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Empirical RQD-based Rock Mass Classification for Isfahan Sandstone Formations

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Abstract: Rock Quality Designation (RQD) is a widely recognized empirical method for quantifying and describing rock mass quality and durability, extensively utilized by geotechnical experts. RQD plays a critical role in designing and constructing support systems, as well as in assessing the stability of rock masses for surface and subsurface construction projects. Accurate RQD values are essential for ensuring reliable and effective designs in civil engineering applications. This study focuses on developing an empirical RQD modification tailored for sandstone formations in Isfahan Province, Iran. A comprehensive field survey was conducted, involving the collection of 75 rock samples from 25 stations, alongside detailed field measurements of rock masses to estimate RQD values. The calculated RQD values were further employed to evaluate geomechanical classification indices specific to the sandstone formations in the region. The findings of this study provide valuable insights into the geotechnical properties of Isfahan's sandstone formations, offering improved accuracy in RQD estimation and enhancing the reliability of designs for civil engineering projects in similar geological settings. These results contribute to optimizing support system designs and ensuring stability in both surface and subsurface constructions.

Keywords: Rock mass classification, Empirical RQD, Isfahan sandstone, Geotechnical assessment, Rock mechanics.

I. INTRODUCTION

Engineering rock mass classification systems are essential tools in geotechnical and civil engineering, offering structured approaches to evaluate the quality and stability of rock masses (Abbas & Konietzky, 2017). These systems categorize rock masses based on their geological and mechanical properties, enabling engineers to make informed decisions during the design and construction of tunnels, foundations, slopes, and other infrastructure (Pantelidis, 2009). Their systematic approach ensures consistency and reliability, providing a foundation for safe and cost-effective engineering solutions (Yang et al., 2022).

The importance of rock mass classification systems lies in their ability to bridge the gap between geological observations and engineering applications. Natural rock masses exhibit considerable variability in structure, strength, and behavior under stress (Azarafza et al., 2017). Classification systems simplify this complexity by providing a set of standardized parameters, such as joint spacing, rock strength, and groundwater conditions (Afrouz, 1992). These parameters are used to assign a numerical or descriptive rating to the rock mass, offering a clear representation of its engineering characteristics (Şen & Sadagah, 2003).

Engineering classifications of geological materials have been extensively studied and widely applied in engineering projects worldwide (Moon et al., 2001). These classifications are typically based on surface or subsurface ground conditions and are designed to assess the stability and behavior of rock masses in various environments (Singh & Goel, 2011). Among the notable systems are:

- Rock Mass Rating (RMR) by Bieniawski (1989), which evaluates rock mass quality based on key geomechanical properties.
- Mining Rock Mass Rating (MRMR) by Laubscher (1990), a modification tailored to mining applications.
- Rock Tunneling Quality Index (Q-system) by Barton et al. (1974), frequently used for tunnel design and excavation analysis.
- TBM Rock Tunneling Quality Index (Q_{TBM}) by Barton (1999), an extension of the Q-system for tunnel boring machines.
- Rock Structure Rating (RSR) by Skinner (1988), focusing on structural and excavation-specific parameters.
- Modified Basic Rock Mass Rating (M-RMR) by Cummings et al. (1982) and Kendorski et al. (1983).
- Alternative Rock Mass Classification System by Pantelidis (2010).
- Slope Mass Rating (SMR) by Romana et al. (2003) focuses on classifying rock slopes.

These systems provide essential frameworks for assessing ground stability and designing support systems, contributing significantly to the success of complex engineering projects.

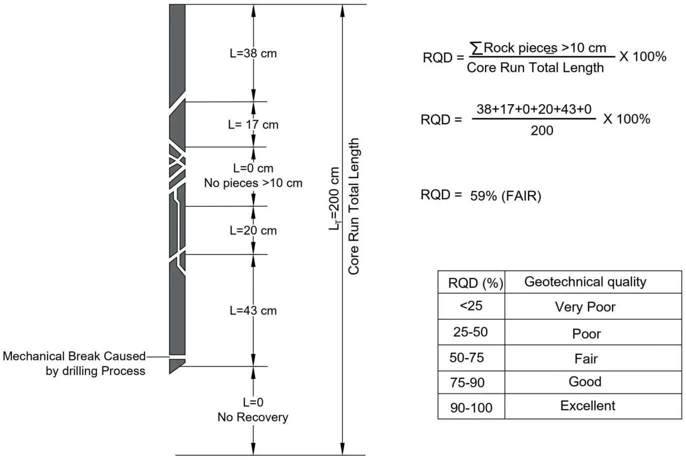
One of the most widely used systems is the RMR system, developed by Bieniawski (1989). This system considers six critical parameters, including uniaxial compressive strength (UCS), rock quality designation (RQD), joint spacing, joint condition, groundwater condition, and orientation of discontinuities (Azarafza et al., 2019). By integrating these factors, the RMR system generates a single score that classifies the rock mass into categories ranging from very poor to very good (Ferrari et al., 2014). This score helps engineers design support systems, evaluate stability, and estimate excavation difficulties (Aksoy, 2008). Another notable classification system is the Q-system, introduced by Barton et al. (1974). The Q-system emphasizes the influence of joint characteristics and their interaction with stress conditions. It uses six parameters, including RQD, joint set number, joint roughness, and water reduction factor, to calculate a Q-value that determines the rock mass's quality. This system is particularly useful in tunnel design, as it provides guidelines for selecting support measures such as rock bolts, shotcrete, and steel ribs (Choi et al., 2002). The Geological Strength Index (GSI) is another important system, designed to estimate the strength and deformability of rock masses based on their geological structure and surface conditions (Marinos et al., 2005). Unlike RMR and Q-systems, GSI relies on visual observations and qualitative descriptions, making it a practical tool in the field. GSI is often integrated into numerical models to predict the behavior of rock masses under various loading conditions, making it indispensable for complex projects (Sonmez & Ulusay, 1999). The application of these classification systems is critical in ensuring the safety and sustainability of engineering projects. They provide a framework for identifying potential hazards, such as rockfalls, slope failures, and excessive deformation, before construction begins. By understanding the behavior of rock masses, engineers can design appropriate support systems, optimize excavation methods, and minimize construction costs. This proactive approach reduces risks and enhances project efficiency.

