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ORIGINAL ARTICLE

A critical review of rock mass classification systems for assessing the stability condition of rock slopes

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Abstract

In the last few decades, several rock mass classification systems have been proposed to identify rock slope stability conditions, having high probability of failure and accordingly prioritize preventive measures. This paper reviews the various classification systems, highlighting their differences and similarities with regard to the factors involved and the mode of their failures. The advantages and limitations of each classification have also been compared. However, many of these existing systems fail to classify slope cuttings according to their actual vulnerability of failure, as they ignore important triggering factors such as earthquakes or precipitation. For example groundwater is considered as an instability causing factor with limited effect, rather than a triggering factor for failure. It is observed that rock slope should be classified according to their potential of failure, taking into account both their condition and the influence of triggering factors upon stability. It is also observed that it is important to analyse each type of failure separately, since each one is influenced by unique factors of instability. Finally, it provides suggestion for the improvement of existing classifications through incorporation of all the critical factors like slope aspect, mode of excavation, earthquake, and rainfall that would have caused slope instability.

Keywords Slope stability · Rock slopes · Rock mass classification

Introduction

Rock mass denotes the rocks in their natural state, along with the discontinuities such as fractures, micro-faults, and joints & shear zones, and is different from an intact rock, which is devoid of such discontinuities. Because of different composition, structure and formational properties, both rock mass and intact rocks are heterogeneous and more likely anisotropic in nature. This is the fundamental explanation for the distinct variation of geomechanical properties of rocks. The rock mass classification systems are globally accepted rock mass categorisation system that gives quantitative values to the quality of rocks and provides guidelines for engineering design purposes using simple arithmetic algorithms that helps to improve rock mass descriptions in terms of structural and inherent properties (Pantelidis 2009).

Rock-cut slope development is often associated with highways construction, where enormous rock surfaces are excavated. Because of varied rock mass characteristics and external environmental exposures, instability in these slopes are frequent. Internal factors affecting slope stability include rock types, slope angle, slope height, and slope orientation with respect to orientation of discontinuities. During the designing of rock-cut slopes or any engineering rock structures, the most essential task includes its site investigations. The detailed geology and geotechnical data of the area are not accessible in the early phase of a rock engineering project for exact designing of engineering structures. As a result, during initial stage of the project, various rock mass classification systems known as empirical approaches are utilised to analyse the stability and feasibility of the design. The rock mass classification system is an effective and convenient tool for expressing characteristics of rock mass and encapsulating different aspects of rock mass (Hudson and Harrison 2000). The most frequent and effective rock mass classifications applied in past several years are Rock quality designation (RQD, Deere 1967), Q-slope (Barton and Bar 2015; Bar and Barton 2017), Rock Mass Rating (RMR, Bieniawski 1976, 1989), Rock Mass Strength (RMS, Selby 1980), Slope Mass Rating (SMR, Romana 1985), Chinese Slope Mass Rating (CSMR, Chen 1995), Continuous Slope

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Mass Rating (CoSMR, Tomás et al. 2007), Geological Strength Index (GSI, Hoek et al. 1995; Hoek and Brown 1997; Marinos and Hoek 2000; Sonmez and Ulusay 2002; Hoek et al. 2013, Marinos and Carter 2018), Slope Stability Probability Classification (SSPC, Hack et al. 2003), Slope Stability Rating (SSR, Taheri and Tani 2006). Slope Rock Mass Rating (SRMR, Robertson 1988), and Rockslope Deterioration Assessment (RDA Nicholson and Hencher 1997; Nicholson 2002, 2003, 2004).

This paper presents a comprehensive overview of the twelve most effective and commonly used rock mass classifications applied for the assessment of rock slope stability. The review of these various rock mass classifications is based on the parameters incorporated in their rating system. This enables the field professionals, such as geologists, mining, and civil engineers to gain a better understanding in terms of qualitative and quantitative assessment of slope stability. This knowledge is crucial for designing rock-cut slopes and other engineering structures in rock mass settings.

Existing rock mass classification systems used for assessing rock slope stability

Rock mass classifications are used to assess the stability of rock-cut slopes based on the most crucial intrinsic and structural factors. Most of the proposed classification schemes used by researchers globally offers a reliable method of quantitatively defining the rock mass state. Table 1 presents a detailed comparison of empirical rock mass classification techniques developed globally for analysing slope conditions along with their advantages and limitations. Some of the classification system has been developed for underground assessment (Q-system, RMR, MRMR, etc.) and they should be used cautiously for slopes with their modified version (RMR, SMR, SRMR, CSMR, etc.) within their bound of case histories from which they are developed.

Factors considered in existing rock mass classification system for rock slopes

Different factors that influences slope stability considered in the existing empirical rock mass classification scheme are presented in Table 2. The main characteristic findings obtained from preliminary study of all the factors considered in the existing empirical rock mass classification systems are as follows:

i. The basis of all the existing rock mass classification systems is comprised of factors which relate to the condition of rock mass along with the geometrical properties of geological structures.
ii. The main variables which are most frequently used in the existing classifications are: i) strength of the intact rock; (ii) state and properties of the discontinuities; (iii) rock quality designation (RQD) index; (iv) spacing of discontinuities; and (v) groundwater condition. It is important to note that the RMR system contains all the above five rating variables, which were primarily designed for underground infrastructure development.
iii. The other important factors like the excavation method, height and dip of the slope, degree of weathering of rock mass, orientation, and dip of geological structures are not frequently used as factors. Some of the vital factors affecting slope stability are rainfall and seismicity which is not included in most of the existing classifications.

