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Rock Slope Stability Analysis based on New Q_{slope} method for Semirom Region in Iran

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Abstract: Rock slope stability is a crucial component of geotechnical engineering, aimed at ensuring the safety and integrity of both natural and artificial slopes within rock formations. This study aims to classify rock slopes based on stability using the Q_{slope} method, an approach originally developed by Bar and Barton in 2017 and later modified by Azarafza et al. in 2020 to accommodate data from Iran. For this research, 12 jointed rock slopes in the Semirom region of Iran were selected as case studies. The analysis revealed that most of these slopes are in stable or uncertain conditions, while two were identified as unstable. The findings underscore the utility of the Q_{slope} method as a fast and efficient tool for assessing rock slope stability. This method offers practical advantages for geotechnical engineers, as it streamlines the evaluation process, especially in regions where geological data may be limited or difficult to obtain. Ultimately, the study contributes valuable insights into slope stability management in Iran, while also confirming the broader applicability of the Q_{slope} method to various geographical contexts.

Keywords: Rock slope, Slope stability, rock mechanics, Q_{slope}, Geology.

I. INTRODUCTION

Rock slope stability is a key aspect of geotechnical engineering, focusing on understanding and maintaining the safety of natural or man-made slopes in rock masses. Rock slopes can be found in various settings, including mountainous terrains, construction sites, and road cuts (Hudson & Harrison, 1997). The stability of these slopes is critical because their failure can lead to landslides, rockfalls, and other hazardous events that threaten human life, infrastructure, and the environment. Various factors, including geological conditions, weathering, water infiltration, and human activities, can affect the stability of rock slopes, making their assessment essential in engineering projects (Singh & Goel, 2011).

Several factors contribute to rock slope stability, with geological structures and rock properties being the most critical. The presence of discontinuities, such as joints, faults, and bedding planes, creates weak zones that may become slip surfaces, leading to slope failure (Singh & Goel, 2011). The strength and type of rock material also play a significant role; for instance, softer rocks like shale are more prone to instability than harder rocks like granite (Azarafza et al., 2017a). Environmental factors, such as freeze-thaw cycles, rainfall, and groundwater seepage, further influence rock stability by weakening the rock mass or increasing pore pressure within fractures (Hudson & Harrison, 1997).

Slope failures in rock masses can occur in several ways, depending on the geological conditions and external factors. Common types of failures include planar, wedge, toppling, and circular slides. Planar failures occur along a single plane of weakness, while wedge failures happen when two discontinuities intersect, forming a wedge-shaped block that slides. Toppling occurs when rock columns or slabs rotate forward, and circular slides are common in heavily weathered or fractured rock, where failure follows a curved path (Azarafza et al., 2021). Identifying the type of potential failure is essential for designing stabilization measures (Singh & Goel, 2011).

To assess rock slope stability, engineers and geologists use various methods, including empirical, analytical, and numerical approaches (Pantelidis, 2009). Empirical methods, such as the Q_{slope} classification system, provide quick assessments by categorizing rock masses based on observable features like joint spacing and rock strength (Bar & Barton, 2017). Analytical methods involve calculating stability through limit equilibrium analysis, which models potential failure surfaces. Numerical methods, such as finite element analysis, offer more detailed simulations by considering complex interactions within the rock mass (Kainthola et al., 2013). Combining these methods helps engineers develop a comprehensive understanding of slope behavior and determine appropriate stabilization measures (Ullah et al., 2020). Empirical methods play a crucial role in the geotechnical evaluation of rock structures, utilizing classification systems specifically designed for stability analysis and engineering design (Azarafza et al., 2022). These rock mass classification systems compile, rank, and quantify data related to geological conditions, geometrical characteristics, discontinuity networks, seepage, and other key factors (Salmi & Hosseinzadeh, 2015).

Several techniques are used to enhance the stability of rock slopes. Reinforcement methods include the installation of rock bolts, anchors, or retaining walls to stabilize weak rock masses (Singh & Goel, 2011). Drainage systems can reduce water infiltration and pore pressure, minimizing the risk of failure due to seepage. In some cases, shotcrete or wire mesh is applied to prevent small-scale rockfalls. Vegetation can also be used to reinforce soil-covered rock slopes, providing additional stability (Hudson & Harrison, 1997). By applying the appropriate combination of these techniques, engineers can significantly reduce the risk of rock slope failures and ensure the safety of surrounding areas (Pantelidis, 2009).