The present study aimed to integrate field surveys and geomechanical index properties to estimate the RQD, recognized as a key parameter in various rock mass classification systems, including RMR, Q-system, SMR, and GSI. By accurately calculating RQD and related parameters, the reliability and applicability of these classification systems can be significantly enhanced for designing effective support systems and analyzing the stability conditions of rock masses. In this research, particular emphasis was placed on bridging the gap between theoretical estimation methods and practical field data for Isfahan sandstones, ensuring a more robust evaluation of rock mass behavior under different geological and engineering scenarios. This approach not only improves the precision of stability assessments but also aids in customizing support systems for diverse geotechnical conditions. So, as a novel contribution, the study introduces an integrated framework that combines advanced computational techniques with traditional geomechanical surveys, enabling a more efficient estimation of RQD and its implications on rock mass classifications.

II. ROCK QUALITY DESIGNATION

RQD is a widely used parameter in geotechnical and geological engineering that provides a quantitative measure of the quality of a rock mass. Originally developed by Deere in 1964 were modified in 1988 and 1989 (Deere & Deere, 1988; Deere, 1989), RQD serves as a key index for classifying rock masses and assessing their suitability for engineering applications such as tunneling, slope stabilization, and foundation design (Zhang, 2016). The RQD value is expressed as a percentage and is based on the percentage of core samples longer than 10 cm recovered from a rock mass during a drilling operation (Palmstrom, 2005). The concept of RQD measurement is provided in Figure 1. RQD plays a critical role in determining the mechanical behavior of rock masses, especially their stability and load-bearing capacity (Singh & Goel, 2011). It provides engineers with a reliable indicator of rock mass integrity by quantifying the degree of fracturing and discontinuities within the rock. Higher RQD values indicate a more intact rock mass, while lower values suggest poor-quality, heavily fractured rock (Deere & Deere, 1988).

The measurement of RQD is typically conducted during core drilling operations. A drill core is extracted, and the lengths of core pieces exceeding 10 cm are measured (Singh & Goel, 2011). The sum of these lengths is divided by the total length of the core run and then multiplied by 100 to obtain the RQD value in percentage terms (Zhang, 2016). The formula is as presented in Figure 1. Core recovery, which represents the percentage of core retrieved from a drilling operation, is closely related to RQD (Deere & Deere, 1988). However, while core recovery measures the total amount of rock recovered, RQD focuses specifically on the quality of the recovered rock based on its length (Lucian & Wangwe, 2013). A core recovery of 100% does not necessarily mean an RQD of 100%, as the latter depends on the extent of fracturing within the recovered core.



$$RQD = \frac{\sum \text{Rock pieces} > 10\ \text{cm}}{\text{Core Run Total Length}} \times 100\%$$

$$RQD = \frac{38+17+0+20+43+0}{200} \times 100\%$$

RQD = 59% (FAIR)

RQD (%)	Geotechnical quality
<25	Very Poor
25-50	Poor
50-75	Fair
75-90	Good
90-100	Excellent

Fig. 1 RQD description and calculation process (Singh & Goel, 2011)

In accordance to the Deere & Deere (1988), RQD values are used to classify rock quality into categories (Singh & Goel, 2011):

- 0 – 25%: Very poor rock,
- 25 – 50%: Poor rock,
- 50 – 75%: Fair rock,
- 75 – 90%: Good rock,
- 90 – 100%: Excellent rock.