The remaining factors seem to be less significant as they are only involved in one or two of the existing classification systems. These factors include the failure history, stabilization and protective measures, the stresses affecting the slope, direct disruptions (such as human activities), and the condition of the slope (such as overhangs, face irregularity, and vegetation cover). However, the presence of groundwater is a factor that is considered in seven of the existing classification systems. This factor is determined through observation of water seepage or permanent water stains on the slope.

The effect of surface water such as water infiltration through fractures and joints present on the slope surface and the movement of loose blocks or rocks caused because of reduction of shear strength due to water flow are not taken into account by any of the classification systems. Some of the existing classification systems do not even consider any water-related factors. Slope morphology is also taken as a factor only in few of the existing classifications like RDA (1997).

Slope failure modes considered in existing rock mass classification systems

The failure mode of rock slope cutting is closely linked to the presence of tectonic fractures or smaller discontinuities. Orientation of these discontinuities with respect to the face of the cut slope has a major influence on the stability and the consequent movement that may take place. As a result, this relative orientation is considered as a critical factor in determining structural instability. However, some classification systems, such as RMR (1989) and RMS (1980), include parameters for discontinuity orientation, but they do not account for the type

Table 1 Rock mass classification system with their advantages–limitations

Classifications system	Advantage	Limitations
Rock Quality Designation (RQD); Deere (1967)	It measures of rock mass quality, provides information on the extent and thickness of weathering as well as identifying natural structural weaknesses like fractures and shear zones of sound rocks	It exhibits directionality and presents varying values for a given rock exposure in different directions. Its initial definition was limited to sound rocks exclusively, which cannot assess the quality of core pieces that are smaller than 10 cm. Additionally, RQD measurements may yield erroneous results due to poor drilling techniques and substandard core handling practices
Rock mass rating (RMR); Bieniawski (1976, 1979, 1989)	It is employed to assess the rock mass quality, pre-plan excavation, and perform procedures within this framework	It is based mainly on case studies of competent rock formations, thereby cannot be applied with full trust in weaker rock masses. This method is discarded for highly fractured and severely crushed rock masses, and it lacks parameters that account for rock type. Moreover, it does not take into account the dip angles of discontinuities
Rock mass strength (RMS); Selby (1980)	It incorporates the influence of weathering on the mechanical properties of a rock mass. It introduces the dip angle of fractures as a novel parameter in rock mass classification. Furthermore, it accounts for the filling material, spacing, and persistence of joints, as well as groundwater flow, to evaluate the strength of the rock mass	This system lacks any parameters that indicate the response of the slope under both static and dynamic stress conditions, and does not incorporate any rock type-specific parameters. Its development is only based on eight distinct field cases
Slope mass rating (SMR); Romana (1985)	It evaluates slope stability by considering the correlation between the orientation of discontinuities and the slope. This approach incorporates the impact of failure mode on slope stability, which represents a novel aspect in the classification of rock slopes	It disregards the influence of precipitation and slope elevation on slope stability, as well as the impact of both horizontal and vertical joint extensions. Additionally, SMR does not incorporate seismic forces while evaluating slope stability. This classification system is inadequate for rock slopes that possess closely spaced discontinuities, and it lacks any parameters related to rock type
Slope rock mass rating (SRMR); Robertson (1988)	It is developed for drill-core samples that comprise weakly altered rock mass constituents. It employs numerous joint parameters to categorise the rock mass	The system is specifically intended for rock masses with joints and foliation, and may not be applicable to non-jointed or massive rock masses. It does not incorporate the impact of excavation method on slope stability. Furthermore, it overlooks the influence of factors such as slope dip and height, groundwater, rainfall, and seismic activity on slope stability. Additionally, it lacks any parameters related to rock type
Geological strength index (GSI); Hoek et al. (1995), Hoek and Brown (1997), Marinos and Hoek (2000); Sonmez and Ulusay 2002, Hoek et al. (2013), Marinos and Carter (2018)	It primarily serves as a tool to assess the deformational properties and deformability of rock masses, utilizing the Hoek and Brown failure criterion for numerical modeling. The Hoek–Brown failure criterion and its corresponding GSI parameter have become widely adopted as effective tools for predicting the strength and deformability properties of highly fractured rock masses	It classification system is based on the assumption that rock mass behaves as a homogeneous and isotropic material, and its response to loading is not affected by the direction of the applied forces. This classification scheme does not incorporate any rock type-related parameters. However, due to the absence of certain critical slope stability factors, the applicability of the GSI method for rock slope design is conditional and restricted to specific scenarios

Table 1 (continued)

