

Empirical correlation for in-situ deformation modulus of sedimentary rock slope mass and support system recommendation using the Q_{slope} method

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Abstract. This article is dedicated to the pursuit of establishing a robust empirical relationship that allows for the estimation of in-situ modulus of deformations (E_m and G_m) within sedimentary rock slope masses through the utilization of Q_{slope} values. To achieve this significant objective, an expansive and thorough methodology is employed, encompassing a comprehensive field survey, meticulous sample collection, and rigorous laboratory testing. The study sources a total of 26 specimens from five distinct locations within the South Pars (known as Assalouyeh) region, ensuring a representative dataset for robust correlations. The results of this extensive analysis reveal compelling empirical connections between E_m , geomechanical characteristics of the rock mass, and the calculated Q_{slope} values. Specifically, these relationships are expressed as follows: $E_m = 2.859 Q_{\text{slope}} + 4.628$ ($R^2 = 0.554$), and $G_m = 1.856 Q_{\text{slope}} + 3.008$ ($R^2 = 0.524$). Moreover, the study unravels intriguing insights into the interplay between in-situ deformation moduli and the widely utilized Rock Mass Rating (RMR) computations, leading to the formulation of equations that facilitate predictions: $RMR = 18.12 E_m 0.460$ ($R^2 = 0.798$) and $RMR = 22.09 G_m 0.460$ ($R^2 = 0.766$). Beyond these correlations, the study delves into the intricate relationship between RMR and Rock Quality Designation (RQD) with Q_{slope} values. The findings elucidate the following relationships: $RMR = 34.05 e^{0.33 Q_{\text{slope}}}$ ($R^2 = 0.712$) and $RQD = 31.42 e^{0.549 Q_{\text{slope}}}$ ($R^2 = 0.902$). Furthermore, leveraging the insights garnered from this comprehensive analysis, the study offers an empirically derived support system tailored to the distinct characteristics of discontinuous rock slopes, grounded firmly within the framework of the Q_{slope} methodology. This holistic approach contributes significantly to advancing the understanding of sedimentary rock slope stability and provides valuable tools for informed engineering decisions.

Keywords: deformation modulus; geomechanical classification systems; Q_{slope} ; rock mass rating; rock quality designation; rock slope mass; sedimentary rock

1. Introduction

The usage of classification systems is crucial to assess rock mass conditions in geo-engineering design and stability analysis, as well as relate it to a quantitative value. These systems have empirical basis between engineering application and the rock mass conditions, giving a fast and friendly alternative for preliminary and general assessments of tunnels, slopes or any other type of excavation (Harrison and Hudson 2000). Regarding rock slopes, the main parameters involved in risk stability are: height and angle of slope, weathering factor, irregularity, intact rock strength, face looseness, block size joint spacing and presence of water at the slope face (Sullivan 2013, Stead and Wolter 2015). In this regard, there are many different

geomechanical classifications applied in slopes, some of the most important are rock quality designation, RQD (Azarafza *et al.* 2021), rock mass rating, RMR (Bieniawski, 1989), slope mass rating, SMR (Romana *et al.* 2003), slope rock mass rating, SRMR (Robertson, 1988), slope stability probability classification, SSPC (Lindsay *et al.* 2001), continuous slope mass rating, CSMR (Tomás *et al.* 2007), global slope performance index, GSPI (Sullivan 2013), slope stability assessment methodology, SSAM (McQuillan *et al.* 2018), and Q_{slope} (Bar and Barton 2017). These empirical classifications are commonly combined with analytical, kinematic and numerical methods to evaluate the design characteristics (Azarafza *et al.* 2017a, b).

The application of specific slope geomechanical classification systems on various rocks, with different heterogeneity, leads to provide information of basic geo-engineering features of rock masses (Siddique *et al.* 2015, Zheng *et al.* 2016, Azarafza *et al.* 2017c, Francioni *et al.* 2019). These developments were done for the inadequacy of the primary classification systems to analyze slopes due to a lack of definition of its specific characteristics and a wide range of the correction factors. On the other hand, using empirical classification systems help to provide

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efficient information about rock mass and act fast in early stages of excavations or construction.

In this regard, Q_{slope} is one of the more recent classification systems, developed by Bar and Barton (2017) and modified by Azarafza *et al.* (2020a). The classification is able to provide rapid information about discontinuous rock slope stability based on simple assumptions (Barton and Bar 2015). This advantage gives a huge flexibility to Q_{slope} and some other classifications like SMR (Jorda-Bordehore *et al.* 2018, Maion 2019, Azarafza *et al.* 2020b), SSAM (Bar and McQuillan 2021), or CSMR (Siddique *et al.* 2021). Thus, the usage of these combined procedures gives some important advantages in slope analysis (Azarafza *et al.* 2021). The capability of the Q_{slope} allow to use it in a large variety of slope stability cases worldwide, but the system still can have further advancements on the characterization of the rock mass features.

The presented study is focused on estimating the rock mass deformation modulus, elastic modulus (E_m) and shear modulus (G_m), by using the Q_{slope} . Besides, the relationship between various classification systems, Q_{slope} and in-situ deformation modulus are determined using an empirical regression analysis. So, based on the outlined study objectives, it is evident that the primary goal of this investigation is to assess and establish the most effective correlations among in-situ deformation modules pertaining to sedimentary rocks. This will be achieved through the utilization of experimental methodologies, with particular emphasis on the Q_{slope} approach. Furthermore, within this research endeavor, there is a deliberate intention to formulate an appropriate protective mechanism for rock slopes under various failures. This proposed support system will be meticulously developed, taking into account the inherent stability traits exhibited by the Q_{slope} structure. In this context, it becomes evident that this article strives to address the limitations inherent in the Q_{slope} method. Through a comprehensive analysis, it endeavors to establish empirical correlations rooted in the Q_{slope} stability number. This involves not only discerning potential rupture patterns but also devising an appropriate support system tailored to accommodate the unique stability requirements of the rock slope mass.

2. Case study

2.1 Geological and geo-structural setting

The South Pars (known as Assalouyeh) region is located in southwest Iran and lies about 300 km southeast of Bushehr City at Bushehr province. Fig. 1 is provided information about South Pars location in Iran. The South Pars region is limited by Assalouyeh anticline at north-line and Persian Gulf at the south-line, which is mostly, covered by Quaternary deposits (recent alluviums) and rocky outcrops formations from Triassic to Upper-Pliocene at north. There are older geological formations in the area studied, Upper-Precambrian, but not exposed to the surface and, therefore, out of the scope of this research. The sedimentary rocks belong to the post-Asmari (Eocene-

Oligocene) like Mishan, Aghajari, Bakhtiari formations, composed by limestones, marlstones, and claystones (Azarafza *et al.* 2019). The geological background of South Pars indicates that the complex tectonical created important folding, faults and intense discontinuity network in rock masses which effected slope stability conditions (Aghanabati 2007).

Based on field survey conducted on the South Pars region, the major part of geological formation outcrops in these parts is sedimentary rocks that belong to Mishan (grey and cream marls), Aghajari (marlstones, limestone, sandstone), Bakhtiari (conglomerate, sandy marly conglomerates) formations. The Mishan Formation, a compositionally and strata mixed siliciclastic-carbonate succession (Chiarella *et al.* 2017), includes the youngest hydrocarbon reservoir (Guri member) in the southeast of the Zagros basin. It consists of carbonate and marl alternations in the lower part passing into marl dominated middle part with carbonate intercalations grading upward to an upper part characterized by marl and coarse siliciclastic alternations with carbonate intercalations. The Aghajari Formation, called also the Upper Fars, develops throughout the Folded Zagros Zone and its thickness in the type section in southwest of Iran is 2966 m (Zabihi Zoeram *et al.* 2014). Quaternary deformation (uplift and compression) led to the accumulation of Bakhtiari Formation conglomerates with varying thickness, reaching 2500 m in some areas in the Zagros zone (Shafiei and Dusseault 2008). Alavi (2004) interpreted the Bakhtiari Formation conglomerate as the proximal facies of the wedge-topdepozone formed atop the frontal part of southwestward-propagating Zagros thrust sheets, which are covered locally by modern alluvial deposits.