These categories provide a basis for preliminary assessments of rock mass suitability for engineering purposes. Despite its widespread use, RQD has limitations. It is influenced by core diameter, drilling technique, and the orientation of fractures relative to the core axis (Zhang, 2016). Additionally, RQD does not account for properties such as joint orientation, roughness, and infill material, which are critical for comprehensive rock mass characterization (Singh & Goel, 2011). Advancements in geotechnical engineering have introduced alternative methods for determining RQD, including digital image analysis and borehole televiewers (Saricam & Ozturk, 2018). These methods provide non-destructive and high-resolution data on rock mass discontinuities, offering an alternative to traditional core-based measurements (Haftani et al., 2016). Advanced statistical and numerical methods are often employed to analyze RQD data (Yu, 2010). Techniques such as regression analysis and probabilistic modeling are used to predict RQD based on geological and geomechanical properties. This enables engineers to estimate RQD in situations where direct measurement is not feasible (Zheng et al., 2020). RQD is instrumental in designing engineering support systems. In tunneling, it helps determine the type and amount of reinforcement required (Singh & Goel, 2011). In slope stability projects, it guides decisions on excavation methods and retaining structures (Zhang, 2016). RQD also influences decisions in foundation design, particularly in assessing the bearing capacity and settlement characteristics of rock masses (Lucian & Wangwe, 2013). Recent research has focused on enhancing the accuracy and efficiency of RQD estimation (Seker & Ocak, 2019). Machine learning algorithms, combined with field data, offer promising avenues for automated RQD prediction (Alzubaidi et al., 2022). Similarly, integrating RQD with remote sensing technologies and GIS tools allows for large-scale rock mass quality mapping, providing valuable insights for regional geotechnical assessments (Chandrasekaran & Kumar, 2019).

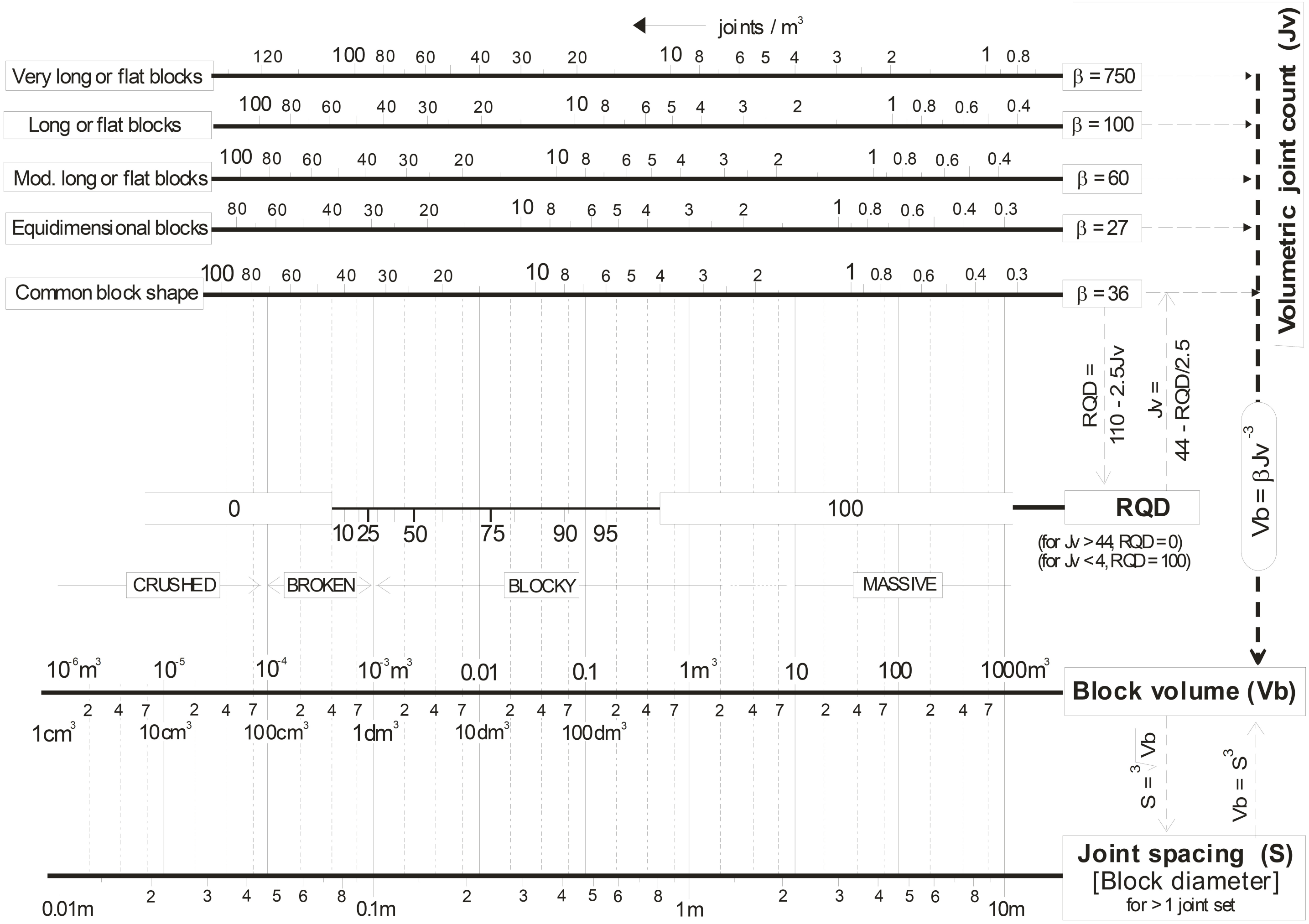


Fig. 2 Correlations between J_v, V_b and RQD (Palmstrom, 2005)