Classifications system	Advantage	Limitations
Chinese Slope Mass Rating (CSMR); Chen (1995)	This formula expands upon the original SMR equation by incorporating two supplementary parameters: the slope height factor (ξ) and the discontinuity factor (λ)	This system's height factor is exclusively applicable for slopes greater than 80 m, and it lacks any rock type-associated parameters. Additionally, seismic forces and precipitation effects are not incorporated in this classification. In cases where favourable fracture conditions exist, the CSMR approach may produce higher ratings than the original SMR
Rock slope Deterioration Assessment (RDA); Nicholson and Hencher (1997), Nicholson (2002), (2003), (2004)	This method integrates slope aspect, face irregularity, vegetation cover, and climatic conditions as factors, which are novel factors in evaluating slope stability. It also accounts for the impact of both static and dynamic loads on slope stability	RDA method inadequately addresses slope stability because it fails to consider important parameters such as the orientation and condition of discontinuities. Furthermore, it neglects to account for the influence of the dip angles of both the discontinuities and the slope during slope stability analysis. Moreover, it lacks any parameter related to rock type
Slope Stability Probability Classification (SSPC); Hack et al. (2003)	While assessing slope stability, this method considers the vulnerability of the rock mass to weathering and its degree of exposure. Furthermore, SSPC accounts for the influence of the slope's height and dip and excavation method on its stability, as well as the orientation and dip angle of discontinuities	This method does not incorporate the influence of groundwater movement on slope stability, and it lacks parameters related to the properties of the rock type. Also, the effects of seismic activity and precipitation are not included in the SSPC classification
Slope stability rating (SSR); Taheri and Tani (2006)	This classification method is highly effective in evaluating the stability of rock slopes with closely spaced fractures. This classification incorporates rock type and seismic activity as parameters, which is a novel aspect. Additionally, this classification considers the influence of excavation method and slope height on slope stability	This method does not incorporate the influence of weathering on the mechanical properties of the rock mass. Additionally, it does not account for the impact of joint spacing and the correlation between the orientation of joints and the slope orientation. No parameters associated with precipitation are included in the method
Continuous slope mass rating (CoSMR); Tomás et al. (2007)	This system replaces the discrete rating values of SMR with continuous functions, due to which it gives higher rating values compared to the discrete system. It can be viewed as a classification system that is less reliant on subjective judgment, as it produces a specific output for each input parameter	This method does not incorporate the influence of precipitation and height of the slope on its stability, and it lacks parameters related to rock type. Also, it does not account for the impact of the lateral and vertical extension of Joints on slope stability, and the effects of seismic activity are not included in this classification. This method is not effective for rock slopes with closely spaced joints
Q-slope; Barton and Bar (2015); Bar and Barton (2017)	This method incorporates all joint-related parameters while evaluating slope stability conditions, and it introduces the stress reduction parameter, a novel parameter for any slope stability classification. Moreover, it accounts for the impact of the environment on slope stability analysis. The method also includes parameter associated with the orientation of joints, in addition to slope angle	This classification method does not account for the influence of slope height and seismic activity on slope stability. Additionally, it lacks parameters related to the properties of the rock type

Table 2 Parameters considered in the existing empirical rock mass classification systems for rock slope

Parameters		RQD	RMR	RMS	SMR	SRMR	GSI(1995)	CSMR	GSI (2000,2002)	GSI(2013)	RDA	SSPC	CoSMR	SSR	Q-Slope
Lithology	Rock type													✓	
General condition of rock mass	Intact Rock Strength		✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	
	RQD	✓	✓		✓	✓	✓	✓		✓			✓		✓
	Disintegration of rock mass			✓					✓		✓	✓			
	Decomposition of rock mass			✓							✓	✓			
Condition of discontinuities	Condition of discontinuities		✓		✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
	Aperture of discontinuities			✓			✓		✓	✓	✓				
	Joint water reduction														✓
	Joint set number														✓
	Volumetric joint count								✓					✓	
Geometric characteristics of discontinuities	Joint alteration													✓	✓
	Dip of discontinuities			✓	✓			✓				✓	✓		
	Orientration of discontinuities		✓	✓	✓		✓	✓	✓	✓		✓	✓		
	Discontinuity Infillings								✓	✓				✓	
	Spacing of discontinuities		✓	✓	✓	✓	✓	✓			✓	✓	✓		
	Defect continuity (Persistence)			✓						✓					
Geometry and condition of slope	Geometrical relationship between slope and discontinuity				✓			✓					✓		
	Slope dip				✓			✓				✓	✓		✓
	Slope height							✓			✓	✓		✓	
	Aspect (Slope direction)										✓				
	Vegetation cover										✓				
Water and climatic condition	Face irregularity										✓				
	Groundwater		✓	✓	✓		✓	✓			✓		✓	✓	
	Rainfall														
Excavaton	Altitude/exposure/climatic conditions										✓				✓
Stresses and direct disturbance	Method of excavation				✓			✓			✓	✓	✓	✓	
	Earthquake (Seismicity)													✓	
	Dynamic stresses										✓				
	Static stresses										✓				
	Direct disturbance														
Mode of failure					✓			✓	✓			✓	✓		
Stress reduction factor															✓

of failure (planar, wedge, or toppling). Other systems, such as SRMR, GSI (1995), and RQD, do not consider discontinuity orientation at all.

Systems like SMR, CSMR, and CoSMR consider factors related to the geometric characteristics of discontinuities to determine different mode of structurally controlled failure (toppling, wedge, or planar). Additionally, the SSPC approach takes into account three different failure types: two structurally controlled failures, namely slides and toppling, and a non-structurally controlled failure due to the extra strength of the rock mass. GSI (2000) is solely focused on non-structurally controlled failures, while the RDA (1997) classification addresses the shallow, weathered failure of rock slopes.

The GSI classification system is based on a continuum mechanical approach, which sets it apart from other classifications such as RMR, SMR, Q-system, etc. that are connected to a discontinuous approach. When compared to other rock mass classifications, GSI has more limited set of parameter classification system that is more qualitative than quantitative. Its great simplicity is a benefit, but its application field is a disadvantage (Yang and Elmo 2022).