In efforts to improve geotechnical design, Azarafza et al. (2017b) sought to estimate critical design parameters such as resistivity, deformability, in-situ stress fields, and reliability—elements considered vital in engineering design. While Ritter (1879) was the first to apply a rudimentary rock classification in tunnel design, it was Terzaghi (1946) who introduced the first comprehensive rock mass classification system, specifically for the design of steel frame tunnel supports. In 1958, Lauffer introduced the concept of ‘stand-up time’ in rock mass classification, which was based on the rock-load theory and aimed at determining appropriate support systems for unsupported tunnels. Building on this, Deere et al. (1970) modified Terzaghi’s original theory by introducing the Rock Quality Designation (RQD), a key measure for assessing rock quality. Their work differentiated between tunnels excavated by blasting and those using machine excavations, providing specific guidelines for the use of steel arches, rock bolts, and shotcrete supports in tunnels with diameters ranging from 6m to 12m (Deere & Deere, 1989). Figure 1 illustrates the RQD calculation in a recovery core-log. Later, Cecil (1970) refined Terzaghi’s classification system, offering valuable qualitative insights into rock mass properties, though certain limitations of the system remained. Deere & Deere (1989) modified the RQD method that was used by different researchers such as Palmstrom (2005), Şen & Eissa (1991), and Romana (1993). RQD is now one of the most efficient methods to quantify the rock mass quality which is commonly used in support system designs and primary decision making for rock engineering.

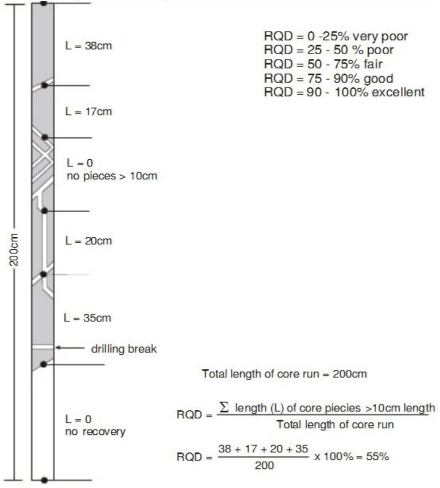


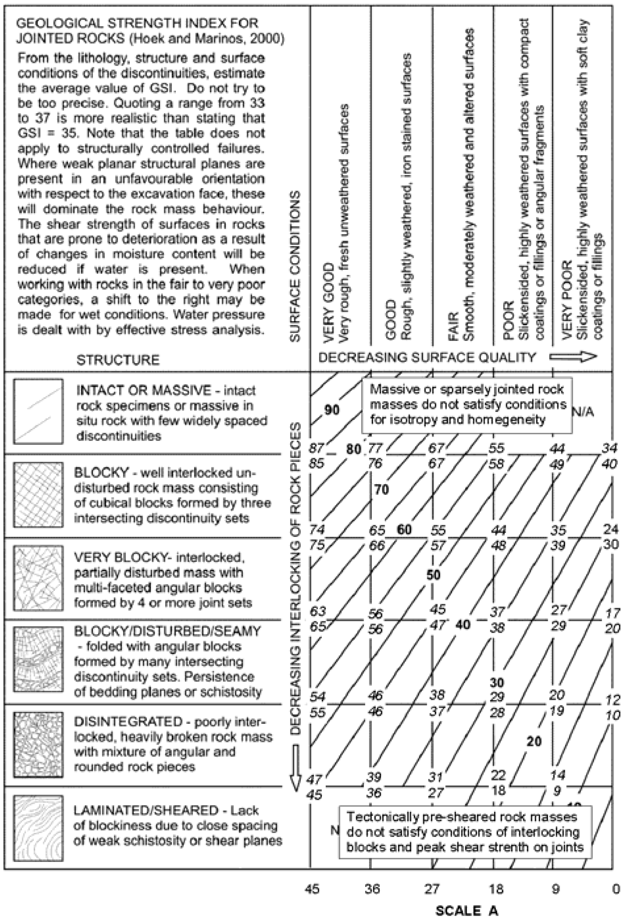
Fig. 1 RQD measurement and calculations (Onsel et al., 2011)

