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Utilizing the Geological Strength Index (GSI) for Rock Mass Strength Assessment in Slopes: A Case Study

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***Abstract*:** Quantifying rock mass conditions is essential in rock mechanics, providing critical insights into quality, strength, and durability. Rock mass classification systems, developed primarily through empirical and experimental studies, serve as vital tools for assessing geotechnical properties. These systems are especially crucial in slope stability analysis, aiding in evaluating structural integrity and guiding the design of reliable stabilization strategies. Among these systems, the Geological Strength Index (GSI) is widely regarded as a robust method for classifying rock masses. Developed by Prof. Hoek and his colleagues, GSI evaluates the geological and geomechanical characteristics of rock masses based on structural and material properties. Its global adoption across engineering and geotechnical projects highlights its reliability and versatility. This study applies GSI to evaluate slope rock mass behavior and its engineering implications. Field investigations were conducted at 12 sites west of Shiraz city as part of a highway development project to analyze the stability of roadside slopes. A comprehensive survey included 24 of Uniaxial Compressive Strength (UCS), point load, Schmidt hammer tests, all aimed at determining the mechanical properties of the rock masses. The collected data were processed using the GSI system, enabling the classification of slope rock masses and the identification of key engineering geological characteristics. The findings offer valuable insights into the stability and geomechanical behavior of the slopes, forming a foundation for reliable design and effective stabilization strategies. This approach underscores the importance of GSI in slope stability assessments.

Keywords: Rock mass classification, Slope stability, Geological strength index, Geotechnical engineering, Rock mechanics.

I. Introduction

Rock mass classification systems are essential tools in the field of geotechnical engineering, particularly in assessing the strength and stability of rock masses for various construction projects. These systems provide a standardized framework to categorize rock masses based on their physical and mechanical properties, such as jointing, weathering, and lithology (Singh & Goel, 2011). They are commonly used in tunneling, mining, slope design, and foundation studies, where understanding the behavior of rock under different conditions is crucial to ensuring the safety and efficiency of engineering projects (Qazi & Singh, 2023). Over time, various classification systems have been developed to address specific engineering needs (Yang et al., 2022). The most well-known systems include the Rock Mass Rating (RMR), the Q-system, and the Geological Strength Index (GSI) which is widely used around the world (Moon et al., 2001; Aydin, 2004; Pantelidis, 2010; Azarafza et al., 2017; Somodi et al., 2021). Each system evaluates a set of parameters, such as uniaxial compressive strength, rock quality designation, RQD (Deere, 1989), joint spacing, and joint condition, to determine the overall quality of a rock mass. These ratings then correlate with rock mass behavior, enabling engineers to predict potential problems like rockfalls, slippage, or the need for reinforcement (Salmi & Sellers, 2021).

The RMR, developed by Bieniawski in 1973 and modified in 1989 (Bieniawski, 1973, 1989), is one of the oldest and most widely applied classification systems (Maazallahi & Majdi, 2021). It is based on a detailed evaluation of several parameters, including the rock's uniaxial compressive strength (UCS), RQD, spacing and condition of joints, groundwater conditions, and the orientation of joints (Aksoy, 2008). The RMR provides an overall rating, which is then used to estimate the rock mass's strength and stability, helping engineers to design safe and cost-effective structures (Ferrari et al., 2014). Another widely recognized system is the Q-system, introduced by Barton in 1974 (Cai & Kaiser, 2006). This system is based on a ratio of several parameters, including the RQD, joint alteration, joint spacing, and the orientation of joints (Singh & Goel, 2011). The Q-system is particularly useful in tunnel design (Choi & Park, 2002), where precise evaluation of the rock mass is required for determining the need for support and reinforcing structures. Unlike the RMR, the Q-system can better account for the influence of joint conditions on the rock mass behavior (Fereidooni et al., 2015). The Geological Strength Index (GSI), developed by Hoek and Brown in the 1980s (Hoek & Brown, 1980), represents a more modern approach to rock mass classification (Sonmez & Ulusay, 1999; Hoek et al., 1998). It provides a more nuanced way of evaluating rock mass quality, considering both the characteristics of the rock and the condition of its discontinuities (Marinos et al., 2005). GSI is particularly useful for evaluating the strength of rock masses in a more comprehensive manner, factoring in the effect of weathering and alteration on rock behavior (Singh & Goel, 2011). The GSI system is widely used in slope stability assessments and is a valuable tool in understanding the long-term behavior of rock slopes under varying environmental conditions (Marinos et al., 2005).

Each classification system provides valuable insights into the mechanical behavior of rock masses (Singh & Goel, 2011); however, they also have their limitations. The accuracy of these systems largely depends on the correct identification and interpretation of the geological parameters that influence rock mass behavior (Azarafza et al., 2022). Moreover, the classification systems may not fully account for all variables, such as the dynamic loading conditions or the complex interactions between rock mass and groundwater, which could significantly affect the stability of a structure (Li et al., 2021; Xia et al., 2022). It is essential to apply rock mass classification systems effectively in slope engineering because slopes are inherently prone to failure due to factors like weathering, jointing, and external forces such as rainfall or seismic activity (Kumar & Pandey, 2021). By applying these classification systems, engineers can assess the potential for slope instability and develop appropriate mitigation strategies (Yodsomjai et al., 2021). This process helps in determining the need for slope stabilization techniques such as rock bolts, mesh, or retaining structures, thereby minimizing the risk of landslides or rockfalls (Hoek et al., 2013). So, the use of rock mass classification systems in slope design is crucial for ensuring safety and stability. By evaluating the various factors that affect rock mass behavior, these systems provide engineers with a comprehensive understanding of potential risks, allowing for the design of appropriate interventions (Aksoy, 2008). Incorporating these systems into slope stability assessments is essential to mitigate risks and enhance the performance of engineering projects in rocky terrains.

