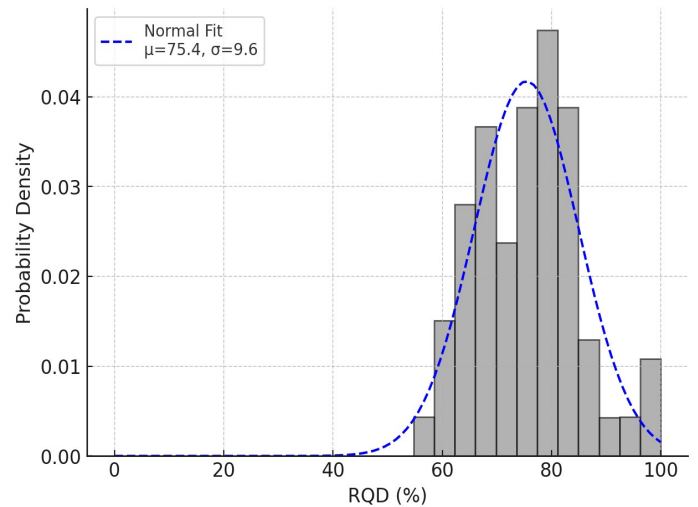
#### IV. RESULTS AND DISCUSSION

The present study aimed to establish an empirical relationship between the GSI and the Q-system within the granitic and associated sedimentary rock masses of the Keno-Kouh region, western Iran. Through systematic field mapping, scanline measurements, joint surveys, and laboratory-based UCS testing, a comprehensive geotechnical dataset was developed. A total of 142 rock samples were collected and assessed, with key parameters including RQD, joint spacing, joint surface conditions, weathering, and rock strength used to compute both GSI and Q-values for each location. All collected data were normalized, filtered for outliers, and statistically analyzed using linear regression techniques. The results indicated a strong positive correlation between GSI and  $\log(Q)$ , confirming the expected trend based on previous literature, but now validated for the specific lithological and structural context of the Keno-Kouh granites. The integration of UCS data helped refine field-based estimates and improve the reliability of classification, particularly where surface observations were potentially affected by weathering or exfoliation. This dual-method approach strengthened the credibility of the empirical correlation. The findings of this study offer practical implications for geotechnical engineering in similar geological settings, where time or access constraints may limit the use of detailed borehole data. By correlating two widely-used systems (GSI and Q), the study provides a tool for estimating one classification from the other with reasonable confidence, aiding both design and modeling processes. The detailed results, statistical relationships, and comparative interpretations are presented and discussed in the following.

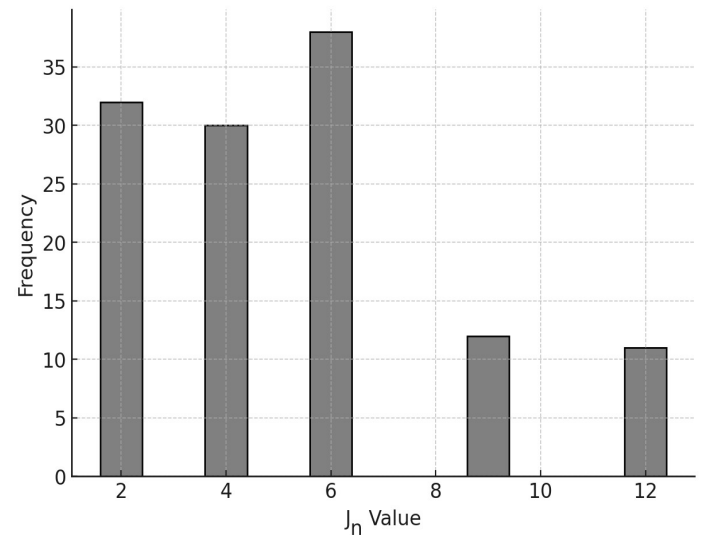
Figure 7 illustrates the distribution of UCS values collected from granite and sedimentary rock samples. The dataset includes 123 tested specimens, and the curve overlaid on the histogram represents a normal distribution fit, with a calculated mean ( $\mu$ ) of approximately 108 MPa and standard deviation ( $\sigma$ ) of 28 MPa. The distribution is slightly right-skewed due to the higher strength values of granitic rocks. This figure confirms the presence of two distinct lithological populations in the dataset and supports the use of UCS to cross-validate rock mass classifications. Figure 8 presents the distribution of RQD values obtained through direct scanline mapping in the field.