These formations replaced with recent alluvial in the region. Fig. 2 is provided the geological map of the studied area. As seen in this map, rocky outcrops are located in north part and alluvial are located in south part of studied area. In this regard, the main focuses of the study is related to the north part that slopes are emplaced. In term of geo-structural survey, South Pars region is divided in to the alluviums flat and rocky mountain related to the Assalouyeh anticline. This division related to the tectonic activity of the region that under Arabian-Central Iranian plates convergence. This movement lead to various anticlines-synclines, folding, faults and a thrusts with general NW-SE strike (Nogol-Sadat and Almasian 1993). Although this trend is generally observed throughout the region, but there are trends such as NE-SW and NN-SS are recorded in the region as well (Aghanabati 2007). The Assalouyeh fault and the mountain front fault are the main faults in region that responsible for various geo-structures deformations. These faults are affected by the Zagros regional faults activities that triggered by plate tectonical actions (Nogol-Sadat and Almasian 1993). These faults triggered the main discontinuity emplacements on South Pars region. Fig. 3 is provides the information about information about main rose-diagram of the discontinuities in the South Pars region. According to this figure, mainly there are four systematic discontinuity sets with non-systematic joints obtained from the field survey for the studied area. These discontinuities



Fig. 1 Location of South Pars (Assalouyeh) region in Iran

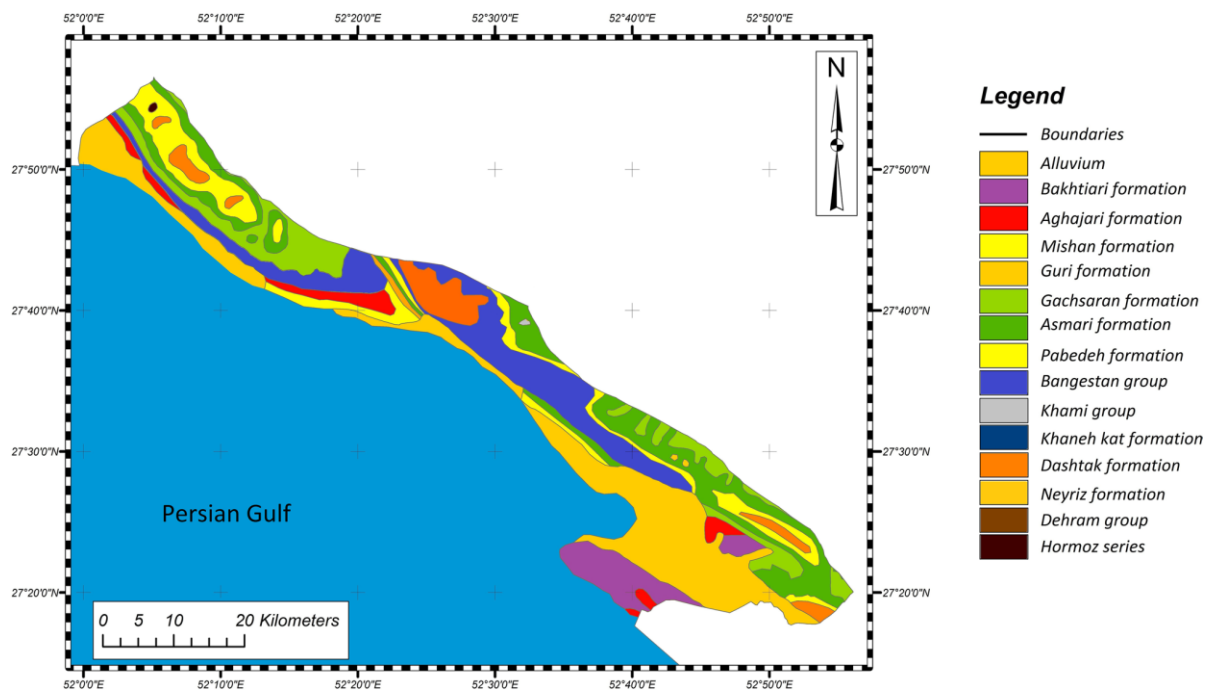


Fig. 2 Geological map of South Pars region (adapted from the Geological Survey of Iran 2009)

are holed by the rocks that range from high-weathered to slightly-weathered. The main orientation of the discontinuities is mostly parallel with NW-SE strike. The NE-SW and NN-SS strikes can be observed with less intensity. This discontinuity density has affected the instability of various geo-structures and slopes in the region and has increased the failure potential.

2.2 Engineering geological survey

Regarding to the engineering geological investigation in studied region, the full-scale site investigation has been conducted. During the field survey, totally 26 specimens are gathered from 5 stations to performing laboratory tests on rocks. These samples belong to the 26 slopes. The points

were chosen based on geological variations and geo-unit condition of different sedimentary rocks. The RQD is measured by field surveying; recording discontinuity volume and rock block condition at the rock slopes (Palmerstrom 2005). Definition of rock quality based on the RQD that estimated from the field ($RQD = 115-3.3 J_v$) indicated that the rock quality is varied 36% from to 64.3%. This variation can be represents the degree of weathering and rock blocks status properly. By using RMR and Q_{slope} classification systems (Bieniawski 1989, Bar and Barton 2017), the general conditions of the slopes was investigated. Table 1 is provided the summary information about geomechanical classification conducted on studied slopes. Referring to this table, the estimated RMR and Q_{slope} are appeared that the main trend of the slopes is from ‘Poor to

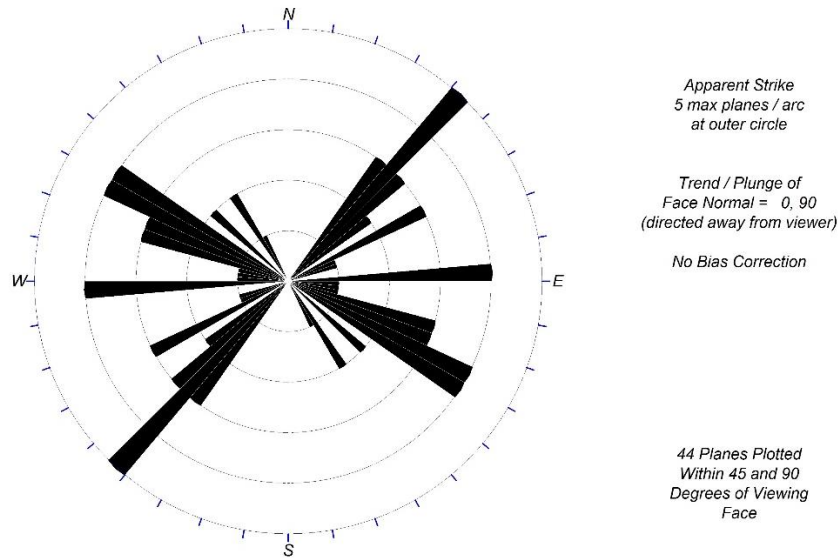


Fig. 3 General rose-diagram for South Pars region (Azarafza *et al.* 2017b)

Table 1 A summary of the geomechanical classification estimated for South Pars region

Classifier	Description	Max	Min	Mean	SD [†]	CV [‡]
RQD	Poor to Fair	64.3	36	50.15	8.271	16.49
RMR	Poor to Fair	52	34	43	5.820	13.53
Q _{slope}	Unstable to Stable	1.17	0.13	0.65	0.301	46.30

[†] Standard deviation; [‡] Coefficient of variation

Fair' which is indicated the varied condition for rock materials. As depicted in the provided table, the geomechanical attributes ascribed to the rock masses fall within the realm of weak to moderate classifications which is ranged from Poor to Fair for RQD and RMR. RQD is ranged from 36.0 to 64.3 and for RMR is ranged from 34 to 52. The evaluation is providing information regarding Q_{slope} value (Q-number) which is located in range from 0.65 to 1.17 for studied slopes. This issue predominantly hinges on the stone's inherent texture and the prevailing pace of weathering within the region. Weathering, a natural process driven by environmental factors, profoundly influences the durability and stability of rock masses. This process entails both physical and chemical changes to rocks over time due to exposure to elements like water, temperature fluctuations, and chemical reactions. Physically, weathering results in cracks, fractures, and particle disintegration, while chemically, it alters mineral compositions and weakens structures. Such weathering-induced changes diminish the overall strength and stability of rock masses. Consequently, engineers must meticulously consider weathering effects when designing structures involving rock masses, as the extent of weathering greatly impacts the performance and longevity of these formations.