The study proposes estimating RQD through a non-destructive and practical approach using field surveys combined with empirical correlations. These correlations, developed by Palmstrom (2005), link the joint network characteristics within the rock mass to volumetric joint count (J_v), block volume (V_b), and RQD. Figure 2 illustrates the key relationships between J_v, block size, and RQD, providing a comprehensive framework for analysis. Palmstrom (2005) developed an empirical relationship to estimate the RQD by linking it to the J_v and V_b. This approach is particularly useful in situations where direct measurement of RQD is challenging, allowing for an indirect yet reliable estimation. The methodology relies on characterizing the geometric properties of joint networks in the rock mass, including the number and spacing of joints, which directly influence the quality of the rock mass and its structural integrity.

The J_v is a measure of the total number of joints per unit volume of rock mass. It is calculated by summing the number of joints intersecting three orthogonal planes within a unit volume (Zhang, 2016). Palmstrom's approach emphasizes J_v as a key parameter because it directly reflects the density and distribution of discontinuities in the rock mass (Sen & Kazi, 1984). Rocks with high J_v values typically exhibit lower quality due to a greater number of fractures, which reduce the intact nature of the material (Zhang and Einstein, 2004). V_b refers to the average size of intact rock fragments within the rock mass, which is inversely related to J_v. Palmstrom demonstrated that smaller block sizes correspond to higher J_v values and, consequently, lower RQD values (Palmstrom, 1995). This relationship underscores the importance of understanding the geometric arrangement of joints, as block size directly influences the mechanical behavior of the rock mass and its suitability for engineering applications (Zhang, 2016). Figure 3 is providing a Relationship between RQD and J_v were estimated by Priest & Hudson (1976). The RQD can also be estimated using the correlation between RQD and J_v were recommended by International Society for Rock Mechanics (ISRM, 1978):

$$RQD = 115 - 3.3J_v \tag{1}$$

Palmstrom's correlation is highly practical in fieldwork where direct measurement of RQD is not feasible, such as in poorly exposed rock masses or during preliminary investigations (Zhang, 2016).

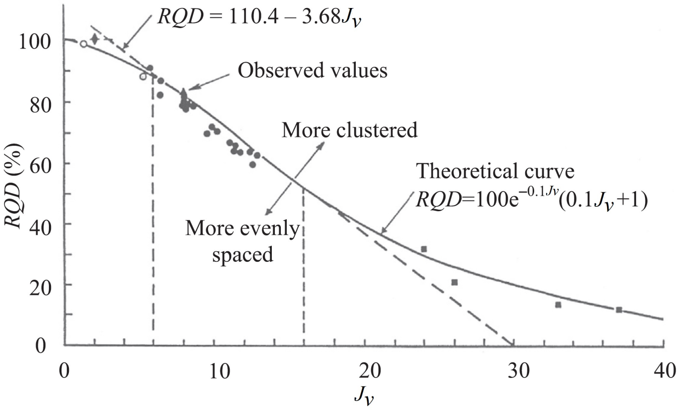


Fig. 3 Relation between RQD and J_v (Priest & Hudson, 1976)

By measuring the joint density and calculating J_v, engineers can predict RQD and assess the quality of the rock mass. This information is crucial for designing support systems, evaluating slope stability, and planning tunneling or excavation activities (Palmstrom, 2009; Azimian, 2016). While Palmstrom's relationship provides a robust estimation method, it assumes uniform joint distribution, which may not always be the case in heterogeneous rock masses. Further refinements and adaptations of his method have been proposed to address these limitations. Nonetheless, his work remains foundational in the field of engineering geology, providing an empirical bridge between joint network properties and rock quality assessment (Palmstrom & Broch, 2006).

III. ENGINEERING GEOLOGY OF STUDIED LOCATION

Isfahan Province, located in central Iran, exhibits diverse geological features shaped by its position in the Central Iranian geological zone. This area is characterized by a mix of igneous, sedimentary, and metamorphic rocks formed across various geological periods (Karimpour et al., 2017). The geological formations in the province include ancient Precambrian basement rocks, Paleozoic and Mesozoic sedimentary layers, and extensive Cenozoic volcanic and alluvial deposits, reflecting a complex tectonic history and varying depositional environments (Mohammadi et al., 2020). The geomorphology of Isfahan Province is marked by contrasting landscapes, including rugged mountain ranges, expansive plains, and desert basins. The province's topography is dominated by the Zagros mountain range in the west and the Central Iranian Plateau to the east (Ghorbani, 2013). Key geomorphological features include folded and faulted ridges, karstic limestone landscapes, and extensive desert plains such as the Dasht-e-Kavir and Dasht-e-Lut, which influence sediment transport and groundwater recharge (Aghanabati, 2007).