II. ROCK MASS CLASSIFICATIONS

Rock mass classification systems play a crucial role in geotechnical engineering and design. These systems provide a standardized way to assess the quality and stability of rock masses, essential for tunnel construction, slope stability, foundation design, and other civil engineering projects. The primary goal of these classifications is to categorize rock masses based on their geological characteristics and mechanical behavior, which helps engineers make informed decisions on the type of support systems required to ensure safety and stability (Singh & Goel, 2011; Azarafza et al., 2017a).

Several rock mass classification systems have been developed over the years, each with its unique approach and focus. The most used systems include the RQD, the Rock Mass Rating (RMR) system developed by Bieniawski (1973), and the Q-system, introduced by Barton et al. (1974). Each of these systems provides a framework for evaluating rock mass properties and determining appropriate support measures based on parameters such as joint spacing, rock strength, and groundwater conditions (Barton & Grimstad, 2014). The RQD, developed by Deere et al. (1970) is a simple yet effective measure for evaluating the quality of rock masses. It is calculated based on the percentage of core pieces longer than 10 cm in a borehole sample. The RQD value ranges from 0 to 100%, with higher values indicating better rock quality. Although RQD provides a quick assessment of rock mass integrity, it has limitations, particularly in highly fractured or weathered rock masses where the RQD may not accurately reflect the true conditions (Deere & Deere, 1989). The RQD calculation process was illustrated in Fig. 1. The RMR system, developed by Bieniawski (1989), is one of the most comprehensive and widely used rock mass classification systems. It considers six key parameters: uniaxial compressive strength (UCS) of the rock, RQD, spacing of discontinuities, condition of discontinuities, groundwater conditions, and orientation of discontinuities. Each parameter is assigned a rating, and the sum of these ratings gives an overall RMR score. The RMR system helps engineers design tunnel supports and assess the stability of slopes and foundations (Singh & Goel, 2011).

The Q-system, introduced by Barton et al. (1974), is another widely used rock mass classification system. It evaluates the quality of rock masses based on six parameters: RQD, joint set number, joint roughness, joint alteration, groundwater conditions, and stress reduction factor. The Q-value is calculated by multiplying and dividing these parameters according to specific formulas. This system is particularly useful in tunnel design, as it provides guidance on the selection of support systems based on the rock mass quality (Palmstrom & Broch, 2006). The Geological Strength Index (GSI) is a more recent rock mass classification system developed by Hoek and Marinos in the 1990s (Sonmez & Ulusay, 1999; Marinos & Hoek, 2000). Unlike other systems that rely on numerical ratings, GSI uses visual observations of rock mass structure and surface conditions to assess the quality of the rock (Marinos et al., 2005). It is particularly useful for estimating the mechanical properties of rock masses, such as strength and deformability, which are critical for designing safe and stable structures in challenging geological conditions (Hussian et al., 2020). Figure 2 presents the main GSI classification chart developed by Hoek and Marinos.



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.

Fig. 2 GSI calculations chart (Marinos et al., 2005)

Rock mass classification systems are widely used in various geotechnical engineering applications. In tunneling, these systems help engineers determine the type and amount of support required to prevent tunnel collapse or deformation. In slope stability analysis, rock mass classification provides insights into the likelihood of slope failure and guides the selection of stabilization measures such as rock bolts, retaining walls, or shotcrete. In foundation design, these systems help assess the bearing capacity and settlement potential of rock masses (Singh & Goel, 2011). Despite their widespread use, rock mass classification systems have limitations. Many systems rely on subjective observations and empirical data, which can lead to variability in results depending on the experience of the engineer or geologist conducting the assessment. Additionally, these systems often do not account for complex geological conditions, such as the presence of faults, weathering, or dynamic loading conditions like earthquakes (Pantelidis, 2009). As a result, they are typically used as a preliminary assessment tool rather than a definitive solution (Nikoobakht & Azarafza, 2016). Thus, rock mass classification systems are invaluable tools in geotechnical engineering, providing a systematic way to assess the quality and stability of rock masses. While they have limitations, rock mass classification remains an essential component of the design and construction process, helping engineers make informed decisions to ensure safety and stability in a wide range of geological settings.