During the field survey, several samples was taken and transferred to the laboratory for conducting tests that revealed geo-engineering characteristics. To estimate the engineering geological properties of the specimens various geotechnical tests were used. The carbonate content

determination (ASTM D4373), uniaxial compressive strength testing (ASTM D7012), and laboratory direct-shear testing (ASTM D5607) are used as basic geotechnical tests to estimate the geo-engineering features.

Regarding investigation that conducted in various types of sedimentary rocks from South Pars region, the geotechnical properties of rock materials are categorized based on geological origin and presented in Table 2. According to Table 2 gathers the geotechnical properties of the sedimentary rock, which displays a wide range of variation. Regarding to this table, it is indicated that the there is a strong link between the geotechnical properties and carbonate content in the geo-units. On the other hand, the porosity was reduced from limestone to claystone in studied area. As the main stiffness parameters like E, UCS and G, the limestone shows high values than marlstone and claystone. Fig. 4 is shows the relation between UCS and E_i values. With respect to this figure, it can be stated that the CS values obtained from samples was strongly increased with intact rock's elastic modulus.

3. Methodology

In the realm of slope engineering and rock mechanics, achieving a proper design entails a comprehensive understanding of both fundamental intact rock properties and the characteristics of the rock mass. However, obtaining these essential properties directly from site measurements

Table 2 The geotechnical characteristics of rock materials from South Pars region

Rock type	Parameters	Max	Min	Mean	SD [†]	CV [‡]
Limestone	Specific gravity, G_s	2.94	2.38	2.66	0.39	14.88
	Dry unit weight, γ_d (kN/m ³)	25.25	21.10	23.17	2.93	12.66
	Saturated unit weight, γ_t (kN/m ³)	23.95	22.44	23.19	1.06	4.603
	Porosity, n (%)	15.11	8.70	11.90	4.53	38.07
	Carbonate content, CC (%)	82.3	41.5	61.90	28.84	46.60
	Water content, WC (%)	6.84	2.55	4.69	3.03	64.61
	Cohesion, c (kPa)	310	140	225	12.24	54.53
	Elastic modulus, E_i (GPa)	35.5	17.00	26.25	6.44	24.53
	Shear modulus, G_i (GPa)	17.42	6.00	11.71	3.37	28.77
	Internal friction, ϕ (degree)	35	19	27	11.31	41.90
Uniaxial compressive strength, USC (MPa)	42	27	34.5	10.60	30.74	
Marlstone	Specific gravity, G_s	2.63	2.45	2.54	0.12	5.01
	Dry unit weight, γ_d (kN/m ³)	23.71	20.00	21.85	2.62	12.03
	Saturated unit weight, γ_t (kN/m ³)	21.21	18.94	20.07	1.60	7.998
	Porosity, n (%)	23.44	8.70	16.07	10.42	64.85
	Carbonate content, CC (%)	63.5	27.6	45.5	25.38	55.73
	Water content, WC (%)	7.93	4.07	6.00	2.72	45.49
	Cohesion, c (kPa)	170	120	145	35.35	24.38
	Elastic modulus, E_i (GPa)	22.5	14.7	18.6	5.15	29.65
	Shear modulus, G_i (GPa)	8.5	5.6	7.05	2.05	29.08
	Internal friction, ϕ (degree)	30	16	23	9.89	43.04
Uniaxial compressive strength, USC (MPa)	35	14	24.5	19.79	60.71	
Claystone	Specific gravity, G_s	2.54	2.39	2.46	0.163	4.302
	Dry unit weight, γ_d (kN/m ³)	20.67	18.11	19.39	1.81	9.345
	Saturated unit weight, γ_t (kN/m ³)	22.76	19.00	20.88	2.65	12.74
	Porosity, n (%)	25.81	10.59	18.20	10.76	59.13
	Carbonate content, CC (%)	38.4	21.1	29.7	12.23	41.11
	Water content, WC (%)	9.36	5.33	7.35	2.84	38.79
	Cohesion, c (kPa)	130	100	115	21.23	18.44
	Elastic modulus, E_i (GPa)	19.6	12.3	15.95	5.16	32.36
	Shear modulus, G_i (GPa)	12.7	7.9	10.3	3.39	32.95
	Internal friction, ϕ (degree)	35	20	27.5	10.68	38.56
Uniaxial compressive strength, USC (MPa)	15	9.3	12.1	4.03	33.17	

[†] Standard deviation; [‡] Coefficient of variation

can be a challenging endeavor. Therefore, the availability of reliable indirect approaches becomes crucial to accurately define these characteristics, ensuring the stability and safety of rock slopes and structures. A slope, subjected to various external forces and environmental conditions, can experience a range of stress responses, which in turn induce strains that have the potential to undermine its stability over time. Deformation, often characterized as a change in shape or configuration, arises in response to factors such as applied loads, stress distributions, temperature fluctuations, or alterations in water content within the rock mass (Mao *et al.* 2023). Notably, the extent of deformability is largely influenced by the weakest components within the rock, with porosity and jointing playing predominant roles in determining the overall response to these factors (Harrison and Hudson 2000). So, deformability in a rock mass encapsulates its response to applied stresses and resultant strains, impacting its structural integrity. This concept holds paramount significance in geotechnical engineering, governing the design and stability assessment of structures like tunnels and slopes (Wu *et al.* 2019). Core to

deformability calculations are parameters that characterize the rock mass' behavior under varying loads (Ryu and Um, 2020). Key parameters for quantifying deformability include the deformation modulus (E_i or E_m), elucidating the rock mass' stiffness and its strain response to stress (Harrison and Hudson 2000). Poisson's Ratio (ν), denoting the ratio of lateral to axial strain, sheds light on the rock mass' lateral contraction under axial compression. Another significant parameter is the shear modulus (G), gauging a rock mass' resistance to shear deformation, vital for analyzing sliding along rock joints or faults (Bieniawski, 1989). Determining these parameters is achieved through lab tests, in situ measurements, or empirical correlations based on geological data. Linear elastic models are often employed for initial assessments, while more intricate numerical techniques like finite element analysis address complex interactions among rock blocks and joints for a comprehensive understanding of deformations. It's crucial to acknowledge that non-linear behaviors might arise under extreme conditions, demanding advanced models that factor in such complexities (Azarafza *et al.* 2021b). Consequently,

grasping deformability intricacies equips engineers to predict and manage deformations effectively, thus upholding the stability of rock structures.

In this context, stiffness parameters emerge as pivotal aspects for the meticulous design and analysis of rock structures. Key among these parameters is the elastic modulus (E), which signifies the material's resistance to deformation under stress. Another crucial factor is Poisson's ratio (ν), which denotes the ratio of orthogonal strain response to an applied stress. These parameters, along with other associated characteristics like axial strain response to uniaxial stress, contribute significantly to comprehending the behavior of rock under different conditions (Clayton 2011, Atel and Martin 2018). These stiffness parameters subsequently facilitate the determination of additional vital variables that play a substantial role in rock mechanics. These include the bulk modulus (K), which gauges the material's response to changes in pressure, the shear modulus (G), which quantifies the material's resistance to shear deformation, and the Lamé's modulus (λ), an indicator of a material's compressibility and shear resistance. As such, it can be contended that two of the most critical intact rock mechanical parameters are the Young's modulus and Poisson's ratio. These parameters are particularly pivotal when considering a linear elastic continuum isotropic material (Kincal and Koca 2019) together with the rock mass characteristics, E_m and G_m (Vásárhelyi and Kovács 2017).