Isfahan lies at the intersection of the Central Iranian microplate and the Arabian Plate, making it a tectonically active region. The province is influenced by compressional forces resulting from the ongoing collision between the Arabian and Eurasian plates (Esmaeili & Moore, 2012). This tectonic activity has led to the formation of numerous faults, folds, and thrust zones. The interplay between tectonics and sedimentation has created diverse geological structures, contributing to the province's mineral wealth and hydrogeological systems (Nasr Esfahani & Vahabi Mogadam, 2010). Prominent faults in Isfahan Province include the Main Zagros Thrust, Karkas Fault, and Qom-Saveh Fault. These faults are seismically active and play a crucial role in shaping the region's geological features (Berberian, 1981). The Main Zagros Thrust marks the boundary between the Zagros Mountains and the Central Iranian Plateau, while the Karkas Fault influences the uplift and deformation of the Karkas Mountain Range. These fault systems are significant not only for their geological implications but also for their role in groundwater movement and seismic risk (Hashemi & Mehdizadeh, 2015). Isfahan Province hosts extensive sedimentary sequences, including limestones, sandstones, and shales from the Paleozoic and Mesozoic eras. The Jurassic and Cretaceous limestones are especially notable for their karstic properties, contributing to aquifer systems and supporting agriculture and water supply in the region (Aghanabati, 2007). Additionally, the Quaternary alluvial deposits in river valleys and plains provide fertile soil for agriculture and are crucial for urban development.

The province also features significant igneous and metamorphic rock formations, particularly in the Karkas Mountains and the southern regions. These rocks, primarily composed of granites, diorites, and metamorphosed sedimentary layers, reflect past volcanic and tectonic activity. The igneous rocks are often associated with mineralization, making Isfahan a hub for mining activities, including the extraction of copper, iron, and other minerals (Nasr Esfahani & Vahabi Mogadam, 2010). The karst landscapes, predominantly formed in the limestone formations, are a hallmark of Isfahan's geology. These karst systems include sinkholes, caves, and underground streams, which are essential for groundwater storage and movement. The region's water resources heavily depend on these karst aquifers, making them a focal point for studies related to water management and sustainability (Aghanabati, 2007). The diverse rock masses in Isfahan, including fractured limestones, tightly folded shales, and weathered igneous rocks, present unique challenges and opportunities for engineering projects. The stability of slopes, tunnels, and foundations in the province requires careful consideration of the geological and tectonic conditions. Understanding the interactions between faults, joint systems, and rock formations is crucial for safe and sustainable infrastructure development in this geologically complex region.

The sandstone formations in Isfahan Province are primarily of sedimentary origin, deposited during various geological periods, especially in the Paleozoic and Mesozoic eras. These sandstones are typically found in association with shales, limestones, and conglomerates, reflecting depositional environments ranging from fluvial to shallow marine settings. The formations often exhibit well-sorted grains, cemented by materials such as silica, calcite, or iron oxide, which contribute to their varying hardness and permeability. Notable sandstone deposits in Isfahan Province are found in areas like the Central Iranian Plateau and adjacent foothills. These formations vary in color, ranging from light beige to reddish-brown, due to the presence of iron oxides. They often display bedding planes, cross-bedding, and ripple marks, which are indicative of their depositional history. The sandstones play a crucial role in groundwater storage and movement due to their porosity and permeability, making them significant aquifers in certain regions. The sandstone formations of Isfahan have substantial implications for construction, mining, and hydrogeology. Their durability and aesthetic qualities make them a valuable resource for building stone and decorative materials. Additionally, the porosity of these formations is vital for groundwater exploration and extraction. However, their strength and stability need careful evaluation when used in engineering projects, as variations in cementation and jointing can affect their load-bearing capacity and long-term performance.