Applicability of the established rock mass classification techniques for evaluating the slope stability

The potential of failure in rock slope cutting depends on its state and the influence of a triggering event or combination of events. Cause of failure involves both the action of a trigger effect (such as rainwater infiltration or earthquakes) and the development or presence of unfavourable conditions on the slope regarding its stability (such as blocked drainage or proximity to the seismic epicentre or proximity and type excavation). Instability of rock-cut slopes is usually caused by any actions that alter the forces acting on the slope, such as weathering, chemical degradation, wind-driven root movement or root growth, increased pore water pressure from rainfall, and continuous freeze–thaw cycle in the cold regions.

Majority of the incidents of rock-cut slope failures along highways are triggered by factors associated with the presence of water, such as rainfall, cloudburst, cycles of freeze–thaw, melting of snow, channelized runoff, and springs or seeps or blockage in the runoff (Wieczorek and Jager 1996). Other major causes of failures are seismicity and human activities like excavation and deforestation, vehicle vibrations, wind, animals burrowing, or wild animals and tree roots (McCauley e.al. 1985).

Critical assessment of parameters presents in the existing rock mass classification systems for rock-cut slope

The lack of a systematic approach for the stability evaluation of rock-cut slopes led to use of rock mass classification systems which were originally developed for the evaluation of the stability of underground excavations. Although, it quickly became apparent that this underground stability evaluating system does not produce adequate results, and thus, the existing classification systems were modified and/or developed to assess the stability of rock-cut slopes only (Hack et al. 2003).

Rock mass classification systems developed for slopes incorporate parameters that reflect the condition of the slopes. During the assessment of the stability condition of slopes, accurately determining these parameters in the field is challenging and essential. Some of the parameters are widely used and are considered in most classification systems, while a few parameters are not commonly used. All those parameters which are used in the existing classification system of rock-cut slopes are discussed in detail below.

Rock Quality Designation (RQD)

The Rock Quality Designation (RQD) was introduced by Don Deere in 1967 as a way to assess the quality of rock in borehole diamond drill-core logs for engineering purposes. There are both direct and indirect methods for evaluating the RQD. RQD is utilised to determine the extent & thickness of the weathered zone, as well as the depth of the solid rock. RQD measure of rock quality is also used as an important parameter in other rock mass classification systems like RMR, SMR, SRMR, CSMR, GSI_{1995}, CoSMR, GSI_{2013}, and Q-slope.

The definition of RQD has differed in various regions worldwide, and in some countries, it no longer aligns with the original principles and methodology developed by Don Deere (Pells et al. 2017). RQD was initially defined for sound rocks and according to ASTM (2002) standard D6032-02 defines 'sound core' is any core which is fresh to moderately weathered and which has sufficient strength to resist hand breakage. To use classification systems like RMR, Q, GSI, and MRMR, estimating RQD from exposures is critical. However, this process is prone to errors and biases as it was only defined for sound rocks and error induced due to poor handling of cores, drilling parallel to and across a joint, separation on closed bedding and foliation surfaces, and core discing. These error will be proportionally reflected error in classification systems which uses RQD as a parameter in its definition. The founders of RMR and MRMR have recognized the inherent limitations of RQD and have suggested using fracture frequency instead (Pells et al. 2017). Furthermore, recent findings demonstrate that GSI can be estimated just as accurately using Hoek's look-up chart as by computing its components, which involve RQD (Pells et al. 2017). Also, RQD only provides accurate data on core drilling, which could not be indicative of the entire rock mass's characteristics at the slope scale.

Strength of intact rock

The strength of an intact rock is a crucial element in most rock slope classification systems. However, in a highly fractured rock, it is difficult to obtain intact rock and the stability of rock slopes is governed by the presence of such discontinuities. The intact rock strength is commonly used in tunnelling and mining industries to classify and describe the rock's properties because of large depth where fractures and joints get closed due to overburden pressure. In these applications, the stress redistribution that occurs in rock masses due to tunnel openings and mining activities can exceed the ultimate bearing capacity of a rock. Furthermore, the density of the discontinuities, particularly the interconnected cracks in a rock, plays an important role in defining the shear strength and deformability of a rock mass. The rock weathers readily along the cracks and joints compared to more homogenous non fractured parts, thus making rock slope more vulnerable. When shear stress is applied to the rock, small movements along the joints can cause minimal contact areas and high local stresses, leading to damage to the rock's asperities.

The strength of intact rock is directly utilised for assessing the stability of a rock slope in classifications system like RMR, RMS, SMR, SRMR, GSI_{1995}, CSMR, RDA, SSPC, SSR, and CoSMR.

Rock type/lithology

The rock type is important in slope stability assessment due to their varying physical and mechanical properties, such as strength, permeability, resistance to weathering, and erosion. Identifying the lithology helps geologists and engineers to determine the possibility of slope failure and accordingly design appropriate measures for slope stabilization. The lithology of the rock also influences the type of excavation, construction, and reinforcement methods to be used. Most slope stability classifications use rock strength, rather using lithology of the rock as parameters for stability assessment. However, a few classifications like SSR consider both rock type and rock's strength as the measuring parameters.

When considering the lithology, the importance of a multilayer structure in sedimentary rock masses (closely spaced bedding planes, as for a typical flysch rock mass) and the possible occurrence of a competence contrast, which is commonly associated with a rhythmic alternation of stronger layers (for instance, limestone beds) and soft interbeds (marls or clays). The lithology and primary structure of the rock mass has also influences on the choice of the reference intact rock strength.