The presented study employs the GSI classification system to evaluate the rock mass characteristics and engineering properties of slopes in the Shiraz region. This approach provides a comprehensive understanding of the geomechanical behavior of the rock masses, forming the basis for a reliable stability assessment of the site. By integrating field data and GSI-based analysis, the study aims to deliver accurate insights into the stability conditions and potential risks associated with the slopes, enabling the development of effective engineering solutions and stabilization strategies.

II. Geological Strength Index (GSI)

The GSI is a widely recognized rock mass classification system introduced by Hoek and his colleagues, which was modified over time (Marinos et al., 2005). It was developed to provide a practical yet scientifically grounded method for evaluating the mechanical behavior of rock masses in engineering applications (Hussian et al., 2020). The GSI system focuses on assessing the quality of a rock mass based on its structure and the condition of its discontinuities, making it particularly effective for use in geotechnical projects such as tunneling, slope stability, and foundation design (Sonmez et al., 2003). At its core, the GSI system is based on two primary parameters: the structure of the rock mass and the surface condition of discontinuities (Hoek et al., 1998). Rock structure refers to the arrangement and spacing of joints, fractures, and other discontinuities within the rock mass. It categorizes the rock mass into blocky, massive, laminated, or disintegrated types. The condition of discontinuities involves evaluating surface roughness, weathering, and the presence of infilling material, which can significantly affect the rock mass's strength and deformation characteristics (Hussian et al., 2020). One of the defining features of GSI is its reliance on a visual assessment approach, which simplifies the classification process. The system uses descriptive charts and diagrams, enabling field engineers to classify rock masses quickly and accurately. This practicality makes GSI particularly suitable for preliminary site investigations where time and resources may be limited (Tsiambaos & Saroglou, 2010).

Although GSI is a qualitative system, it has strong correlations with quantitative rock mass properties (Hussian et al., 2020). Parameters such as UCS, tensile strength, and deformation modulus can be estimated using GSI values combined with the Hoek-Brown failure criterion (Tsiambaos & Saroglou, 2010). This integration allows GSI to serve as a bridge between empirical observations and analytical modeling in rock engineering (Singh & Goel, 2011). GSI is highly adaptable, making it suitable for a wide range of rock mass conditions, from intact and massive rock to heavily fractured and weathered masses (see Figure 1). The system includes extended charts and guidelines for weak or heterogeneous materials, such as flysch or schist, which exhibit complex geomechanical behaviors. This adaptability ensures the broad applicability of GSI across diverse geological environments (Wang & Aladejare, 2016).

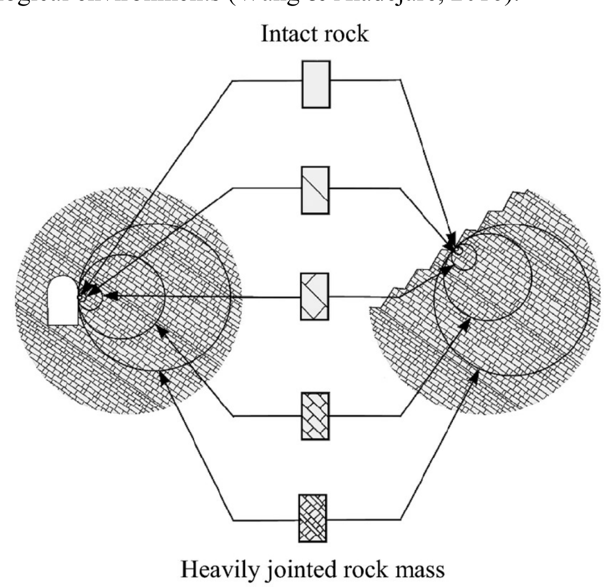

Fig. 1 Scale impact on GSI values (Renani & Cai, 2022)

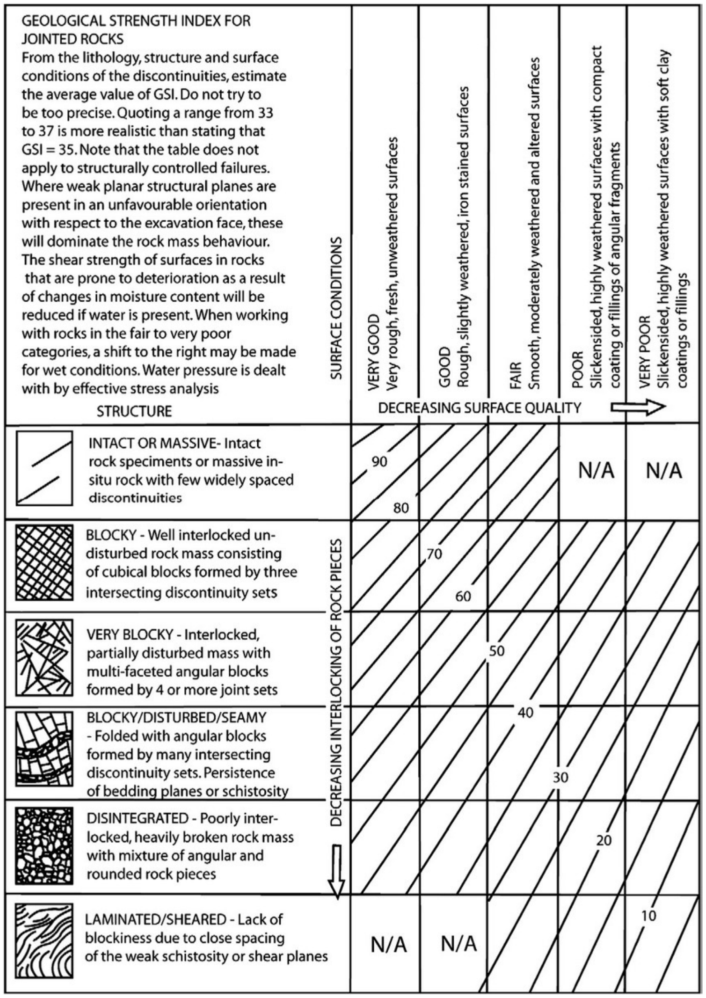

Fig. 2 A GSI chart for jointed rock mass (Marinos et al., 2005)