There are many analytical and empirical relationships to characterize the slope mass. For instance, Bieniawski (1978) and Serafim and Pereira (1983) use the RMR to define an equation for the E_m considering different rock mass qualities, while Grimstad and Barton (1993) used the Q-system. Palmstrom and Singh (2001) defined a relationship between uniaxial compression strength and Young's modulus of the intact rock, while Ván and Vásárhelyi (2010) presented a similar approach for the rock mass homologous values using the RMR. In addition, Davarpanah *et al.* (2020) gather some interesting review and propose relationships among the critical mechanical properties of different rock types. These expressions have been modified by many different researchers (Sanei and Faramarzi 2014), as well as using other classification systems like the geological strength index, GSI (Hoek and Diederichs 2006). The advantages of using rock mass classification systems to estimate the E_m and G_m values are the economical and easiness of the approach (Kincal and Koca 2019). These parameters are usually obtained using the existing empirical equations based on RMR or Q systems, applied at the early stages of rock mass geotechnical investigations. Such indirect approaches to define rock mass characteristics usually give adequate results compared to in-situ tests (Clerici 1992). However, it is recommended to use more than one approach to verify its reliability. The use of explosives in mining or civil excavations can also reduce the rock mass quality at the surface, generating disturbed zones with the creation of fractures, the aperture on natural joints and the movement of blocks, being necessary to consider its potential affection in each case for the geomechanical characterization (Hoek *et al.* 2002).

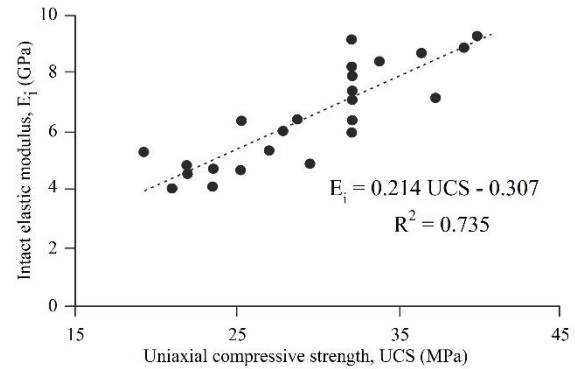


Fig. 4 The relationship between UCS and E_i values for studied samples

Aside from the aforementioned research, the presented study attempts to provide an empirical link between Q_{slope} and stiffness parameters. There is comprehensive study performed in South Pars region in Iran regarding field survey, sampling and geo-mechanical investigation, having a total of 26 specimens from 5 points of South Pars region.

The specimens were subjected into geomechanical index tests such as uniaxial compressive strength (UCS) and direct-shear tests according to the ASTM D7012 and ASTM D5607, respectively. The intact rock elastic modulus (E_i) is estimated under UCS test, with strain monitoring stages based on measure mean value of the tangent elasticity modulus (E_{tan}) and 50% of the UCS (E_{50}) from the stress-strain variation curve. The engineering classification based on Q_{slope} requirements is described for the studied region. The Q_{slope} value is estimated by using the Q_{slope} number was estimated directly by using both Bar and Barton (2017) and Azarafza *et al.* (2020) relationships.

Results were statistical analyzed using ordinary and least squares regression analysis in order to obtain the correlations. The empirical relationships are obtained based on best-fitting line and fit equations. Developed relationships are controlled by coefficient of determination (R^2) given as the correlation ratio between the measured data. The error rates of the evaluation are estimated by using mean squared error (MSE), and root-mean square error (RMSE). MSE and RMSE are known as statistical risk function that corresponds to the expected value of the squared error loss. The error rates were calculated based on empirical equations obtained from ground data. The R-square and error rates control the performance and accuracy of the estimated relations for stiffness parameters and Q_{slope} value.

3.1 Principal of Q_{slope}

The Q_{slope} is originated based on the Q-system, developed by Barton *et al.* (1974), involves assigning a Q-value to a rock mass based on parameters such as rock quality designation (RQD), spacing of discontinuities, condition of discontinuities, groundwater conditions, and orientation of discontinuities. The Q-value indicates the overall quality and stability of the rock mass. The Q-system is widely used in tunneling and underground excavations.

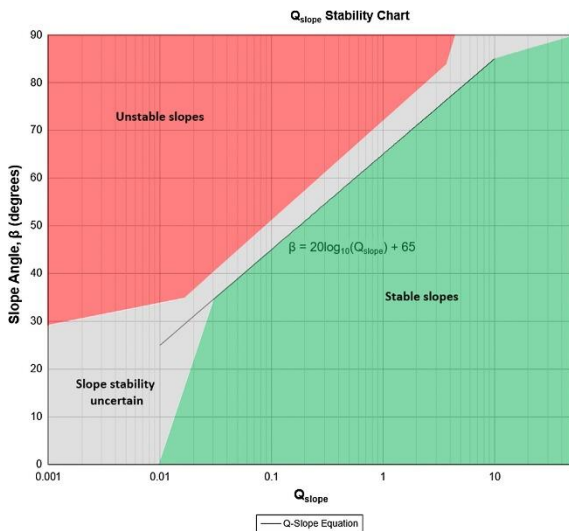


Fig. 5 The Q_{slope} stability chart (Bar and Barton 2017)

The Q_{slope} approach presents an empirical technique designed to assess the stability of slopes, building upon the Q-system framework. This method relies on a stability chart, illustrated in Fig. 5 (Bar and Barton 2017), which was further refined by Azarafza *et al.* (2020a). Central to the methodology is the Q_{slope} value, a correlation elucidated in Eq. 1) by Bar and Barton (2017), which intricately incorporates pivotal components such as the shear-force element (J_r/J_a), block size (RQD/J_n), and the external loading or stress factor.

$$Q_{slope} = \frac{RQD}{J_n} \left(\frac{J_r}{J_a} \right) \frac{J_{wice}}{SRF_{slope}} \quad (1)$$

where, RQD is rock quality designation, J_n is discontinuity set number, J_r is discontinuity roughness, J_a is discontinuity alteration, J_{wice} is environmental-geological condition rate, and SRF_{slope} is strength reduction factor (Kouhdaragh *et al.* 2022, Ao *et al.* 2023). Devised to offer stability assessments for rock slopes using constrained on-site data, this approach finds widespread utilization among diverse geotechnical engineers on a global scale, across various projects. The Q_{slope} method furnishes dependable insights into the stability status of rock slopes, irrespective of the extent of potential failures. However, it does not encompass factors like failure types, mechanisms, and support systems. The study at hand endeavors to propose a support system recommendation within the framework of the Q_{slope} system.

3.2 Q_{slope} based stability analysis

The Q_{slope} method is an empirical approach used for stability analysis of rock slopes. It's an extension of the Q-system, which is a rock mass classification system developed for tunneling and underground excavations. The Q_{slope} method focuses on providing a simplified yet practical way to assess the stability of rock slopes in various geological conditions and projects (Jordá-Bordevore 2017). Geotechnical engineers can use the Q_{slope} method to calculate a Q_{slope} value based on the modified Q-system information and the additional factors mentioned above.

This Q_{slope} number (Eq. (1)) is used to determine the overall stability condition of the rock slope. A higher Q_{slope} number generally indicates better stability, while a lower number suggests potential instability under various slope angles (see Fig. 5). While the Q_{slope} method provides a practical tool for preliminary stability assessments of rock slopes, it's important to note its limitations. Q_{slope} does not cover details related to specific failure types, mechanisms, or support systems. Therefore, while it can offer valuable insights into stability, it's often used as a part of a broader analysis that might include more detailed numerical modeling and consideration of specific failure modes. In essence, Q_{slope} -based stability analysis offers a quick and pragmatic approach for assessing the stability of rock slopes in various projects worldwide. It's particularly useful when detailed site-specific data might be limited, but it's important to consider the method's scope and complement it with more comprehensive analyses as needed.