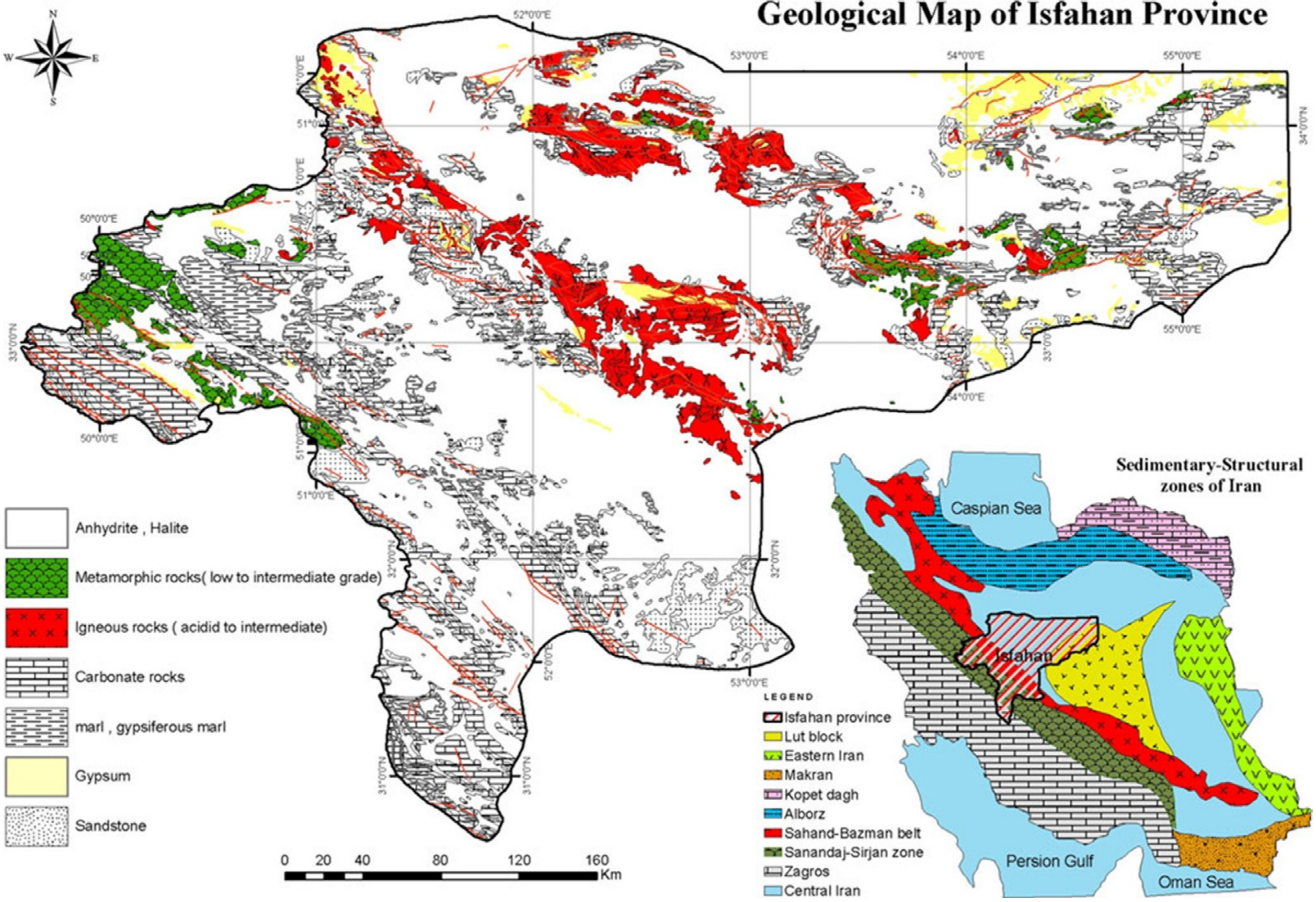


Fig. 4 Geological map of Isfahan Province (Esmaeili & Moore, 2012; Azarafza et al., 2020)

During this study, a comprehensive field survey was conducted to collect and analyze 75 rock samples from 25 stations, primarily located in sandstone formations (Figure 4). Detailed field measurements of rock masses were carried out to estimate RQD values. The majority of the stations were situated in the northern and western parts of the province, with two stations in the southern region and six in the east. The geomechanical survey involved on-site calculations of J_v and V_b values using Palmstrom's method. Rock samples were collected as surface rock blocks, and the surface RQD was calculated directly from these measurements. This dual approach allowed for a more precise evaluation of rock mass quality, combining field-based observations with empirical data to enhance the reliability of the RQD estimations.

Based on the analysis of Figures 2 and 3, combined with field survey results, the RQD for the sandstone formations in the studied area varies from 0 to 74, with an average value of 45. This indicates that the surface rock masses, which are predominantly weathered, exhibit extensive joint networks compared to subsurface levels. Consequently, the overall rock mass quality ranges from very poor to good, with the majority falling into the "poor" category. Field observations reveal that weathering is more pronounced at surface levels, particularly affecting joint networks and block integrity. Despite this, the rock blocks themselves exhibit high intact durability, suggesting that the sandstone at the block level is both reliable and durable. However, at the rock mass level, the influence of pervasive weathering and jointing significantly reduces the overall quality, necessitating consideration of these formations as weak materials, especially in surface applications. This highlights the dual nature of the sandstone formations in the region: while the intact rock material shows resilience and strength, the rock mass quality, impacted by weathering and jointing, requires careful evaluation and design considerations for engineering applications.

IV. Results and Discussion

A comprehensive field survey was performed across 25 stations distributed throughout the sandstone formations of Isfahan Province. Seventy-five representative rock samples were collected for geomechanical assessment. The calculated parameters, including J_v, V_b, and estimated RQD, provided the basis for evaluating rock mass quality in the studied area. Table 1 presents the statistical summary of the key geomechanical parameters derived from the field observations. The RQD values ranged between 0 and 74, with an average of 45, reflecting rock masses that are generally classified as poor to fair quality. The J_v values varied widely, indicating substantial heterogeneity in joint intensity across the surveyed formations. The observed spatial variation in RQD is primarily attributed to localized weathering, differences in joint orientation, and the lithological variability of the sandstone units. Stations located in the northern and western regions generally exhibited higher RQD values, corresponding to relatively intact rock masses, whereas southern and eastern stations showed lower RQD values due to intensive surface weathering.