Discontinuities and their properties

Discontinuities in rocks play the most important role in slope stability assessments as it strongly controls the strength and stability of a rock mass. Discontinuities like joints, fractures, bedding planes, and faults can weaken the rock resulting in development of potential failure surfaces. The attitude of the discontinuity like its orientation & dip, aperture or opening of a joint, and spacing between the fracture planes are used to model the rock body to determine the potential for failure. Further, their geometry affects the modes of slope failure (planer, wedge and topple) (Fig. 1). In slope stability assessments, the presence of discontinuities is often determined using geological mapping, core drilling, and geophysical surveys. Such information is critical for understanding the extent of slopes stability. Properties like aperture and spacing of joints or fracture plane is considered in rating system. RMR, RMS, SMR, GSI_{1995}, CSMR, CoSMR, and RDA, while the surface condition of discontinuity is used by RMR, SMR, SRMR, GSI_{1995}, CSMR, CoSMR, GSI_{2000}, Q-slope, and SSPC. However, the SSR do not consider the discontinuity properties in its rating system. The orientation and dip of discontinuity are incorporated into classifications system of RMS, SMR, CSMR, CoSMR, and SSPC, whereas RMR used orientation property without considering its dip amount. For slope stability evaluation, the RMS

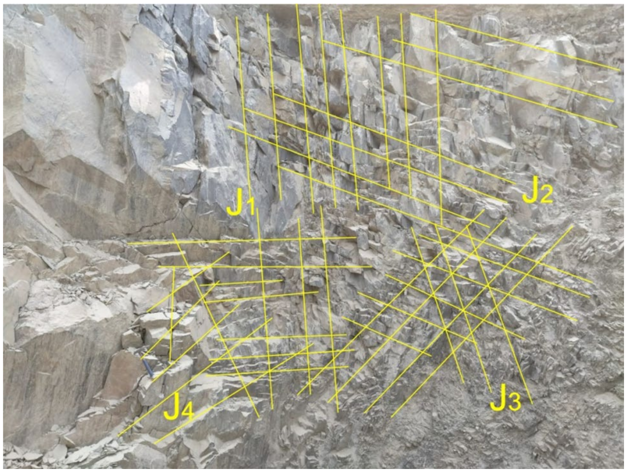


Fig. 1 Effect of discontinuity (J_1, J_2, J_3, & J_4 marks different joint sets) in the generation of small rock blocks

classification takes into account the persistence of discontinuity, while the Q-slope classification evaluates various other properties of discontinuity such as the joint set number, joint alteration, and joint water reduction parameters. The spacing of discontinuity is considered in most slope stability classifications, such as RQD, RMR, RMS, SMR, SRMR, GSI_{1995}, CSMR, RDA, SSPC, GSI_{2000}, GSI_{2013}, SSR, CoSMR, and Q-slope.

Commonly, the presence of cohesive infilling material such as clays within rock joints results in an overall decrease in the strength of the rock mass, since the shear strength of the clay is lower than the shear resistance of the rock joint. Furthermore, if the clay or other infilling material of joints is subjected to freeze–thaw cycles or water comes in contact it can expand and contract, leading to additional stress within the joint. This can cause the joint to open up, allowing water to enter and further weaken the rock mass. It is important to consider the properties of the infilling material when assessing the stability of rock slopes.

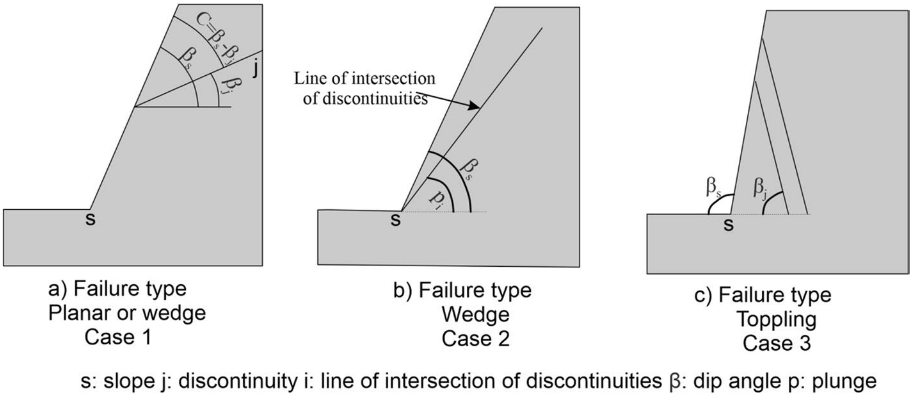
Geometrical relationship between slope and discontinuity

The assessment of slope stability requires sound knowledge of the relation between the orientation of slope and the geometry of the discontinuities present and its overall effect on the mode of slope failure (planar or wedge failure). The slope stability is affected by its inclination angle, orientation of the discontinuities, and properties of the underlying rock mass. Presence of discontinuities, like joints, fractures, and bedding planes, can weaken the slope and increase the chances of failure because of reduction in rock mass strength. The degree of parallelism between the discontinuity and the slope orientation also affects the slope's stability where the failure chance rises as the degree of parallelism increases. Similarly, as the difference between the dip angle of discontinuity and slope dip angle increases, rock mass surpass the angle of friction, leading to instability, with steeper slope angle having greater chance of failure. RMR uses the parameter F (effect of discontinuity strike and orientation of tunnelling) to take discontinuity dip angles into account. This "corrective" parameter makes a comparison between the tunnel axis and the primary discontinuity set's orientation. Comparing the discontinuity orientation with the slope face strike is another common application of this method in rock slope stability issues. The relation between the dip angle of a discontinuity and the slope's dip angle is referred to as the auxiliary angle C. It can be easily calculated and is illustrated in Fig. 2. Table 3 provides an overview of the formulas utilised to determine the angular relationships A, B, and C. These relationships are based on the dip and dip direction of both the slope and the discontinuities that impact it.