III. Q$_{\text{SLOPE}}$METHOD

The Q_{slope} method is an adaptation of Barton's original Q-system (Bar & Barton, 2017), which was initially designed for underground stability analysis and support design. This updated system is specifically aimed at reducing the maintenance needs or bench-width requirements of slopes, including both natural cuts and open-pit mining slopes. It provides geo-engineers with a tool to assess the stability of in-situ excavated rock slopes and make necessary slope angle adjustments as the rock mass conditions become clearer during construction. Barton & Bar (2015) recommend applying Q_{slope} to address various types of rock slope failures, including planar, wedge, toppling, and localized debris failures. Barton et al. (1974), through their experimental work on underground spaces at the Norwegian Geotechnical Institute (NGI), introduced the Q-system, also known as the rock mass quality or rock tunneling quality index. This system is founded on several key causative factors that influence rock mass stability and performance in tunneling applications which are illustrated in Eq. 1.

$$Q = \frac{RQD}{J_n}\frac{J_r}{J_a}\frac{J_w}{SRF} \tag{1}$$

In Eq. 1, RQD refers to Deere's RQD, which measures the integrity of rock based on the percentage of intact core pieces in a sample. J_n represents the number of joint sets, J_r describes the roughness of the joint surfaces, and J_a refers to joint alteration, which accounts for the weathering and condition of the joints. J_w is the joint water reduction factor, indicating the influence of groundwater, while SRF is the stress reduction factor that considers in-situ stresses under tunneling conditions (Barton et al. 1974). In the Q-system, three primary components are evaluated based on field observations: block size (RQD/J_n), inter-block shear strength (J_r/J_a), and active stress conditions (J_w/SRF). The resulting Q-value can range from 0.001, indicating exceptionally poor rock quality, to 1000, representing exceptionally good rock quality (Azarafza et al. 2020a). Figure 3 provides the Q-system chart based on Barton et al. (1974). This chart mainly used to suggest support system and develop primary rock mass quality and stability regarding rock mass conditions.

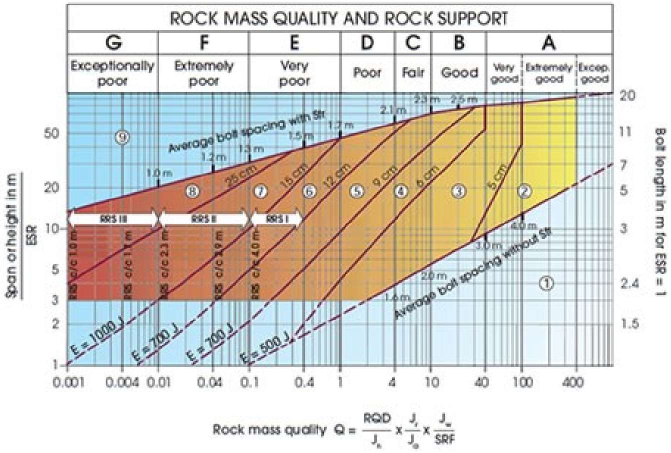


Fig. 3 Q-system analysis chart (Bartonet al., 1974)

The Q_{slope} classification system uses the same six parameters found in the standard Q-system—RQD, J_n, J_r, J_a, J_w, and SRF—but they have been modified for slope stability assessment. In this version, the parameters are adjusted to RQD, J_n, J_r, J_a, J_{wice}, and SRF_{slope} (Barton and Bar 2015). Bar & Barton (2017) presented the Q_{slope} formulation specifically for evaluating slope stability were illustrated in Eq. 2.

$$Q_{slope} = \frac{RQD}{J_n}\left(\frac{J_r}{J_a}\right)\frac{J_{wice}}{SRF_{slope}} \tag{2}$$