3.3 Regression analysis

Regression analysis is a statistical technique utilized to investigate the connection between one or more independent variables and a dependent variable. It aims to quantify the influence of the independent variables on the outcome of interest. Linear regression is a fundamental form that assumes a straight-line relationship between variables, while multiple regressions extend this to consider multiple predictors simultaneously. In contrast, logistic regression is employed for binary classification tasks, estimating the probability of an input belonging to a particular category. Polynomial regression accommodates nonlinear relationships, and techniques like ridge and lasso regression address multicollinearity issues (Braun and Oswald 2011). Regression analysis entails determining the coefficients that optimize the fit of the regression equation to the data, often using optimization algorithms. Model performance is assessed through metrics like the R-squared value, indicating the proportion of variance explained by the model (Montgomery *et al.* 2021). Widely applicable across disciplines such as economics, social sciences, and engineering, regression analysis serves to predict outcomes, understand variable relationships, and unveil data patterns (Liang and Zeger 1993).

Regression analysis for correlated data which is used in this article as well as most geotechnical application commonly referred to as longitudinal or repeated measures regression, addresses scenarios where observations are not independent and may exhibit correlation or dependency.

This type of analysis is particularly useful when studying data collected from the same subjects over multiple time points or conditions (Montgomery *et al.* 2021). It enables researchers to model and account for the inherent correlations between measurements, providing more accurate and nuanced insights into the relationships between variables. By considering the within-subject correlations, longitudinal regression techniques can offer a clearer understanding of how changes in independent variables are associated with changes in the dependent variable over time or across conditions. This approach is

widely employed in fields like medicine, psychology, and social sciences, where data points are linked by virtue of their origin from the same subjects or entities, allowing for a more comprehensive exploration of dynamic patterns and trends.

Regression analysis for correlated data in the context of rock slope analysis offers several advantages and comes with certain limitations. On the advantageous side, this approach recognizes and accounts for the inherent dependencies or correlations among measurements taken from the same rock slope over time or under varying conditions. By considering these correlations, it provides a more accurate understanding of how changes in influencing factors affect the stability of the slope. This is particularly valuable in the field of rock slope engineering, where factors like weather conditions, geological shifts, and support system effectiveness can exhibit temporal variations. By capturing these intricacies, correlated data regression enables engineers and researchers to develop predictive models that better reflect real-world conditions, enhancing the precision of stability assessments and risk predictions. However, this approach is not without its limitations. One significant challenge is the need for a substantial amount of high-quality longitudinal data, which can be resource-intensive to collect. Additionally, the complexity of the analysis and interpretation increases with the presence of multiple correlated variables. Handling missing data and selecting appropriate correlation structures can also be demanding tasks. Furthermore, while correlated data regression captures dependencies, it might not always uncover the underlying causal relationships between variables. Despite these limitations, when carefully applied, regression analysis for correlated data provides a powerful tool for understanding the dynamic behavior of rock slopes and aiding in effective slope stability management strategies.

4. Relationship between Q_{slope} and geotechnical index values

Some of the key factors in safe design of slope stability, or controlling its instability, are the geotechnical characteristics, especially stiffness parameters (rock mass elastic and shear modulus, E_m and G_m) and discontinuity network. The mean values of elastic and shear modulus were obtained from the samples used to estimate the empirical relation between the material properties and geotechnical indexes (Table 3). Besides, the main conditions of the rock slopes are investigated using data from Table 3 and the existing experimental relations gathered in Table 4. After providing basic information about the stiffness parameters, it is necessary to evaluate the E_m and G_m by using field correction.

Referring Table 3 it can be stated that, the empirical relations often help engineers and researchers make quick estimations or predictions about various rock mass characteristics without the need for complex numerical modeling. These relations are developed through statistical analysis of collected field data from various rock

Table 3 The empirical relations for geotechnical indexes in South Pars sedimentary rocks

Relationship	Unit	R ²	MSE	RMSE
$\gamma_d = 0.1 \text{ CC} + 18.5$	kN/m ³	0.994	0.13840	0.14286
$\gamma_t = \text{CC} + 21.7$	kN/m ³	0.951	0.10763	0.13274
$\text{UCS} = 0.3 \text{ CC} + 11.7$	MPa	0.969	0.11506	0.11989
$c = 2.5 \text{ CC} + 26$	kPa	0.935	0.24649	0.21455
$\phi = 0.11 \text{ CC} + 23$	degree	0.945	0.20065	0.24887

engineering projects, laboratory tests, or case studies (Azarafza *et al.* 2020a). Empirical relations can cover a wide range of topics related to rock mass behavior, stability, and properties (Singh and Goel 2011, Kincal and Koca 2019). Empirical relations serve as practical tools for engineers and practitioners, allowing them to quickly estimate or predict rock mass behavior and characteristics. However, it's important to recognize that empirical relations have limitations, especially when applied outside the specific range of conditions for which they were derived. They should be used with caution and ideally validated against site-specific data whenever possible. On the other hand, they possess limitations that necessitate cautious application. These relations are often developed within specific geological contexts or projects, making their utility reliant on similar conditions. Their lack of mechanistic insight can compromise accuracy when conditions diverge from the original dataset. Empirical relations are sensitive to data quality, necessitating comprehensive and accurate data collection. They may yield non-unique solutions due to simplifications, and their applicability might be restricted to a particular range of parameters. Changing geological conditions and anisotropy can further challenge their reliability. Despite these constraints, empirical relations remain useful for preliminary assessments, yet their context and limitations must be carefully considered, with site-specific data validation preferred whenever feasible. To address the constraints and minimize uncertainties associated with empirical methodologies, a range of statistical techniques are employed. MSE and RMSE are one of the well-known statistical metrics commonly used to quantify the accuracy of predictive models or empirical relations by measuring the differences between predicted values and actual observed values. In the context of rock slope stability empirical relations, these metrics play a pivotal role in assessing the reliability of predictions. By calculating MSE and RMSE, engineers can gauge how well the empirical relation aligns with observed data. Lower values indicate a better fit, prompting the identification of potential model improvements. These metrics aid in model selection, parameter refinement, and ultimately guide the process of enhancing the accuracy and precision of empirical relations used in rock slope stability analysis.

Regarding Table 4, the main part of empirical relations used in the estimation of E_m and G_m are established on RMR and RQD. So, it is indicated that these classifications play a key role in the estimation of in-situ deformation modulus. Initially, the relation between RMR and Q_{slope} was

Table 4 Summary of deformation modulus and geomechanical classifications relation