The development of GSI integrates geological observations with engineering requirements (Li et al., 2021). It recognizes that geological factors, such as lithology, weathering, and tectonic history, play a crucial role in determining rock mass behavior (Hoek et al., 2013). Figure 2 illustrates the GSI chart for rock mass specifications. By emphasizing these aspects, GSI provides engineers with a classification system that aligns with both geological principles and practical engineering needs (Hong et al., 2017). In slope stability analysis, GSI is instrumental in assessing the strength and durability of rock masses under various loading and environmental conditions (Sonmez et al., 2003). The system helps engineers estimate shear strength and deformation parameters, which are critical for evaluating slope stability and designing stabilization measures (Kumar & Pandey, 2021). By identifying weak zones and potential failure mechanisms, GSI contributes to the development of reliable slope management strategies (Hamasur, 2023). GSI also finds application in advanced numerical modeling, where accurate input parameters are essential for reliable predictions (Marinos et al., 2005). By providing realistic estimates of rock mass strength and deformation characteristics, GSI enables the development of more accurate models. This capability is particularly valuable in large-scale projects involving complex geological conditions (Day et al., 2019).

Compared to other rock mass classification systems, such as the RMR or Q-system, GSI offers several advantages. It simplifies the classification process while maintaining a strong theoretical foundation. Additionally, GSI's focus on visual assessment and its adaptability to weak or heterogeneous materials make it a versatile tool in geotechnical engineering. Despite its advantages, GSI has limitations. The system relies heavily on the experience and judgment of the engineer conducting the assessment, which may introduce variability. Furthermore, the qualitative nature of GSI can pose challenges in cases where precise quantification is required (Hussian et al., 2020). Efforts to address these challenges include the development of hybrid systems that combine GSI with other classification methods (Day et al., 2019). Over the years, GSI has undergone significant refinement to enhance its applicability. Extensions of the system now cater to specific geological conditions, such as weak rocks and heterogeneous masses. Moreover, researchers have developed relationships between GSI and various rock engineering parameters, expanding its use in design and analysis (Pozo, 2022).

One of GSI's primary applications is in estimating rock mass strength for various geotechnical engineering projects, such as slope stability assessments, tunnel design, and foundation planning. The GSI system evaluates the rock mass based on two major factors: the structure of the rock mass and the condition of the discontinuities within it. These factors are visually assessed, making the GSI a practical tool for field engineers who may need to evaluate rock masses quickly and efficiently (Marinos et al., 2005). One of the significant advantages of using the GSI system is its compatibility with the Hoek-Brown failure criterion, a well-established empirical model used to estimate the strength and failure conditions of rock masses (Xia et al., 2022). The Hoek-Brown criterion is particularly valuable for characterizing the strength of rocks that are heavily jointed or fractured. The GSI value, which ranges from 0 to 100, is used in the Hoek-Brown equation to derive the rock mass's UCS and other key parameters related to its mechanical behavior (Feng et al., 2018). Figure 3 provides a graphical description of GSI applications for Hoek-Brown equation to derive the rock mass's engineering geological properties. The Hoek-Brown failure criterion itself incorporates several factors, including the rock's intact strength (represented by the uniaxial compressive strength of the intact rock) and the effects of the discontinuities, such as joint spacing, roughness, and weathering (Hoek et al., 2002).

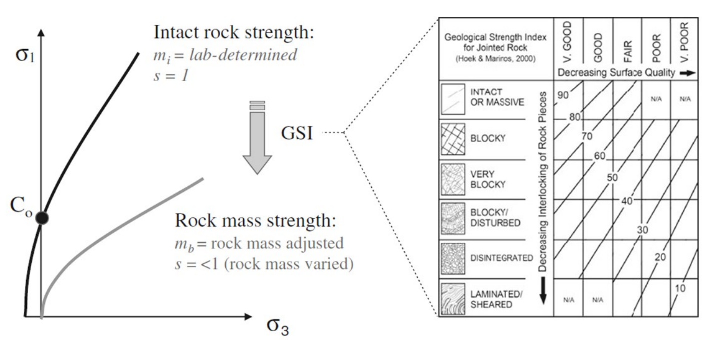

Fig. 3 Application of GSI in rock mass engineering geological specification (Rocscience, 2023)

These parameters are critical for predicting how the rock mass will behave under different loading conditions, such as those found in slope failures or tunnel construction. The relationship between the GSI and the Hoek-Brown parameters is established through empirical data, providing a reliable means for engineers to estimate the strength and stability of rock masses based on visual inspections (Hoek & Brown, 2019). In practice, the GSI classification system helps determine several important rock strength parameters that are necessary for stability analysis. These include the rock mass's cohesion and friction angle, which are fundamental for understanding the shear strength of the material (Renani & Cai, 2022). Using GSI values in conjunction with the Hoek-Brown criterion, engineers can estimate the shear strength parameters of the rock mass, which can then be used in slope stability analysis, foundation design, and other critical geotechnical assessments (Zuo & Shen, 2020). The integration of GSI with the Hoek-Brown failure criterion also allows for a more comprehensive analysis of rock mass behavior in response to different environmental conditions (Hoek & Brown, 2019). Factors such as groundwater conditions, loading scenarios, and seasonal weathering can significantly affect the strength of a rock mass (Hoek et al., 2002). By using GSI in conjunction with the Hoek-Brown criterion, engineers can account for these variables and produce more accurate and reliable stability models (Hamasur, 2023). This approach is particularly useful in projects where rock masses are complex or exhibit significant variability in terms of jointing, weathering, and other geological features (Hong et al., 2017).