An inverse correlation between RQD and Jv was observed, consistent with the empirical relationships proposed by Palmstrom (2005) and Priest & Hudson (1976). As the joint density increased, the proportion of intact rock fragments (and thus RQD) decreased. Table 2 summarizes the correlation coefficients among the key parameters. The strong negative correlation between RQD and J_v ($r = –0.86$) demonstrates the sensitivity of RQD to joint density, reaffirming that denser joint networks significantly reduce rock mass integrity. Similarly, a positive correlation between RQD and V_b ($r = +0.79$) confirms that larger block volumes correspond to higher-quality rock masses. These results validate the applicability of Palmstrom's empirical approach for sandstone formations in central Iran. Spatial analysis revealed a gradual decline in RQD from northwest to southeast, coinciding with an increase in J_v values and intensified weathering. This trend suggests that geological structures, particularly fault zones and surface exposure, exert significant control over rock mass quality. Table 3 categorizes the stations based on their calculated RQD classes according to Deere & Deere (1988), highlighting regional variability in rock quality. The predominance of poor to fair classes (approximately 68% of stations) indicates that the majority of sandstone rock masses in the province require moderate to strong support measures during construction activities such as tunneling or slope stabilization.

Field observations revealed that surface weathering significantly affects joint integrity and reduces apparent RQD. Highly weathered outcrops displayed fragmented joint planes, while subsurface exposures maintained more intact blocks. To quantify this effect, comparative analyses between surface and subsurface measurements were performed at selected stations (Table 4). The consistent increase in RQD with depth (average +26%) confirms that weathering exerts a major degrading influence on surface rock quality, leading to conservative RQD estimations when relying solely on surface data. Therefore, empirical RQD modifications for Isfahan sandstones should account for depth-dependent variability.

The classification results presented in Table 3 highlight a predominance of poor to fair rock mass conditions within the studied sandstone formations. This distribution reflects the combined influence of structural discontinuities, sedimentary heterogeneity, and surface degradation processes.

Table 1 Summary statistics of geomechanical parameters obtained from sandstone

Parameter	Min	Max	Mean	St.Dv.	Classification
RQD (%)	0	74	45	18.6	Poor to Fair
J_v (joints/m^3)	1.5	16.2	8.7	4.2	Moderate to Dense
V_b (m^3)	0.012	0.380	0.085	0.062	Variable sizes
Weathering Index	1.0	4.5	2.8	0.9	Moderate weathering

Table 2 Correlation matrix among principal geomechanical parameters

Parameter	RQD	J_v	V_b	Weathering Index
RQD	1.00	–0.86	+0.79	–0.86
J_v	–0.86	1.00	–0.82	+0.73
V_b	+0.79	–0.82	1.00	–0.59
Weathering Index	–0.68	+0.73	–0.59	1.00

Table 3 Distribution of rock mass quality classes across study stations

RQD Range (%)	Classification	No. of Stations	Percentage of Total (%)	Engineering Implication
0 – 25	Very Poor	3	12	Requires intensive support; unsuitable for surface foundations
25 – 50	Poor	8	32	Reinforcement necessary; moderate excavation difficulty
50 – 75	Fair	9	36	Stable with localized support
75 – 90	Good	4	16	Minimal reinforcement required
90 <	Very Good	1	4	Suitable for direct excavation

Table 4 Comparison between surface and subsurface RQD measurements at representative stations

Station ID	Depth (m)	Surface RQD (%)	Subsurface RQD (%)	Difference (%)	Dominant Weathering Features
S01	0.5	28	52	+24	Iron oxide staining, minor fracturing
S02	0.8	33	59	+26	Joint widening, clay infilling
S03	1.1	26	48	+22	Oxidation, partial disintegration
S04	1.4	39	66	+27	Surface exfoliation, moderate alteration
S05	1.0	42	68	+26	Clay infilling, granular disintegration
S06	1.3	37	63	+26	Surface exfoliation, moderate alteration
S07	1.2	34	63	+29	Joint widening, clay infilling
S08	1.6	45	70	+25	Moderate alteration, clay-lined joints
S09	1.0	40	65	+25	Oxidation, partial disintegration
S10	1.5	47	74	+27	Joint widening, clay infilling
S11	0.8	31	57	+26	Joint widening, clay infilling
S12	1.2	36	61	+25	Moderate alteration, clay-lined joints
S13	0.8	41	68	+27	Oxidation, partial disintegration
S14	1.2	38	62	+24	Joint widening, clay infilling
S15	1.4	29	51	+22	High joint density, surficial loosening
S16	1.0	43	69	+26	Joint widening, clay infilling
S17	1.3	30	54	+24	Joint widening, clay infilling
S18	1.5	46	72	+26	Moderate alteration, clay-lined joints
S19	1.4	35	60	+25	Oxidation and partial discoloration
S20	1.5	48	74	+26	Joint widening, clay infilling
S21	1.2	32	56	+24	Slight oxidation, compact structure
S22	1.6	39	66	+27	Joint separation, minor leaching
S23	1.0	44	44	+25	Stable core, surface rusting
S24	1.3	27	27	+22	Oxidation and partial discoloration
S25	1.8	50	74	+24	Joint widening, clay infilling

Stations falling within the very poor and poor categories are generally associated with shallow weathered zones or proximity to faulted areas, where the joint spacing is considerably reduced and secondary mineralization has weakened the rock fabric. In contrast, the good and excellent quality classes are typically observed in deeper or more compact sandstone layers with minimal exposure to atmospheric weathering. The observed variability implies that local geological and geomorphological conditions, rather than lithology alone, govern the rock mass quality. From an engineering standpoint, this heterogeneity necessitates the use of adaptable design parameters, particularly in tunnel and slope projects, where localized reinforcement strategies can optimize safety and cost efficiency.