In the Eq. 2, J_{wice} represents the environmental and geological condition number, while SRF $_{slope}$ is composed of three strength reduction factors: SRF_a (physical condition number), SRF_b (stress and strength number), and SRF_c (major discontinuity number). The remaining parameters—RQD, J_n, J_r, and J_a—are unchanged from the original Q-system (Barton and Bar 2015). These adjustments tailor the Q_{slope} specifically for assessing rock slope stability, considering both environmental and structural factors (Kouhdaragh et al., 2022). The results of the Q_{slope} method were presented as a stability chart, as shown in Fig. 4. The Q_{slope} has been modified and updated over time based on studies conducted in various regions around the world by different scholars. For Iran, extensive research was conducted by Azarafza et al. (2020;2022b), adapting the method to suit local geological conditions. These modifications have enhanced the system's applicability to diverse environments. In recent years, the Q_{slope} method has gained increasing attention from researchers and professionals due to its simplicity and ease of implementation in the field. It allows for quick primary stability checks and basic calculations for slope stabilization, making it a valuable tool for geo-engineers during preliminary assessments. Its straightforward approach and practical application have contributed to its widespread use in various geological projects.

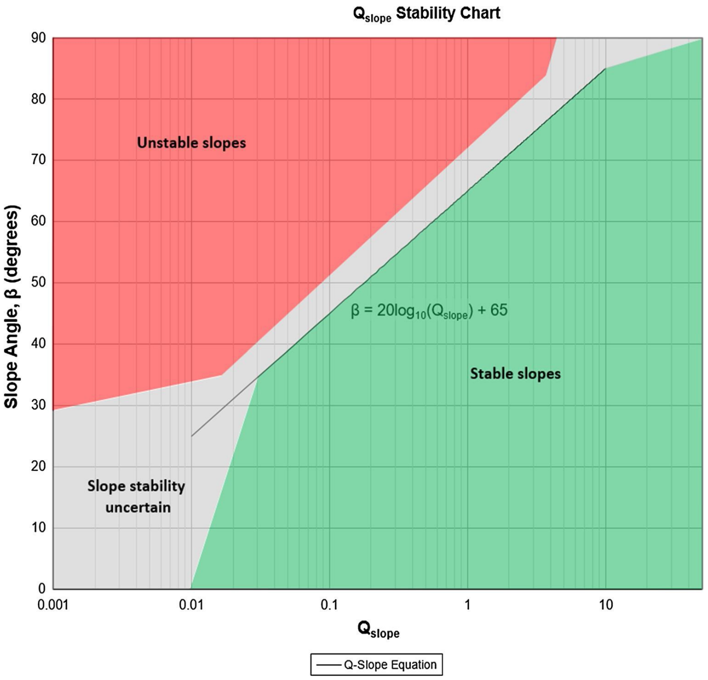


Fig. 4 Q_{slope} stability chart (Bar & Barton, 2017)

IV. STUDIED REGION

The Semirom region is in the southwestern part of Isfahan Province, Iran, and is known for its mountainous terrain and scenic landscapes. Situated at the foothills of the Zagros Mountains, Semirom is characterized by a combination of high altitudes and rolling valleys, making it a region with diverse topographical features. The region is located at an elevation of around 2,200m above sea level, and its terrain includes vast orchards, particularly apple orchards, which Semirom is famous for (Hashemi et al., 2009). The region is bordered by Kohgiluyeh and Boyer-Ahmad Province to the west and Chaharmahal and Bakhtiari Province to the south (Hajehforoshnia & Karam, 2022).