While the GSI and Hoek-Brown criterion provide a valuable foundation for rock mass strength estimation, there are some challenges associated with their application (Sari, 2012). The accuracy of the GSI classification depends heavily on the experience and judgment of the field engineer conducting the visual assessment (Zuo & Shen, 2020). Variability in the classification process can arise when dealing with highly heterogeneous or weak rock masses, which may require further investigation through laboratory testing or more advanced analytical methods (Hoek & Brown, 2019). Despite these challenges, the GSI and Hoek-Brown criterion remain indispensable tools in geotechnical engineering (Sonmez et al., 2003). Their ability to estimate rock mass strength parameters based on both geological observations and empirical relationships provides engineers with a reliable method for assessing rock stability and designing appropriate stabilization measures (Hoek et al., 2002). By incorporating these tools into slope stability analyses, tunnel designs, and foundation assessments, engineers can better manage the risks associated with rock mass instability, ensuring safer and more cost-effective geotechnical projects (Renani & Cai, 2022).

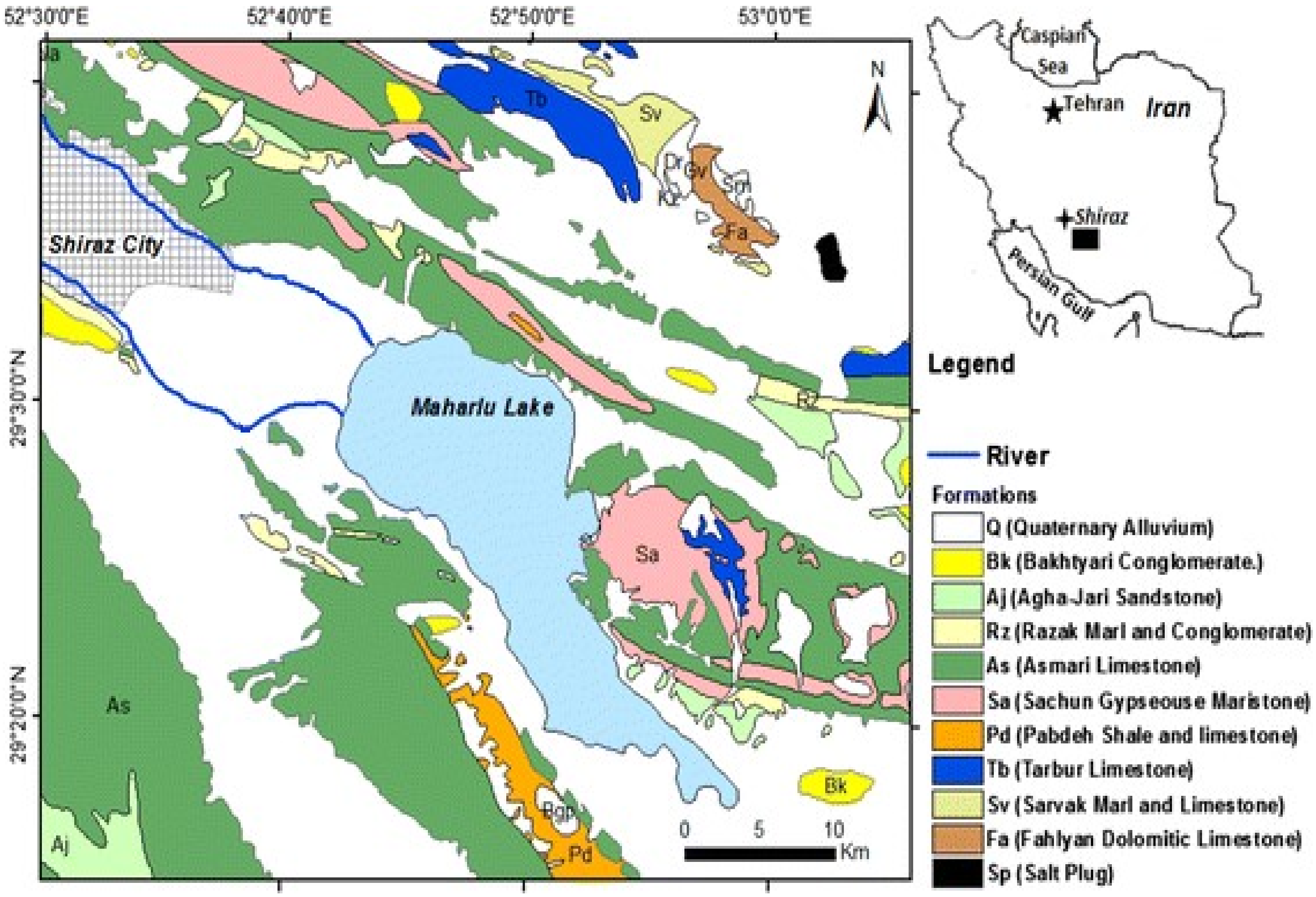

Fig. 4 Geological map of the studied area (adapted from Khosravi et al., 2018)