Slope angle

Slope angle is a critical factor in assessing slope stability as it determines the amount of gravitational force acting on a slope. A steeper slope is more unstable compared to gentle

Fig. 2 Auxiliary angle C value: **a** potential scenarios of planar or wedge failure; **b** potential scenarios of wedge failure; **c** a case of toppling



a) Failure type Planar or wedge Case 1

b) Failure type Wedge Case 2

c) Failure type Toppling Case 3

s: slope j: discontinuity i: line of intersection of discontinuities β: dip angle p: plunge

Table 3 Formulas employed to compute the angular correlations of A, B, and C

Failure mode	Angular relationship	Calculation of A	Calculation of B	Calculation of C
Planar	$\lvert \alpha j - \alpha s \rvert < 90°$	$A = \lvert \alpha j - \alpha s \rvert$	$B = \beta j$	$C = \beta j - \beta s$
	$\lvert \alpha j - \alpha s \rvert > 90°$	$A = 360° - \lvert \alpha j - \alpha s \rvert$	$B = \beta j$	$C = \beta j - \beta s$
Wedge	$\lvert \alpha i - \alpha s \rvert < 90°$	$A = \lvert \alpha i - \alpha s \rvert$	$B = \beta i$	$C = \beta i - \beta s$
	$\lvert \alpha i - \alpha s \rvert > 90°$	$A = 360° - \lvert \alpha i - \alpha s \rvert$	$B = \beta i$	$C = \beta i - \beta s$
Toppling	$90° < \lvert \alpha j - \alpha s \rvert < 270°$	$A = \lvert\, \lvert \alpha j - \alpha s \rvert - 180° \,\rvert$	Not necessary	$C = \beta j + \beta s$

α = Strike of slope & discontinuity; β = dip of slope & discontinuity; s = slope & j = discontinuity slope, as the former is acted upon by a stronger driving force as compared to resisting force which cause slope failure. Thus, a slope angle is useful in identifying potentially unstable slope. Slope angle can also be used to compare the stability of different slopes and suggest scientific slope stabilization measures, such as retaining walls or soil reinforcement. However, other factors like soil type, weathered zone depth, saturation, and vegetation cover also greatly impact stability of a slope. Therefore, the slope angle should be considered in conjunction with these factors in a comprehensive slope stability assessment. Classification, such as Q-slope, CSMR, CoSMR, SMR, and SSPC, uses slope angle as a factor in slope stability evaluation. Figure 3 depicts the plot between slope angle and Q-slope value for evaluating the condition of slopes.

Slope height

The slope height plays a crucial role in determining the stability of the slope. As the slope height of the rock mass increases, the weight of material and the driving force acting along the failure plane also increase causing slope instability. Furthermore, a high slope has a greater impact of erosion and weathering which contributes to slope instability. By measuring the height of the slope, engineers and geologists can evaluate the potential risk and can determine appropriate stabilization measures. Slope height has been considered in several classifications, such as CSMR, RDA, SSPC, and SSR. The SSR slope height vs. SSR value chart is presented in Fig. 4.

Slope aspect

The slope aspect is a significant factor in evaluating slope stability as it determines the amount and direction of solar radiation received by a slope which in general affects the temperature, moisture content, and vegetation cover of the slope. It affects wind patterns and precipitation quantity which influence soil erosion and deposit. Additionally slope aspects also affect the development of freeze–thaw cycles in areas with winter freezing temperatures, leading to changes in soil strength and stability. According to the study conducted by Flatland (1993), Mazzoccola and Hudson (1996), and Watters (1998), it has been revealed that the south-facing slopes experience a greater number of freeze–thaw cycles per year when compared to north-facing slopes. North-facing slopes are in shadow for majority of the day time and therefore experience minimum temperature variation (Fig. 5), making them the least susceptible to instability.

The amount of solar radiation that a surface receives is highly affected by its geometric characteristics, such as its slope and aspect. Revfeim (1978) has given an equation which enables the estimation of solar radiation on a