Index	Relation	Rock types	Reference
RQD	$E_m/E_i = 0.231 (RQD) - 1.32$	Granite, gneiss, limestone, sandstone	Coon and Merritt (1970)
	$E_m/E_i = 0.15$	General rocks	AASHTO (1989)
	$E_m/E_i = 10^{0.0186RQD - 1.91}$	General rocks	Zhang and Einstein (2004)
RMR	$E_m = 2RMR - 100$	General rocks	Bieniawski (1978)
	$E_m = 10^{(RMR - 10)/40}$	General rocks	Serafim and Pereira (1983)
	$E_m/E_i = [0.0028RMR^2 + 0.9e^{RMR/22.82}]/100$	Napa basalts, quartzite, amphibole	Nicholson and Bieniawski (1990)
	$E_m = 300 \times 10^{-3} \exp(0.007RMR)$	General rocks	Kim (1993)
	$E_m/E_i = [1 - \cos(\pi \times RMR/100)]/2$	General rocks	Mitri <i>et al.</i> (1994)
	$E_m = \exp(4.407 + 0.081RMR)$	Sedimentary rocks	Jasarevic and Kovacevic (1996)
	$E_m = 0.0097RMR^{3.54}$	General rocks	Aydan <i>et al.</i> (1997)
	$E_m = 10^{[(RMR - 20)/38]}$	General rocks	Verman <i>et al.</i> (1997)
	$E_m = 0.1 (RMR/10)^3$	Greywacke, sandstone	Read <i>et al.</i> (1999)
	$E_m = 0.736e^{0.0755RMR}$	Quartzdiorite, limestone, marlstone	Gokceoglu <i>et al.</i> (2003)
	$E_m/E_i = e^{(RMR - 100)/17.4}$	Genesis	Ramamurthy (2004)
	$E_m = 0.0876RMR$	General rocks	Galera <i>et al.</i> (2005)
	$E_m/E_i = 10^{[(RMR - 100)(100 - RMR)/4000 \exp(-RMR/100)]}$	Greywacke, agglomerate	Sonmez <i>et al.</i> (2006)
	$E_m = 110 \exp[-((RMR - 110)/37)^2]$	General rocks	Shen <i>et al.</i> (2012)
	$E_m = 9 \times 10^{-7}RMR^{3.868}$	Phyllite, schist, sandstone, dolomite	Khabbazi <i>et al.</i> (2013)
	$RMR = 30.652 \times E_m^{0.6216}$	Basalts, tuffites, diabases	Alemdag <i>et al.</i> (2015)
	$RMR = 38.043 \times E_m^{0.3291}$	Andesite, Agglomerate, claystone, sandstone, conglomerate, shale	Kincal and Koca (2019)
Q-system	$E_m = 25 \log Q$	General rocks	Barton (1983)
	$E_m = 10Q^{1/3}$	General rocks	Barton (1995)
	$E_m = 8Q^{0.4}$	General rocks	Palmstrom and Singh (2001)
	$E_m = 10^{(0.32 \log Q + 0.585)}$	General rocks	Kang <i>et al.</i> (2013)

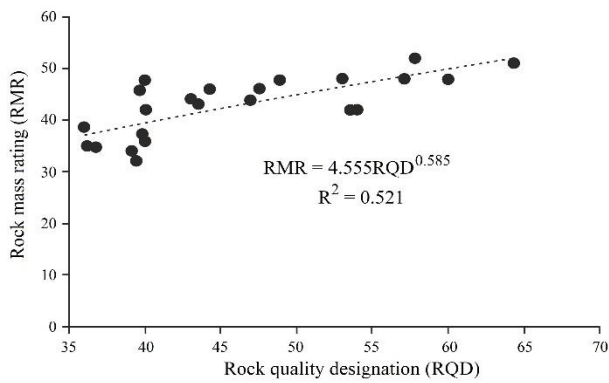


Fig. 6 RMR values versus RQD for South Pars sedimentary rocks

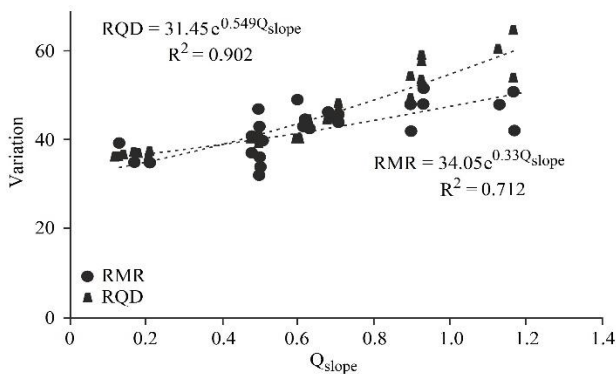


Fig. 7 RMR, RQD values versus Q_{slope} for South Pars sedimentary rocks

determined and correlated based on experimental relations and results of the intact rock laboratory tests. Fig. 6 displays the RMR and RQD relations, which were estimated during field survey. According to these figures, the relations between RMR and RQD for South Pars sedimentary rock can be describe as Eq. (1). By investigating the correlation between these classifications with Q_{slope} , the relations between the RMR, RQD and with Q_{slope} can be obtained and explained as Eqs. (2) and (3). The variation graph of the geo-mechanical classifications is provided in Fig. 7. Obtaining that the RQD and RMR values increase as the Q_{slope} values increase. R^2 coefficients obtained for RMR are much lower than RQD, but both relations follow the similar trend.

The exponential and power trend-line obtained from RMR and RQD values from Fig. 7 provides a direct link between these classifications. After obtaining the empirical relations between classifications, the Q_{slope} and in-situ deformation modulus can be estimated.

$$RMR = 4.555 RQD^{0.585} , R^2 = 0.521 \quad (2)$$

$$RMR = 34.05e^{0.333Q_{slope}} , R^2 = 0.712 \quad (3)$$

$$RQD = 31.45e^{0.549Q_{slope}} , R^2 = 0.902 \quad (4)$$

The correlation between the rock mass deformation modulus and intact rock modulus is presented in Figs. 8 and 9. E_m , G_m expressions, and their comparisons with E_i , G_i ,

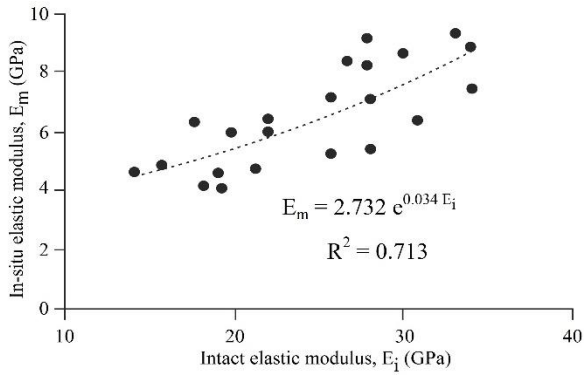


Fig. 8 The variation graph for E_m , E_i relationship of South Pars sedimentary rocks

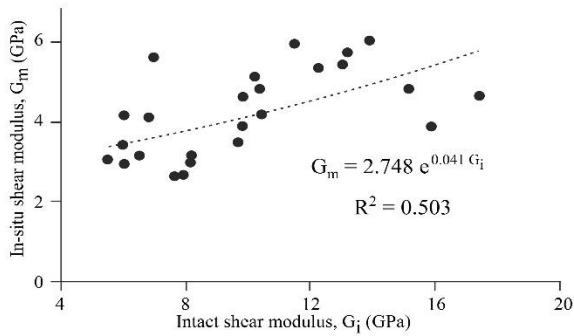


Fig. 9 The variation graph for G_m , G_i relationship of South Pars sedimentary rocks

are illustrated in these figures, obtaining exponential relations as illustrated in Eq (4) and (5). The curves of these expressions show a general trend of variation, which indicates the increase of E_m and G_m regarding E_i and G_i .

$$E_m = 2.732e^{0.034E_i} , R^2 = 0.713 \quad (5)$$

$$G_m = 2.748e^{0.041G_i} , R^2 = 0.503 \quad (6)$$

The definition and measurement of the deformation modulus in sedimentary rock mass is more difficult than in other geo-units, like igneous rocks, due to the difficulty to define the discontinuity network and weathering conditions. In this regard, the RMR classification was calculated to cover the joints' condition and degree of weathering in the studied rock slopes. Figs. 10 and 11 provide the RMR variation obtained for rock mass, which is used to correlate the deformation modulus in sedimentary rock slopes. The following overall relationships were presented, based on the RMR system.

$$RMR = 18.12E_m^{0.460} , R^2 = 0.798 \quad (7)$$

$$RMR = 22.09G_m^{0.460} , R^2 = 0.766 \quad (8)$$

$$E_m = 1.405e^{0.035RMR} , R^2 = 0.772 \quad (9)$$

$$G_m = 0.913e^{0.035RMR} , R^2 = 7.681 \quad (10)$$

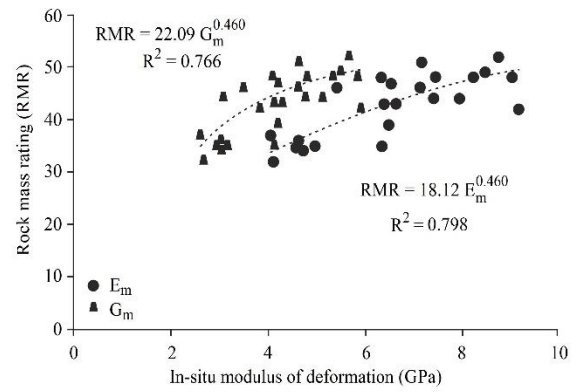


Fig. 10 The variation graph for RMR value and deformation modulus of sedimentary rocks