III. Materials and Methods

This study investigates the application of the GSI classification system, integrated with the Hoek-Brown failure criterion, to evaluate the strength and stability of slope rock masses in the Shiraz region. The methodology encompasses a combination of field surveys, laboratory testing, and analytical modeling to assess the geomechanical behavior of the studied rock masses. This approach ensures a comprehensive understanding of the rock mass characteristics and supports reliable stability assessments. As known, Shiraz region is located in southwestern Iran, lies within the Zagros Fold-Thrust Belt, a geologically significant region characterized by complex structural and stratigraphic features. The region is part of the larger Zagros Mountain range, which was formed as a result of the collision between the Arabian and Eurasian tectonic plates (Habibi et al., 2018). This tectonic activity has given rise to a series of folds, faults, and thrust zones that dominate the geological landscape. The area is primarily composed of sedimentary rock formations, including limestone, sandstone, marl, and shale, ranging in age from the Mesozoic to the Cenozoic era (Stoneley, 1981). These formations are often interspersed with evaporitic layers of gypsum and anhydrite, which can significantly influence the geomechanical behavior of the rock masses (Aghanabati, 2009). The vicinity of Shiraz is also marked by extensive karstic features due to the dissolution of limestone formations, resulting in caves, sinkholes, and other karstic landforms (Dastanpour, 1996). These features, combined with varying degrees of weathering and fracturing, contribute to the heterogeneity of the rock masses (Keshavarzi et al., 2020). Additionally, the region experiences seasonal climatic variations, including periods of heavy rainfall, which can exacerbate weathering and slope instability. Understanding the geology of Shiraz and its surrounding areas is critical for addressing geotechnical challenges, particularly in infrastructure development projects such as highways, where slope stability is a key concern. The interplay between tectonics, lithology, and climatic factors makes the geology of this region a focal point for engineering studies and hazard mitigation efforts (Aghanabati, 2009). The geological map of Shiraz city and vicinity area has been provided in Figure 4.

The research focuses on 12 sites located west of Shiraz city, selected along a highway development route where slope stability is a critical concern. Serval slopes and outcrops for some of the rock slopes has been provided in Figure 5. The sites were chosen based on geological diversity, exposure of rock masses, and relevance to the project's engineering requirements. Extensive field surveys were conducted at each site to document the geological conditions, including rock structure, jointing patterns, discontinuity conditions, and weathering levels. During the field surveys, the GSI classification system was employed to evaluate the quality of the rock masses. Engineers visually assessed the structural characteristics and surface conditions of the discontinuities using GSI charts and guidelines. This process involved categorizing the rock masses based on blockiness, surface roughness, joint infilling, and the degree of weathering. The GSI values were assigned to each slope, forming the basis for subsequent geomechanical analysis.