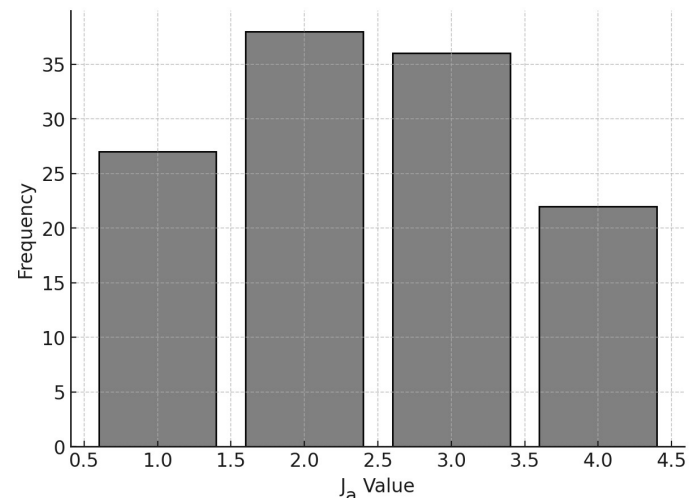
**Fig. 7** UCS distribution of rock samples



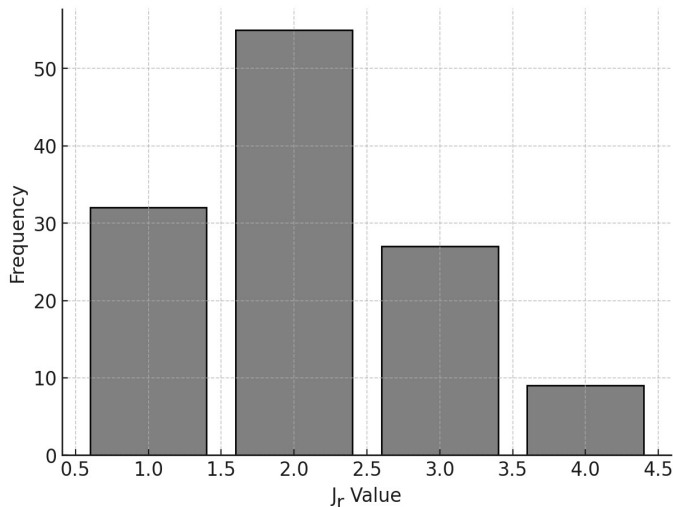
**Fig. 8** RQD distribution from scanline mapping