The climate of the Semirom region is classified as cold semi-arid, with significant variations in temperature between the seasons. Winters are long and harsh, with frequent snowfall due to the high altitude, while summers are short and mild. The region receives an average annual precipitation of around 500 mm to 600 mm, most of which falls during the winter and spring months (Yavari et al., 2019). The snow that accumulates during the winter often melts in the spring, contributing to the formation of rivers and streams that nourish the fertile valleys. However, the region can also experience dry spells, particularly in late summer (Hamedanian et al., 2017). The geology of the Semirom region is largely influenced by its location within the Zagros orogenic belt, which is a major tectonic feature in Iran. The area is primarily composed of sedimentary rocks, including limestone, sandstone, and shale, which are indicative of its long geological history. The rock formations in Semirom are typically from the Mesozoic and Cenozoic eras, with extensive folding and faulting due to the tectonic activity in the region (Moghadam & Padyab, 2010). These geological structures contribute to the occurrence of jointed rock slopes, making it an area of interest for geological and geotechnical studies, particularly in assessing slope stability. Figure 5 provides a geological map of studied region.

The Semirom region, being part of the Zagros Mountains, is situated in one of the most tectonically active regions of Iran. This tectonic activity has resulted in complex rock formations, with various folds, faults, and fractures. The predominant rock types in the area include limestones and dolomites, which are prone to karstic processes, creating cavities and underground streams. These formations contribute to the unique geological features of the region, but they also present challenges, particularly in terms of slope stability and infrastructure development (Hashemi et al., 2009).

While the natural beauty and resources of Semirom make it a valuable region, it also faces several environmental and geological challenges (Hamedanian et al., 2017). The steep terrain and tectonic activity make certain areas prone to landslides, rockfalls, and slope instability, particularly in regions with jointed rock formations. Additionally, climate change and fluctuations in precipitation patterns have led to concerns about water scarcity during dry periods. These challenges require careful management and ongoing geological assessments to ensure the stability and sustainability of the region's natural and agricultural resources (Hashemi et al., 2009). The present study attempts to analysis the stability of 12 rock slope in Semirom region were mostly located roadside and developmental areas.

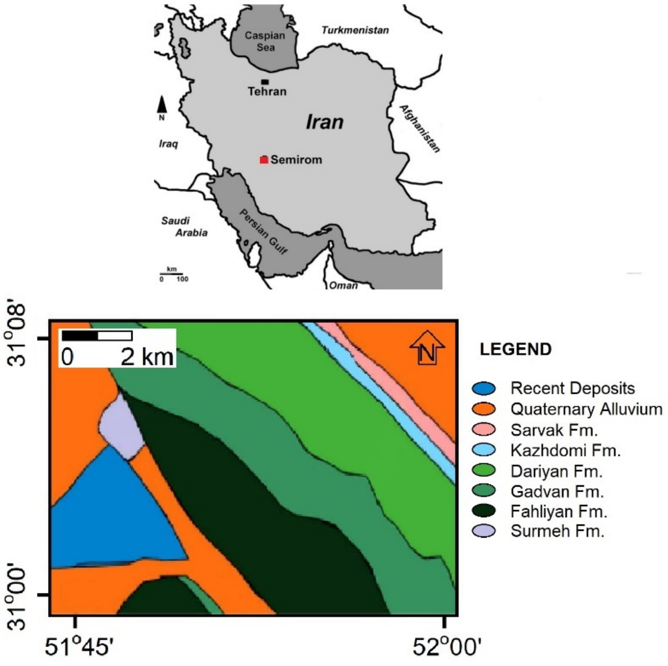


Fig. 5 Geological map of Semirom (Hamedanian et al., 2016)

Fig. 6 A view of one of the slope cases (case 7)

Fig. 7 A view of one of the slope cases (case 12)

V. RESULTS AND DISCUSSION

This study focused on assessing the stability of 12 jointed slopes in the Semirom region, located along a roadside development. The area raised concerns about slope stabilization and the need for proper geotechnical measures. To evaluate the stability of these slopes, the Q_{slope} method was used. During the field survey, key features of the rock masses and their discontinuities were documented for each slope, and Q-values were calculated based on guidelines by Bar & Barton (2017). These values were then applied to an updated chart developed by Azarafza et al. (2020). The results showed that while most of the slopes were either stable or in uncertain condition, two were found to be unstable.