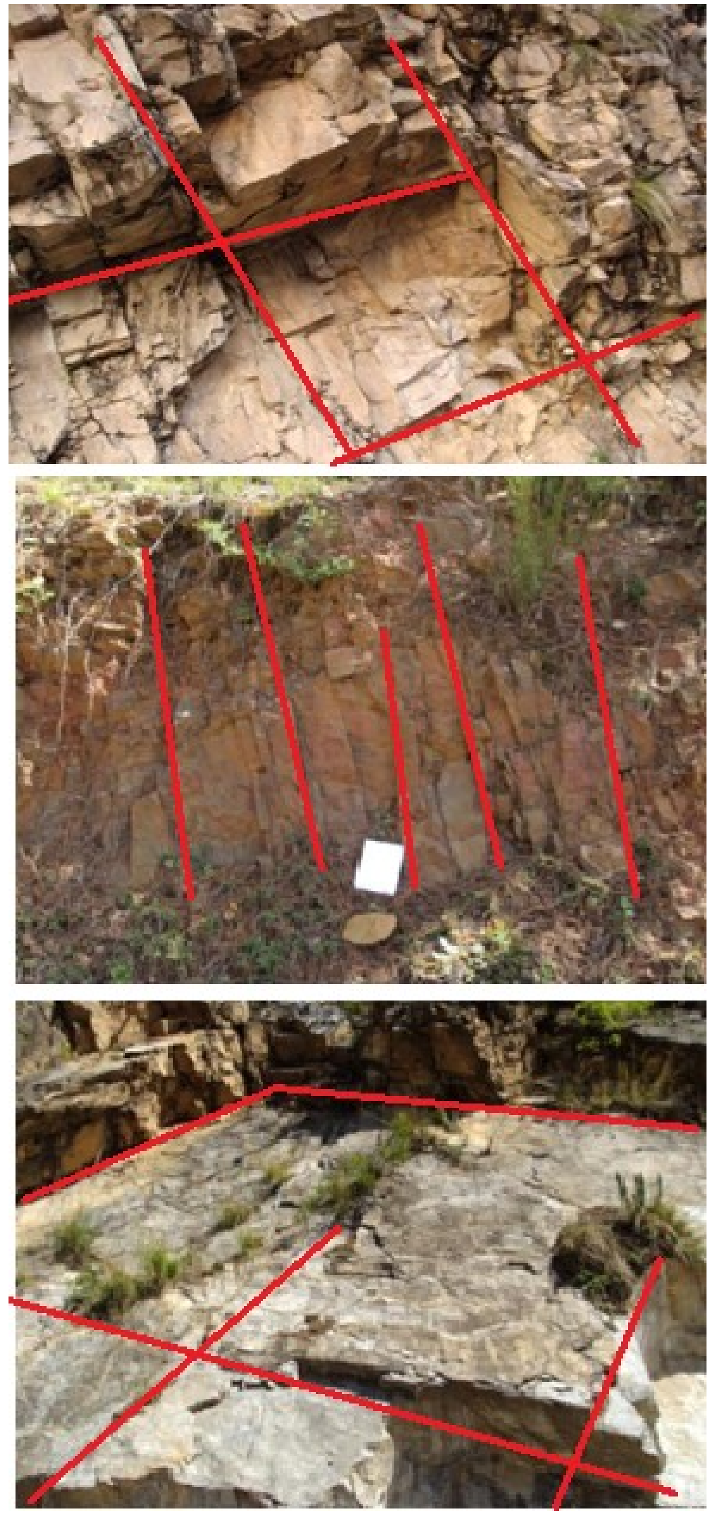

Fig. 5 A view of the several rock mass outcrops in studied region

To supplement the field observations, samples of intact rock were collected from each site for laboratory testing. A total of 24 samples underwent UCS testing to determine the intrinsic strength of the intact rock. Additionally, 24 point load tests and 24 Schmidt hammer tests were conducted to evaluate the rock's mechanical properties. These tests provided essential data for calibrating the Hoek-Brown parameters and verifying the reliability of the GSI-based assessments. The GSI values obtained from the field surveys were used in conjunction with the

Hoek-Brown failure criterion to estimate the geomechanical parameters of the rock masses. This included calculating the rock mass's uniaxial compressive strength, cohesion, and friction angle. The Hoek-Brown criterion, with its incorporation of GSI, allowed for a detailed assessment of the rock mass strength and deformation properties, which are critical for understanding slope stability. The geomechanical parameters derived from the GSI and Hoek-Brown criterion were input into slope stability models to evaluate the safety and stability of the slopes. These models accounted for site-specific conditions such as slope geometry, groundwater presence, and loading scenarios. Stability analysis was performed using limit equilibrium methods and numerical modeling to identify potential failure mechanisms and assess the need for stabilization measures. To ensure the reliability of the findings, the results of the GSI-based classification and the stability analysis were compared with observations of in situ slope performance. Field observations of existing slope failures or stable conditions provided a basis for validating the model predictions. Any discrepancies between the models and real-world conditions were analyzed to refine the methodology.

The data collected from field surveys, laboratory tests, and stability analyses were systematically analyzed and interpreted. The results were documented in a structured format, highlighting the correlation between GSI values, rock mass strength parameters, and slope stability conditions. The insights gained from this analysis contribute to a deeper understanding of the applicability of the GSI system in geotechnical projects. So, based on the stability analysis, appropriate stabilization strategies were proposed for slopes deemed at risk of failure. These strategies included recommendations for rock bolts, retaining walls, drainage systems, and surface protection measures. The study aimed to provide cost-effective and site-specific solutions to enhance slope stability and mitigate potential hazards. Finaly, this methodology integrates field-based classification, laboratory testing, and analytical modeling to evaluate rock mass behavior and slope stability. By leveraging the strengths of the GSI system and the Hoek-Brown failure criterion, this study provides valuable contributions to the field of geotechnical engineering. The proposed approach ensures accurate assessment and practical solutions for managing slope stability challenges in the Shiraz region.

IV. Results and Discussion

As outlined in the preceding sections, this study employs the GSI method to evaluate the characteristics of the host rock masses along the road construction route in the Shiraz region. The GSI method provides a field-based and experimental approach to determine the GSI value, which reflects the condition of the rock mass. This value, ranging from 0 to 100, corresponds to rock mass conditions varying from highly porous and weak to dense and competent. To achieve this, a comprehensive field survey was conducted at 12 strategically selected stations along the route. Key geomechanical properties of the rock masses, including joint characteristics, spacing, roughness, and weathering conditions, were meticulously recorded. Additionally, the geological conditions of the host rocks were analyzed to ensure an accurate and reliable assessment. Table 1 presents the main geometrical properties of the studied slopes. It should be noted that the values provided in Table 1 are average values, recommended and recorded based on the guidelines established by Hudson & Harrison (1997). Also, Table 2 provides geotechnical properties of slope materials that estimated by samples and conducting tests on them.

The geometrical properties of the 12 analyzed slopes, as shown in Table 1, exhibit a diverse range of structural conditions. Dip angles vary from 35° to 55°, with corresponding directions ranging between 90° and 160°. Joint spacing, an essential factor influencing slope stability, is recorded between 0.3 m and 1.4 m. The infill materials predominantly consist of clay, sand, and silt, with some slopes containing no infill material, indicating more intact rock masses. These variations highlight the need for detailed slope-specific evaluations to ensure the reliability of geotechnical designs in this region. The GSI values, summarized in Table 3, range between 40 and 60, reflecting the moderately weathered and fractured nature of the rock masses. Slope 5 shows the highest GSI value of 60, suggesting dense and robust rock conditions with rough, unfilled joints. Conversely, Slope 1 has a GSI of 42, indicating weaker rock mass with smooth, slightly weathered joints. These differences are primarily attributed to variations in joint condition and weathering intensity, which significantly influence rock mass stability. Also, the RMR values, derived from key parameters such as GSI, RQD, and joint condition, range from 58 to 72, as presented in Table 3. Slope 5 achieves the highest RMR of 72, corresponding to its high GSI and excellent RQD (90%). Lower RMR values, such as 58 for Slope 1, are attributed to reduced GSI and moderate RQD (70%). These findings suggest that RMR is strongly correlated with the geological and structural integrity of the slopes, emphasizing its importance in slope stability assessment. Joint conditions, including roughness, infill type, and weathering, significantly affect the mechanical performance of the slopes. Table 3 illustrates that slopes with rough, fresh joints (e.g., Slope 10) generally exhibit higher GSI and RMR values. In contrast, slopes with smooth or clay-filled joints (e.g., Slope 6) show lower ratings. This relationship underscores the critical role of joint characteristics in determining the mechanical behavior and stability of rock masses. The combined analysis of GSI, RMR, RQD, and joint conditions highlights distinct stability profiles for each slope. Slopes with higher RMR and GSI values, such as Slopes 5 and 10, are expected to demonstrate greater stability under load and environmental conditions. Conversely, slopes with lower values, like Slopes 1 and 6, may require additional reinforcement or stabilization measures to mitigate potential risks. This variability highlights the necessity for tailored geotechnical solutions based on detailed field and laboratory assessments. The findings presented in Tables 1 to 3 provide a comprehensive framework for evaluating rock slope stability in this region. Engineers and geologists can utilize this data to design effective stabilization strategies, including slope reinforcement, drainage improvement, or shotcrete application, depending on the slope's specific characteristics. Future studies should focus on integrating advanced numerical modeling and monitoring systems to validate and enhance these assessments. The results of this investigation offer valuable insights into the stability and mechanical performance of the rock slopes, contributing to informed decision-making in the design and construction of road infrastructure in the region.