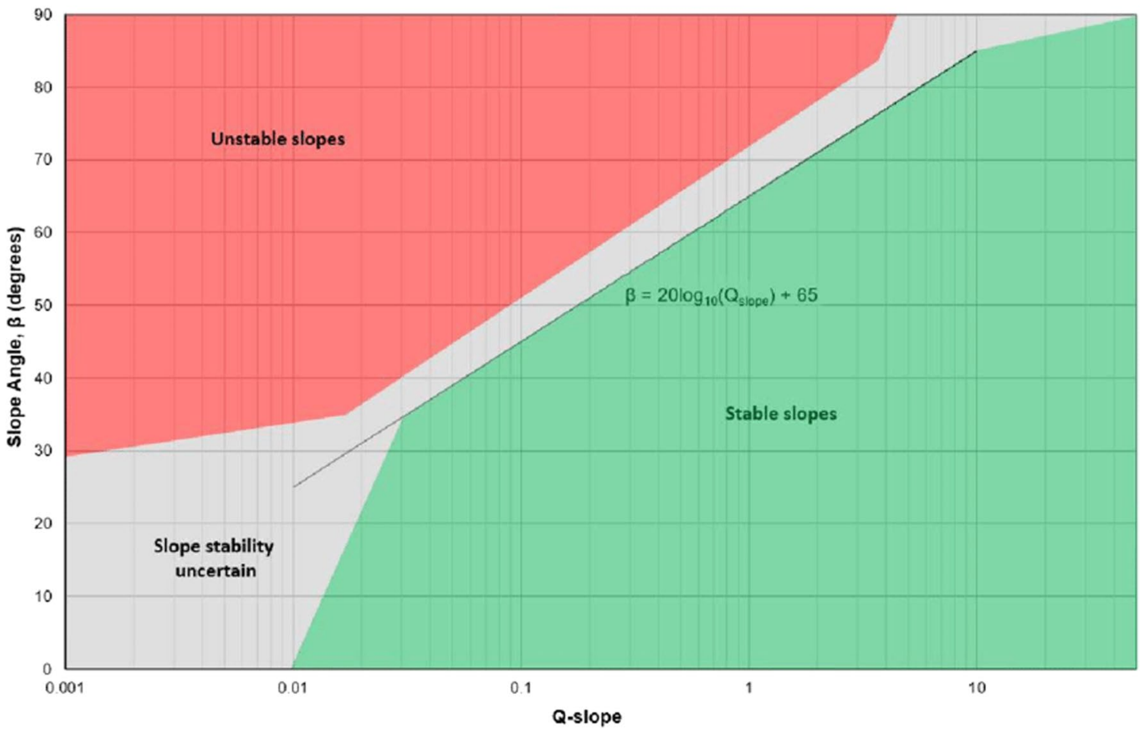


Fig. 3 Plot between slope angle and Q-slope value (Bar and Barton 2017)

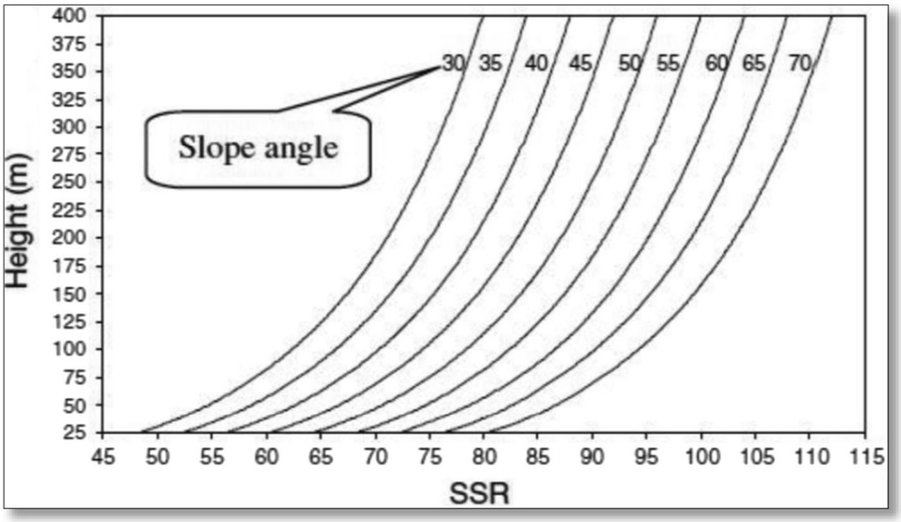


Fig. 4 Slope stability condition is assessed through plot between slope height and SSR value for given slope angle (Taheri and Tani 2006)

horizontal surface, based on the diffuse and direct components of global radiation.

Revfeim (1978) presented the following equations to compute the ratio, R_d, of direct radiation on a slope to that on a horizontal surface:

$$R_d(\varphi, \delta, \beta, \mathrm{b}) = (\sin \varphi/\sin \varphi) \\ (\mathrm{d} - \sin \mathrm{d} \cos \mathrm{e} \cos \mathrm{g}/\cos \omega)/\omega \mathrm{s} \\ - \tan \omega \mathrm{s} \tag{1}$$

$$\Phi = \sin^{-1}(\sin \varphi \cos \beta - \cos \varphi \sin \beta \cos \mathrm{b}) \tag{2}$$

$$d = 1/2\left(h_1 - h_0\right) \text{ and e} = 1/2\left(h_1 - h_0\right) \tag{3}$$

$$\mathrm{g} = \sin^{-1}(\sin \beta \sin \mathrm{b} \sec \varphi) \tag{4}$$

$$\omega = \cos^{-1}(-\tan \varphi \tan \delta) \tag{5}$$

$$\omega \mathrm{s} = \mathrm{Ar} \cos (-\tan \varphi \tan \delta), \tag{6}$$

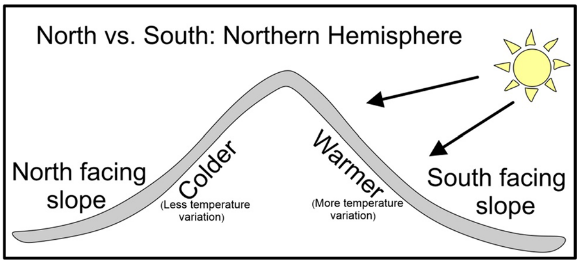


Fig. 5 Temperature variation related to slope aspect

where φ is the latitude, δ is the declination, β is the slope, and b is the aspect (with south = 0◦, north = 180◦, and east/west = 90◦). The parameter h_0 represents the sunrise hour angle for a surface with an arbitrary slope. For a horizontal surface, it is equal to ωs (computed using Eq. (6)). Otherwise, it is calculated as the maximum value between − ωs and g − ω∗. The parameter h_1 represents the sunset hour angle for a surface with an arbitrary slope. For a horizontal surface, it is given by − ωs. Otherwise, it is computed as the minimum value between ωs and g + ω∗.

Thus, slope aspect provides an understanding of physical and environmental conditions affecting the slope stability, which is important for vulnerability assessment and slope stability analysis. Although the slope aspect is a crucial factor for evaluating slope stability, but is not considered in most of the classification system except RDA.