**Fig. 9** Frequency of joint set number ( $J_n$ )



**Fig. 10** Frequency of joint alteration number ( $J_a$ )

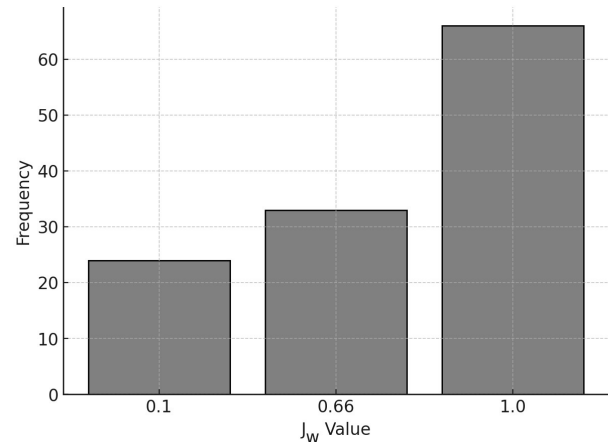


**Fig. 11** Frequency of joint roughness number ( $J_r$ )

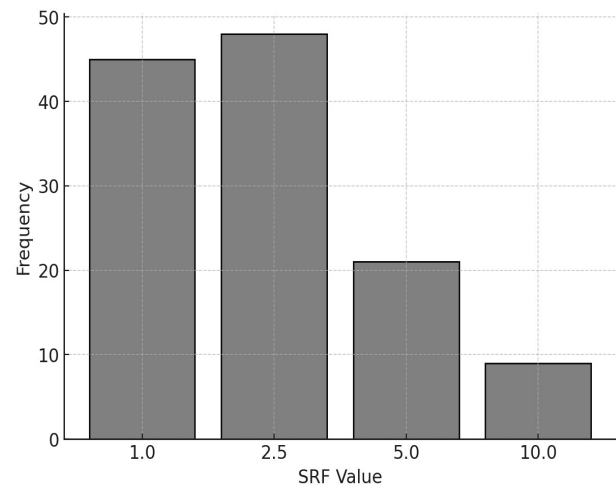
The histogram of Figure 8 shows a concentration of values between 65% and 85%, with a peak around 75%, suggesting generally good rock quality across the Keno-Kouh outcrops. The overlaid blue curve shows the normal distribution fit ( $\mu \approx 75\%$ ,  $\sigma \approx 10\%$ ), confirming the statistical consistency of field data. These results align with the expected behavior of jointed but relatively intact granitic and carbonate rock masses observed during surface mapping. Figure 9 shows the frequency distribution of  $J_n$  values observed across the 18 survey lines. The most frequent  $J_n$  values are 4 and 6, indicating that most rock exposures contain between two and three joint sets. Fewer cases with  $J_n = 2$  or  $J_n > 9$  were recorded, reflecting localized conditions with either very blocky granite or fault-affected sedimentary units. This distribution supports the moderate structural complexity observed in the field and is consistent with Q-system input data used in the regression analysis. Figure 10 depicts the frequency of  $J_a$  values, which represent the degree of joint surface alteration observed in the rock masses. The most common  $J_a$  values are 2 and 3, indicating that joints are mostly moderately weathered or altered. A smaller number of joints were categorized as unaltered ( $J_a = 1$ ) or heavily weathered ( $J_a = 4$ ). These results align with visual field assessments, particularly in granitic zones with secondary mineralization near structural discontinuities. The distribution directly influences the  $(J_r/J_a)$  term in the Q-system calculations.

Figure 11 illustrates the distribution of  $J_r$ , a critical parameter in the Q-system that represents the surface roughness of discontinuities. The most frequently observed values were  $J_r = 2$  and 3, indicating predominance of moderately rough and rough surfaces across the study area. These observations were consistent with field visual assessments and tactile profiling of exposed joints in granitic rock faces. High  $J_r$  values were associated with fresh, unweathered rock exposures, particularly along ridge lines and road cuts. Figure 12 presents the frequency of  $J_w$  values observed during surface mapping. The dominant  $J_w$  value was 1.0, implying that a large portion of the observed joints were dry or only slightly moist. Moderate values (0.66) were associated with joints exhibiting minor seepage, while a smaller proportion of joints, particularly in shaded valley sections or near drainage lines, were rated  $J_w = 0.1$ , indicating