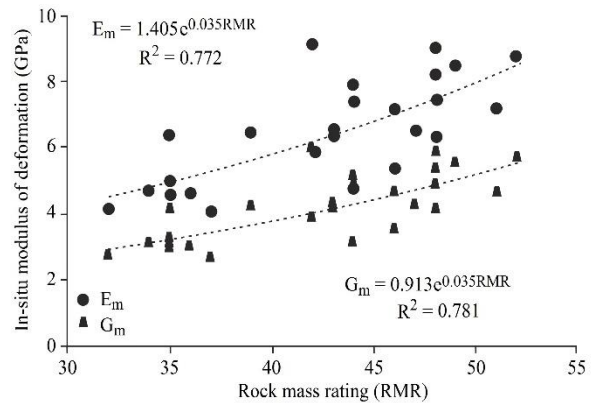


Fig. 11 The relations for E_m , G_m versus RMR for South Pars sedimentary rocks

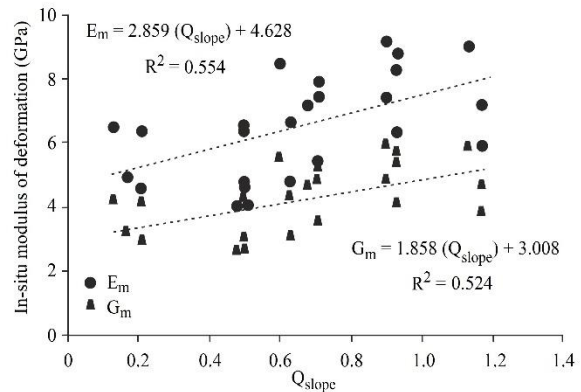


Fig. 12 The relations for E_m , G_m versus Q_{slope} for South Pars sedimentary rocks

Referring the RMR and Q_{slope} relationships, presented in Fig. 7, the Q_{slope} and deformation modulus for sedimentary rock slope in South Pars region is presented in Fig. 12, gathered in Eqs. (10) and (11).

$$E_m = 2.859Q_{slope} + 4.628 , R^2 = 0.554 \quad (11)$$

$$G_m = 1.858Q_{slope} + 3.008 , R^2 = 0.524 \quad (12)$$

Empirical relations tailored for rock slope stability play a pivotal role due to their pragmatic utility in real-world

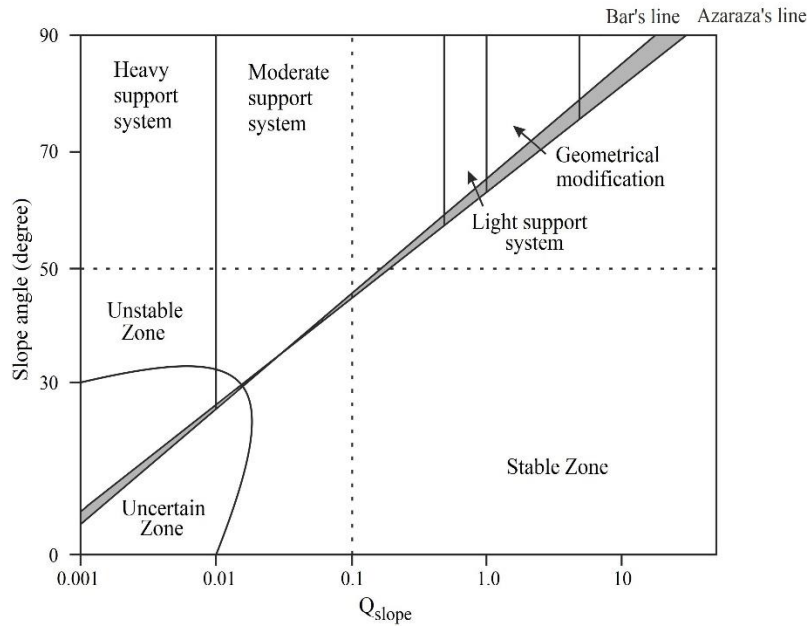


Fig. 13 The stability chart for Q_{slope} -based support system suggestion

Table 5 The support system suggestion for slopes based on Q_{slope} value

Q_{slope}	Possible failure type				Slope support system
	Planar	Wedge	Toppling	Mass	
0.001	Highly probable	Improbable	Improbable	Highly probable	Heavy support system/ geometrical modification/ drainage net/ sewing mesh
0.005					
0.01					
0.05	Probable	Highly probable	Highly probable	Probable	Moderate support system/ geometrical modification/ drainage net
0.1					
0.5					
0.7					
1.0	Improbable	Probable	Probable	Improbable	Light support system/ geometrical modification
5.0					
7.0					
10	Improbable	Improbable	Improbable	Improbable	Geometrical modification
10					
					Not support required

contexts. These relations draw from concrete observations and data amassed from actual slope failures and stability assessments, making them invaluable tools for engineers, geologists, and researchers grappling with slope design, construction, and risk mitigation. Their significance lies in their capacity to provide a more practical and nuanced understanding of slope behavior by considering the intricate interplay of geological attributes, environmental factors, and structural complexities that influence stability. Furthermore, empirical relations offer swift and cost-effective preliminary assessments, aiding in the swift identification of potential risk zones that warrant further investigation. They augment analytical methods by providing practical guidance, ensuring that the decisions made regarding slope reinforcement, design, and safety are grounded in empirical insights. In essence, these relations not only encapsulate historical lessons from slope failures but also empower professionals to make informed choices, ultimately contributing to safer and more resilient rock slope engineering practices.

In general, the Rock Mass Rating (RMR) and Q-system methodologies offer distinct advantages for evaluating the stability of rock slopes. RMR's simplicity lies in its numerical assignment to key rock mass parameters, facilitating its widespread adoption among professionals. Its incorporation of field data enables swift preliminary assessments, aiding in early decision-making. Moreover, RMR's extensive use and empirical refinement contribute to its reliability across diverse geological settings. Conversely, the Q-system provides a more comprehensive analysis by considering six parameters, encompassing rock quality, stress conditions, and geological features. Its detailed evaluation includes structural geology aspects like joint orientation, enriching the understanding of slope behavior. Additionally, the Q-system's utility extends to complex situations where various factors interact. By offering nuanced insights, both RMR and the Q-system assist in making informed choices about slope design, reinforcement, and risk mitigation, ensuring safer rock slope engineering practices. Result of RMR and Q-system

methods which is covered by Q_{slope} procedures can be reinforce slope stability condition and providing more efficient information regarding in-situ deformation modulus. Also, using such geomechanical classification system helps to improve the practical efficiency in design and construction stages. The practical efficiency of Q_{slope} , which employs the Q-system for rock slope stability assessment, is underscored by its ability to provide tailored solutions for intricate slope engineering challenges. By integrating geological, structural, and geotechnical parameters, Q_{slope} offers a holistic understanding of slope behavior, enhancing the accuracy of stability predictions.

This approach facilitates the identification of potential failure modes and the design of targeted reinforcement measures, optimizing the allocation of resources. Moreover, Q_{slope} 's adaptability to diverse geological contexts and complex conditions underscores its practicality for real-world applications. The ability to account for factors such as joint orientations, groundwater conditions, and rock quality enhances its predictive power, leading to more effective slope management strategies and ultimately contributing to safer and more efficient rock slope engineering practices.