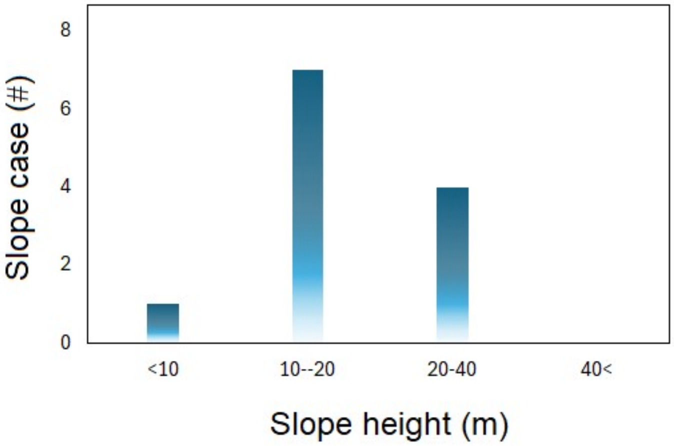


Fig. 8 Height variation for studies slopes

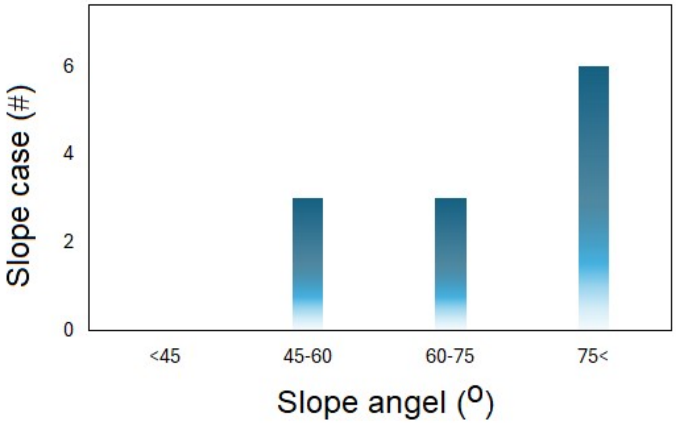


Fig. 9 Slope angle variation for studies slopes

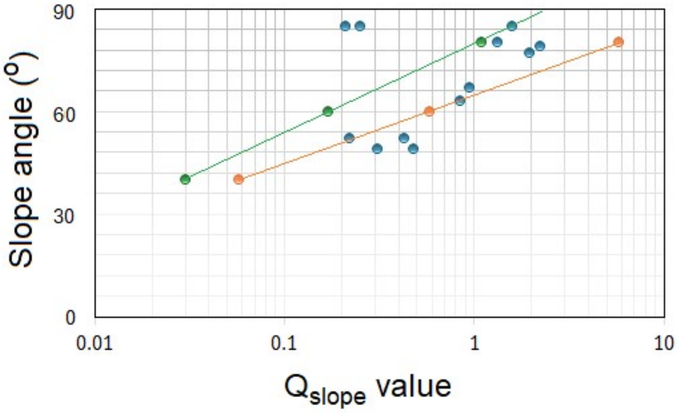


Fig. 10 A view of one of the slope cases (case 7)

Figures 8 to 10 present the results of the stability analysis. According to the findings from the study on the main slopes in the Semirom region and the application of the Q_{slope}, most of the slopes are in an uncertain condition in terms of stability. In such cases, a more detailed and in-depth stability analysis is necessary. For the two slopes identified as unstable, stabilization measures such as slope geometry modification, rock bolting, and other reinforcement methods are recommended.

VI. CONCLUSION

This article aimed to evaluate the stability of slopes in the Semirom region using the Q_{slope} method, a new empirical approach. For this purpose, 12 slopes were selected for analysis. The Q_{slope} method was chosen due to its user-friendly nature, simplicity, and efficiency. Originally developed by Bar and Barton in 2017, it was later adapted for Iranian data by Azarafza et al. in 2020. In this study, the modified version for Iran was applied. The results revealed that most slopes are in uncertain or critical conditions, with two identified as unstable. Therefore, stabilization measures are necessary for these slopes.

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AUTHORS' CONTRIBUTIONS

Alireza Moharami and Mahsa Azadi conducted the main data analysis, contributed to the data collection, preprocessing, interpretation, and were responsible for drafting the initial manuscript. Alireza Moharami assisted in the development of the methodology and performed validation 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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