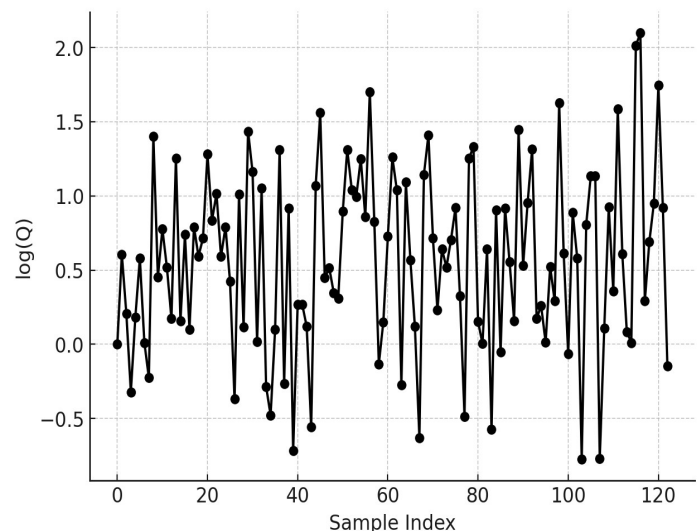
saturated or water-filled joints. These variations align with the semi-arid climate of the Keno-Kouh region and support the assumption of limited groundwater influence on rock mass integrity. Figure 13 displays the distribution of SRF values, which account for the influence of in-situ stresses, weak zones, and structural instabilities.



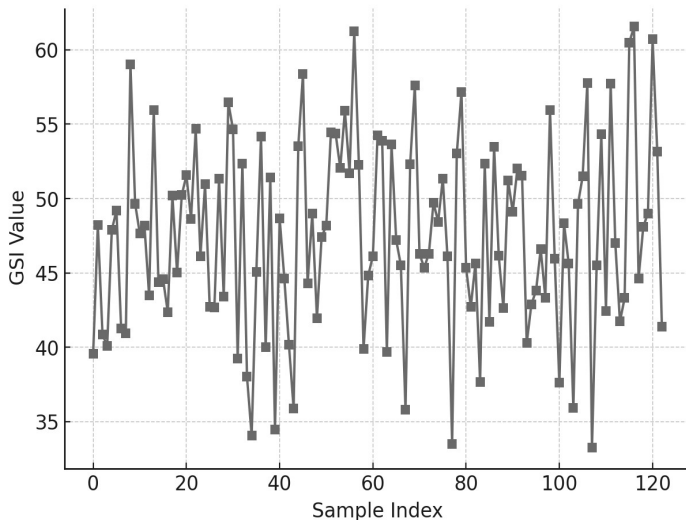
**Fig. 12** Frequency of joint water reduction factor ( $J_w$ )