The reliability of the proposed empirical modification was verified by comparing the field-measured RQD values with those predicted using Palmstrom's original correlation. A regression analysis was conducted across all 25 stations using the measured J_v as the primary independent variable. The resulting correlation demonstrated a strong inverse relationship between RQD and J_v, consistent with theoretical expectations. However, a noticeable underestimation was observed in the predicted RQD values for highly weathered outcrops, indicating that the original Palmstrom model tends to over-penalize jointed but partially intact sandstones. This deviation highlighted the necessity of introducing a local correction factor to account for geological and climatic influences specific to Isfahan's sandstone formations. To refine the model, a regional correction coefficient (k = 0.92) was incorporated into Palmstrom's equation, producing the modified empirical relationship:

$$RQD_{\mathrm{mod}} = 0.92\times(110-2.5J_v) \qquad (2)$$

This adjusted expression effectively compensates for the overestimation of joint density effects and the underrepresentation of intact block durability in the field-measured data. The calibration process utilized paired datasets of observed and predicted RQD values, optimizing the coefficient through iterative regression until the minimum root mean square error (RMSE) was achieved. The inclusion of this correction term improved the overall correlation coefficient (R^2) from 0.73 to 0.81, representing a significant enhancement in predictive performance. The model thus better reflects the true in-situ behavior of the sandstone masses under natural weathering and tectonic conditions. Figure 5 illustrates the validation results, showing the scatter distribution of measured versus predicted RQD values. The majority of data points align closely with the 1:1 reference line, particularly within the RQD range of 30–70%, which represents the dominant class in the studied formations.

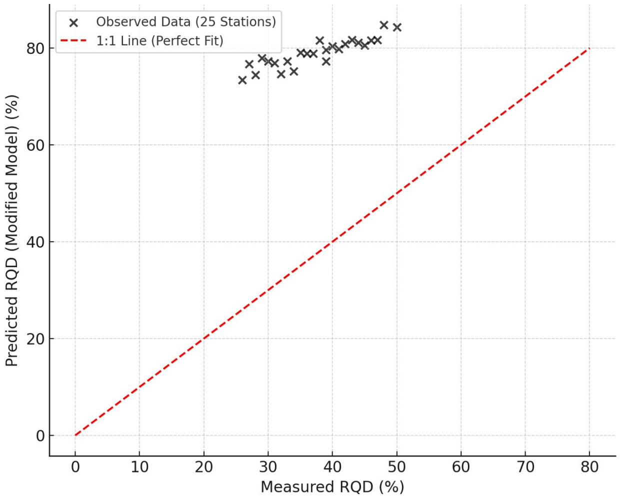


Fig. 5 Validation of the modified empirical rqd model

Slight deviations are evident at lower RQD values (<25%), corresponding to stations located in highly weathered zones with clay infill or granular disintegration. Despite these minor inconsistencies, the overall agreement between predicted and measured RQD values confirms the robustness of the modified equation. The residual analysis also indicates that prediction errors are randomly distributed rather than systematic, validating the statistical soundness of the adjusted correlation.

From an engineering perspective, the modified empirical model provides a practical and non-destructive method for estimating RQD in sandstone formations where core drilling is either uneconomical or technically challenging. It bridges the gap between empirical correlations and field observations, enabling faster yet reliable assessments of rock mass quality. Furthermore, this modification can be directly integrated into classification systems such as RMR, Q-system, and GSI to improve the accuracy of support design and stability analysis. Given the satisfactory validation results, the modified RQD correlation can be regarded as a regionally optimized tool for geotechnical applications in central Iran, with potential adaptability to other arid and semi-arid sandstone terrains exhibiting similar geological characteristics.

V. Conclusion

This study provides valuable insights into the geomechanical characterization of sandstone formations within Isfahan Province. By conducting a detailed field survey and collecting 75 rock samples from 25 strategically distributed stations, an accurate estimation of RQD was achieved. The integration of field-based measurements with Palmstrom's method for calculating J_v and V_b proved to be an effective approach for assessing rock mass quality. The results highlight the spatial variability in RQD values across the province, influenced by geological and geomorphological factors. The majority of the sampling was concentrated in the northern and western regions, with additional representation from the southern and eastern parts of the province, ensuring a comprehensive understanding of the sandstone formations. This work underscores the importance of combining empirical methods with direct field observations to improve the accuracy and reliability of geomechanical evaluations. These findings contribute to the broader understanding of rock mass stability and provide a foundation for designing effective engineering support systems for construction and mining projects in the region.

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Authors' contributions

Narges Hayati conducted the main data analysis, contributed to the data collection, preprocessing, and interpretation, and was responsible for drafting the initial manuscript. Mohammad Khaleghi performed checks, provided supervision, conceptual guidance, and critical revision of the manuscript. All authors read and approved the final manuscript.

Conflict of interest

The authors have not disclosed any competing interests.

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