Table 1 Geometrical property of the studied slopes

Slope ID	Dip	Direction	Spacing	Infill
S1	45	120	0.5	Clay
S2	35	90	0.8	Silt
S3	50	150	0.3	No infill
S4	40	110	0.7	Clay
S5	55	135	1.4	Clay
S6	38	140	0.6	No infill
S7	42	100	1.5	No infill
S8	48	130	0.9	Clay
S9	37	95	0.8	No infill
S10	52	145	1.4	Clay
S11	47	125	0.6	Silt
S12	50	160	1.3	No infill

Table 2 Geotechnical properties of the slope rock mass

Sample ID	UCS (MPa)	Point-load (KPa)	Schmidt rebound
SS1	40	800	35
SS2	42	820	37
SS3	38	780	34
SS4	50	950	40
SS5	48	920	39
SS6	47	940	41
SS7	30	700	28
SS8	32	720	29
SS9	31	710	30
SS10	55	1100	45
SS11	53	1080	45
SS12	54	1080	45
SS13	60	1200	48
SS14	58	1180	47
SS15	59	1180	49
SS16	41	810	36
SS17	49	930	39
SS18	33	730	31
SS19	56	1100	45
SS20	61	1210	50
SS21	39	790	34
SS22	51	960	42
SS23	34	740	32
SS24	57	1120	46

Table 3 Geomechanical classifications for the slope rock mass

Slope ID	GSI	RMR	RQD (%)	Joint Condition
S1	42	58	70	Smooth, slightly weathered joints
S2	45	62	75	Rough, partially infilled
S3	50	68	80	Planar, weathered
S4	48	65	78	Stepped, fresh joints
S5	60	72	90	Rough, no infill
S6	55	70	85	Smooth, clay-filled joints
S7	50	68	80	Rough, silty infill
S8	44	60	73	Rough, partially infilled
S9	46	63	76	Planar, weathered
S10	58	71	88	Smooth, clay-filled joints
S11	52	66	86	Planar, weathered
S12	49	64	79	Smooth, clay-filled joints