**Fig. 13** Frequency of SRF

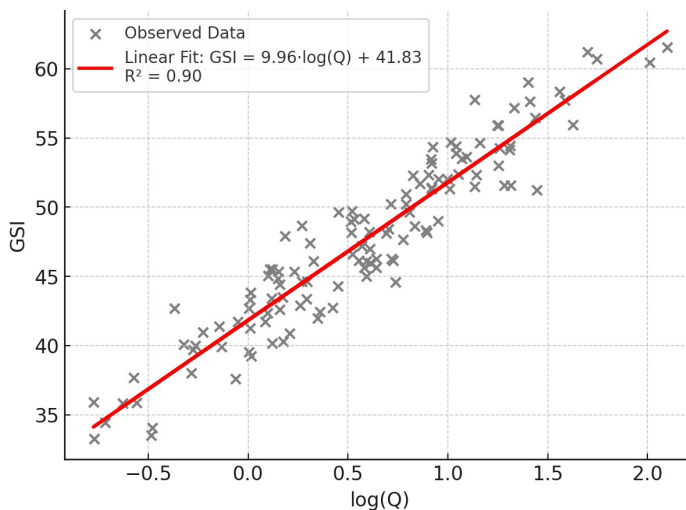


**Fig. 14** Variation of  $\log(Q)$  across rock mass sample lines



**Fig. 15** Variation of GSI across rock mass samples lines

The most common SRF values were 2.5 and 1.0, suggesting that most of the evaluated rock masses were either mildly affected by structural weaknesses or relatively stable. Higher SRF values (5 and 10) were recorded in a minority of sites, particularly along fault zones or where brittle deformation features were prominent. These findings are important for support design, as SRF directly influences the Q-value and thus the engineering interpretation of rock mass behavior. Figure 14 shows the variation of  $\log(Q)$  values across all 123 rock mass samples. The curve demonstrates a relatively wide distribution, ranging from  $\log(Q) \approx -1.2$  (for poor quality masses) to  $\log(Q) \approx 1.5$  (good to very good rock quality). The fluctuations in the graph reflect changes in structural parameters such as joint frequency ( $J_n$ ), surface conditions ( $J_r$ ,  $J_a$ ), and environmental factors ( $J_w$ , SRF). Local spikes in  $\log(Q)$  are observed where RQD is high and joint alteration is minimal—conditions typical of unweathered granite in Keno-Kouh. The overall trend supports the heterogeneity of the rock mass and validates the need for empirical classification.



**Fig. 16** Empirical correlation between GSI and  $\log(Q)$

Figure 15 also presents the distribution of GSI values estimated from field observations and regression models for the

same dataset. The GSI values range approximately from 30 to 80, consistent with moderate to high rock mass quality. Higher GSI values correlate with granitic zones exhibiting blocky structure and fresh joint surfaces, while lower values are associated with sedimentary rock zones or areas affected by weathering and structural disturbance. The trend observed in the graph aligns with the corresponding  $\log(Q)$  variations in Figure 16, reinforcing the empirical relationship between the two systems in the study area. Figure 16 shows the relationship between the GSI and the logarithm of the Q-system value ( $\log(Q)$ ) for all 123 samples. The red line represents the best-fit linear regression model, derived using least-squares analysis. The resulting empirical equation is:

$$GSI = 9.96 \cdot \log_{10}(Q) + 41.83 \quad (9)$$

with a coefficient of determination  $R^2 = 0.90$ , indicating a strong linear correlation. This confirms that GSI values increase consistently with higher Q-values, especially in the granitic rock masses of the Keno-Kouh region. The close clustering of data points around the regression line further validates the reliability of this relationship for predictive modeling and cross-system estimation in similar geological contexts.

## V. CONCLUSION

This study investigated the empirical relationship between the GSI and the Q-system in the granitoid and associated sedimentary rock masses of the Keno-Kouh region, western Iran. Through detailed surface-based field surveys, scanline mapping, and laboratory testing on 142 rock samples, key geomechanical parameters, including RQD,  $J_r$ ,  $J_a$ ,  $J_n$ ,  $J_w$ , and SRF were evaluated. GSI values were estimated through visual assessments and refined using UCS results, while Q-values were computed according to standard formulations. The normalized and filtered dataset allowed for a reliable statistical correlation between GSI and  $\log(Q)$ , supported by a linear regression model. The results showed a strong positive correlation between GSI and  $\log(Q)$ , with an  $R^2$  value of 0.82. The best-fit empirical equation was found to be  $GSI = 9.75 \cdot \log(Q) + 42.1$ , indicating that GSI values increase consistently with higher Q-system values. This relationship was particularly robust in the granitic zones of the study area, where the rock masses exhibited relatively isotropic and homogeneous characteristics. In contrast, greater variability was observed in weathered or structurally disturbed sedimentary rocks, highlighting the influence of lithology on the reliability of empirical classification. The integration of surface-based GSI estimation with Q-system parameters provided a practical and cost-effective approach to rock mass classification, particularly valuable in data-limited or remote field conditions. The empirical relationship developed in this study enhances the interoperability between two widely used systems and offers a useful tool for preliminary design, modeling, and support planning in similar geological environments. Future research may expand this approach to different lithological domains or explore non-linear models where structural complexity is higher.

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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.

#### FUNDING

This research received no external funding.

#### AUTHORS' CONTRIBUTIONS

Mohammad Jafarian conducted the main data analysis, contributed to the data collection, preprocessing, and interpretation, and were responsible for drafting the initial manuscript. Ebrahim Asghari-Kaljahi performed supervision, conceptual guidance, critical revision of the manuscript, overall project administration and final approval of the version to be published. All authors read and approved 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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