The social impact of employing empirical relations customized for rock slope stability is significant, as it directly contributes to ensuring the safety and well-being of communities living in proximity to potentially hazardous slopes. By integrating practical insights garnered from real-world slope failures and stability assessments, these relations empower engineers, urban planners, and local authorities to make informed decisions that safeguard lives and property. This proactive approach aids in mitigating the potential risks associated with unstable rock slopes, thereby minimizing the likelihood of disasters and subsequent social upheaval. Furthermore, the utilization of empirical relations enhances public awareness by fostering a better understanding of the risks posed by geological hazards. Local communities become more informed about potential slope instability, allowing for more effective evacuation plans, emergency response strategies, and community resilience initiatives. Through the application of these relations, social equity is fostered by reducing the disproportionate vulnerability that marginalized communities might face in the event of a slope failure. In essence, the use of empirical relations for rock slope stability resonates beyond technical aspects, significantly contributing to the broader social fabric by promoting safety, preparedness, and sustainable urban development.

5. Support system suggestion based on Q_{slope}

As mentioned, Q_{slope} allow to analyze rock slopes regarding the slope geometry and block size, shear force and stress elements, which can be merged and, at the same time, analyze it at an early stage (Azarafza *et al.* 2020a). In this regard, some scholars have used SMR, SSAM, and CSMR classifications. However, there are several necessities that required considering in Q_{slope} , especially parameters estimation and support system suggestion. Hence, it is important to provide comprehensive information to cover these necessities. Jorda-Bordehore *et al.* (2018), Maion (2019) and Azarafza *et al.* (2021)

investigate the Q_{slope} relation with other classification systems that lead to add and modify the current status of the coupled Q_{slope} -SMR method, which is used for support system suggestion. Table 5 provides the modification support system design, based on the mentioned researchers' work, which can be used in stabilization of slopes using Q_{slope} values. Regarding Table 5, there are several requirements that have to be considered during the field survey. For example, the slope condition and discontinuities orientations Bar and Barton (2017).

The suggested support system presented in Table 5 has been prepared based on field perceptions, as well as experimental integration of support system design data. In this regard, a comprehensive field survey was performed from the studied slopes, recording all the information related to instability. Table 5 shows the different stability status of slopes under different failure mechanism. Field experience on Q_{slope} eliminated from studied slopes indicates that the obtained Q_{slope} values under 0.005 are the most probable class for various failures types. Also, the obtained Q_{slope} values higher than 7.0 are indicate the most improbable phase for slope instabilities. It should be noted that the failures type are not directly affected by the Q_{slope} value, but it can be impacts on rock quality which lead to slopes' instabilities. This impact is considered in other classifications like RMR, RQD and SMR (Deere and Deere 1988, Bieniawski 1989, Romana *et al.* 2003). The main variation between semi-stable and unstable slopes can be considered from 0.1 to 0.5 in Q_{slope} . Fig. 13 provides a graphical stability condition with support system suggestion based on Bar and Barton (2017) stability charts.

Upon examining Fig. 13, one can discern Barton's stability chart, notable for its delineation of discernible zones that delineate optimal conditions. What sets this chart apart from the conventional stability chart is its inclusive nature, encompassing stability considerations for both the original (Barton and Bar 2017) and modified (Azarafza *et al.* 2020a) scenarios. Furthermore, this unique rendition offers tailored support system recommendations for each delineated section. A nuanced comprehension of this chart underscores its division into four principal zones, each indicative of distinct support requirements. With an amplification of instability and a reduction in the Q_{slope} number, the support system's capacity to withstand challenges must correspondingly heighten to effectively maintain the desired range. Supplementary details concerning the retention system type and potential rock domain failures are presented in Table 5. This information is comprehensive, drawing insights from both the associated figure and the table highlighting limitations of the original Q_{slope} method. With respect to Table 5, it offers diverse stability scenarios for slopes, serving as a valuable resource for preemptively addressing stabilization needs. This table systematically categorizes potential failure types according to their underlying destabilization mechanisms. Furthermore, leveraging the insights of seasoned rock engineering experts, the table provides a spectrum of appropriate intervention levels for stabilization. This, in turn, facilitates informed recommendations for the most suitable support systems to counteract potential instability.

Q_{slope} offers several distinct advantages when suggesting support systems for rock slopes which can be summarized as follow:

Tailored Support Solutions: One of the primary strengths of Q_{slope} is its capacity to provide support system recommendations that are specifically aligned with the unique characteristics of the rock slope under consideration. By factoring in parameters such as joint orientations, rock quality, and stress conditions, Q_{slope} ensures that the suggested support systems are finely tuned to address the specific failure mechanisms that could arise in that particular geological context. This tailoring enhances the effectiveness of support measures and minimizes the risk of over-engineering or under-protection, optimizing the allocation of resources.

Comprehensive Risk Mitigation: Q_{slope} 's incorporation of comprehensive ranges of geotechnical factors enables it to offer a well-rounded perspective on potential instability. This holistic understanding aids in identifying critical zones that require immediate attention and assists in developing support systems that holistically address the various failure modes.

Informed Decision-Making: The detailed insights provided by Q_{slope} empower engineers and decision-makers with a deeper understanding of the slope's behavior and potential failure scenarios. This enables them to make informed choices when selecting support systems, determining reinforcement methods, and planning maintenance schedules. Q_{slope} 's ability to quantify the stability characteristics of different portions of the slope aids in prioritizing interventions, thereby streamlining decision-making processes and ensuring the efficient utilization of resources.

Site-Specific Optimization: Q_{slope} 's reliance on site-specific parameters ensures that the suggested support systems are optimized for the actual conditions of the rock slope. This means that the support measures recommended by Q_{slope} are not based on generic assumptions but rather on the actual geological and geotechnical characteristics of the slope.

Flexibility Across Geological Contexts: Q_{slope} 's adaptability makes it suitable for a wide range of geological contexts and rock types. Whether dealing with hard or soft rocks, jointed or massive formations, the Q -system's versatility allows it to account for the inherent complexities of different rock types. This flexibility is particularly valuable when dealing with projects in diverse regions, ensuring that the suggested support systems remain relevant and effective across varied geological landscapes.

6. Conclusions

Evaluation of rock mass deformability is an important, but very challenging, task in the stability analysis, being crucial for the primary support system implementation. In this regard, empirical classifications play a key role to provide the basic information.

The presented study attempts to provide an empirical relationship based on Q_{slope} classification system for fast stability analysis of rock slopes. This study outlines the key aspects of slope mass modulus of deformation and provides the empirical relationship based on Q_{slope} classification. According to the experimental correlations between E_m , geomechanical indexes of rock mass and calculated Q_{slope} values, the following relationships are achieved: $E_m = 2.859$

$Q_{\text{slope}} + 4.628$ ($R^2 = 0.554$), and $G_m = 1.856 Q_{\text{slope}} + 3.008$ ($R^2 = 0.524$). Besides, the correlations between in-situ modulus of deformations with RMR were calculated as well, obtaining the following results $RMR = 18.12 E_m^{0.460}$ ($R^2 = 0.798$) and $RMR = 22.09 G_m^{0.460}$ ($R^2 = 0.766$). In addition, the correlation between RMR and RQD with Q_{slope} were also determined, $RMR = 34.05e^{0.33Q_{\text{slope}}}$ ($R^2 = 0.712$) and $RQD = 31.42e^{0.549Q_{\text{slope}}}$ ($R^2 = 0.902$). Finally, it is suggested and empirical support system based on Q_{slope} for discontinuous rock slopes based on field survey and ground experiences.

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Abbreviations

E_m	Elastic modulus/Young's modulus
G_m	Shear modulus
E_i	Intact rock elastic modulus
E_{tan}	Tangent elasticity modulus
RMR	Rock mass rating
RQD	Rock quality designation
SMR	Slope mass rating
SSAM	Slope stability assessment methodology
CSMR	Continuous slope mass rating
UCS	Uniaxial compressive strength
MSE	Mean squared error
RMSE	Root-mean square error
ASTM	American society for testing and materials
R^2	Coefficient of determination