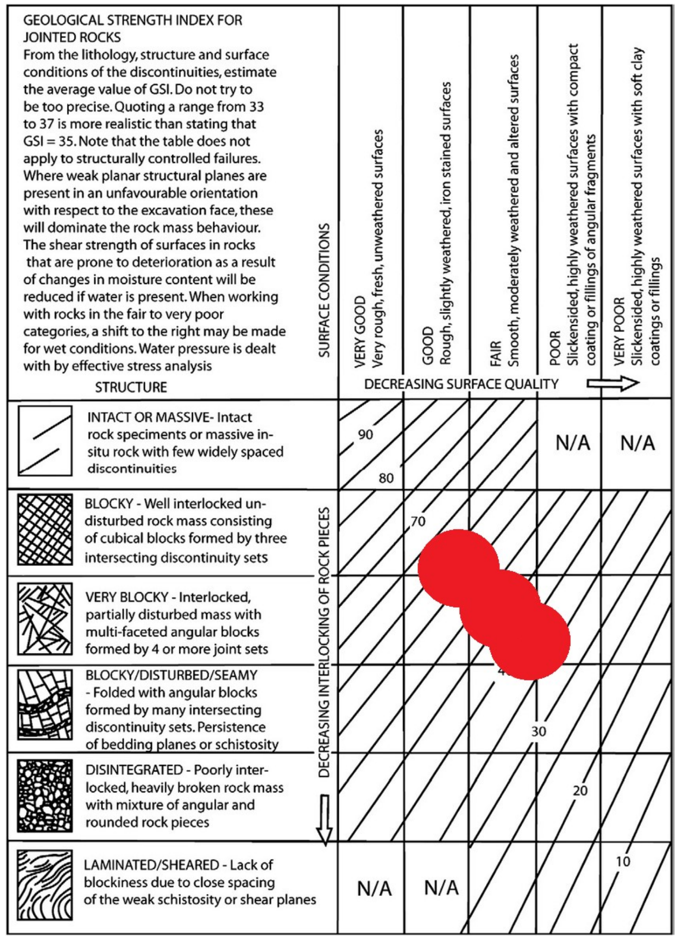

Fig. 6 A GSI chart that provided for studied stations

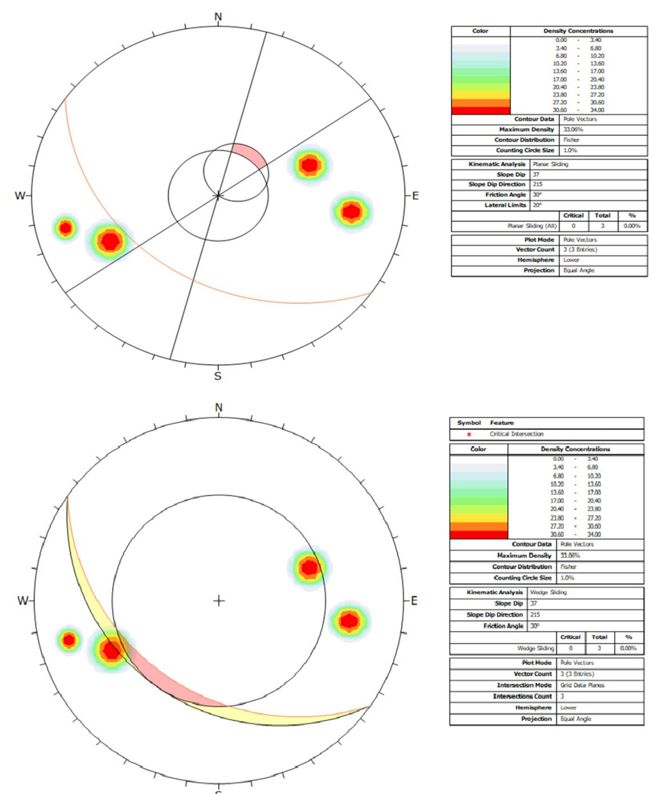

Fig. 7 A kinematic analysis for critical slopes with low GSI

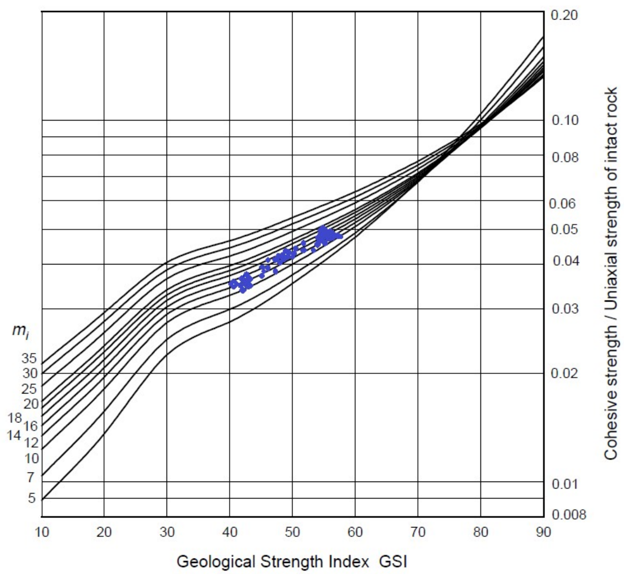

Fig. 8 GSI chart for estimating cohesive values

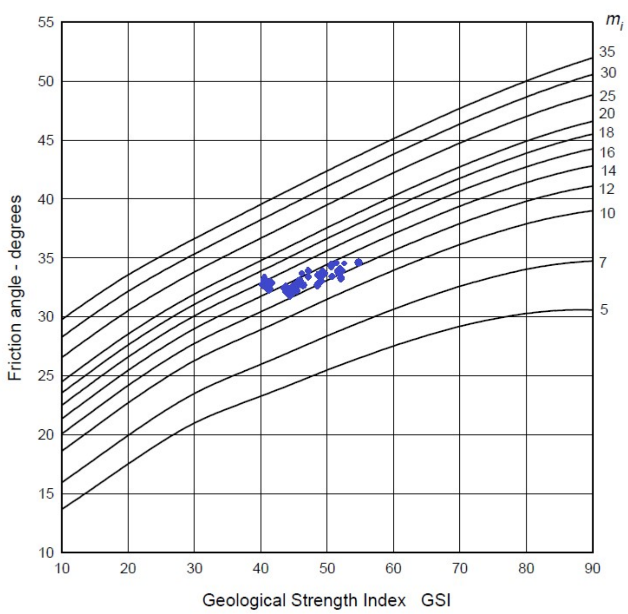

Fig. 9 GSI chart for estimating friction angle values

V. Conclusion

This study comprehensively analyzed the stability characteristics of 12 rock slopes in a road construction project using key geotechnical parameters, including geometrical properties, GSI, RMR, RQD, and joint conditions. The results demonstrate significant variability in slope conditions, emphasizing the importance of detailed field evaluations for informed decision-making in geotechnical engineering. The GSI values, ranging from 40 to 60, highlight the moderate quality of the rock masses, influenced by varying degrees of weathering and joint surface conditions. Higher GSI values, as observed in Slope 5, are associated with robust and dense rock masses, while lower values, such as in Slope 1, indicate weaker rock conditions requiring potential stabilization measures. The RMR, which incorporates GSI, RQD, and joint characteristics, further supports these findings, with values ranging between 58 and 72. High RMR values suggest better slope stability, underscoring the strong correlation between these parameters. The study also highlights the critical role of joint conditions in influencing rock mass stability. Slopes with rough, fresh, or unfilled joints, such as Slope 10, exhibit higher stability potential, while those with smooth or clay-filled joints, such as Slope 6, show lower stability profiles. These insights are vital for designing slope-specific reinforcement measures to mitigate risks associated with potential slope failures. The findings provide a robust framework for evaluating rock slope stability and guiding engineering designs. By incorporating comprehensive field data and systematic analysis, this study contributes to the safe and sustainable development of infrastructure in geologically complex regions. Future research should integrate advanced modeling and real-time monitoring techniques to enhance slope stability assessments and develop more effective geotechnical solutions.

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Authors' contributions

Maryam Nazari and Shahrzad Alivand conducted the main data analysis, contributed to the data collection, preprocessing, and interpretation, and were responsible for drafting the initial manuscript. Fariba Alizadeh performed checks, 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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