Weathering

The assessment of slope stability is greatly influenced by weathering, as it alters the mechanical and physical characteristics of the soil and rock masses, affecting the probability of failure. Weathering processes, such as freeze–thaw cycles, oxidation, and chemical decomposition, increases porosity and decreases the strength of the material, making it more likely to erode, slump, or fail. On the other hand, cementation and induration resulting from weathering can improve the slope stability increasing its cohesion and internal strength. A detailed understanding of the impact of weathering on slope stability is therefore critical for accurate slope stability assessments and for designing effective stabilization measures. Figure 6a, b, depicts the highly weathered slope condition. To quantify the degree of weathering, a classification system was employed, based on the framework proposed

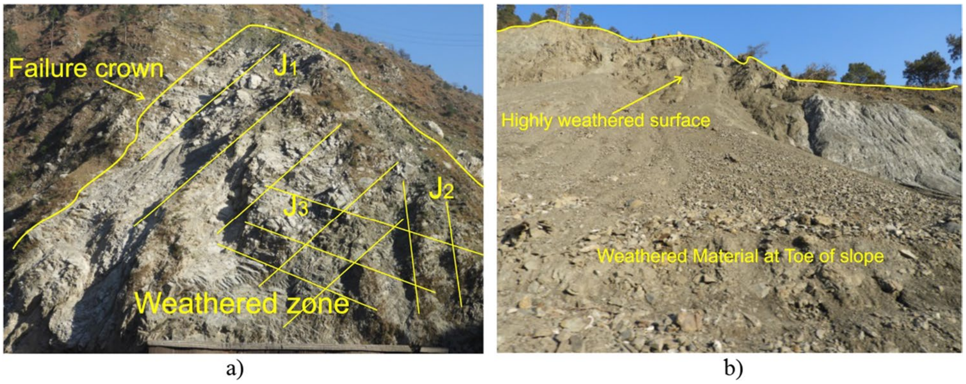


Fig. 6 **a**, **b** Numerous loose and small blocks formed due to intense weathering of the rock mass along the weak planes (such as joint), which increases the risk of slope failure during intense rainfall

by the International Society for Rock Mechanics (ISRM) in 1981, as depicted in Table 4. As the extent of weathering increases, the chance of slope failure also increases. None of the classification methods directly considers the effects of weathering; however, indirect weathering and disintegration parameter of rock is used in SSPC, RMS, RDA, and SSR classification.

Groundwater outflow

The presence of water alone can increase the potential of slope failure (for example, by exerting hydrostatic pressures on walls of joints) or in combination with other factors such as diurnal temperature changes (freeze–thaw cycles of trapped water in the cracks or pores) and earthquakes. Although water has a detrimental effect on slope stability, its impact in existing rock mass classification systems is minimal, constituting maximum up to 15% in RMR (1989) (Pantelidis 2009). Furthermore, the SRMR, GSI (1995), SSPC, and Q-slope classifications completely ignore the influence of groundwater, while the term "wet conditions" is considered in GSI (2000) classification system. The extent to which groundwater affects rock mass characteristics is determined by the volume of water seepage through the slope face, which can be broadly categorised as dry, damp, wet, dripping, and flowing, or quantified by litres per minute per square meter (Table 5). However, most of rock mass classification systems solely account for groundwater's impact on the stability of rock slopes and overlook the detrimental effects of surface water on slope stability, as illustrated in Fig. 7. Groundwater is used as a parameter in many slope stability classifications like RMR, RMS, SMR, CSMR, CoSMR, GSI_{1995}, GSI_{2000}, RDA, and SSR, but none consider the effect of surface water.

Table 5 Relationship of groundwater inflow per 10 m of tunnel length as per RMR 1989 classification

Ground water inflow	p_w/σ_1	General conditions
None	0	Completely dry
< 10 (litres/min)	0–0.1	Damp
10 – 25 (litres/min)	0.1–0.2	Wet
25 – 125 (litres/min)	0.2–0.5	Dripping
> 125 (litres/min)	> 0.5	Flowing

p_w = joint water pressure; σ_1 = major principal stress

Table 4 Weathering classification for rock materials (ISRM 1981)

Term	Symbol	Description	Grade
Fresh	F	No visible sign of rock material weathering; perhaps slight discoloration on major discontinuity surfaces	I
Slightly weathered	SW	Discoloration indicates weathering of rock material, and discontinuity may be somewhat weaker externally than in its fresh condition	II
Moderately weathered	MW	Less than half of the rock material is decomposed and/or disintegrated to soil. Fresh or discoloured rock is present either as a continuous framework or as corestones	III
Highly weathered	HW	More than half of the rock material is decomposed and/or disintegrated to soil. Fresh or discoloured rock is present either as a discontinuous framework or as corestones	IV
Completely weathered	CW	All rock material is decomposed and/or disintegrated to soil. The original mass structure is still largely intact	V
Residual soil	RS	All rock material is converted to soil. The mass structure and material fabric are destroyed. There is a large change in volume, but the soil has not been significantly transported	VI

Fig. 7 Presence of surface water or flowing channels of water contributes to the occurrence of slope failure

Rainfall

Rainfall plays a vital role in slope stability, as it weakens the rock masses and surficial soil cover, further increasing the chance of failure. Saturated weight of the material above the slope gets increased due accumulation of water. Rainfall penetrating through the soil cover can lead to expansion and contraction of the constituent clay minerals, thus reducing the strength of the soil. The rainwater seepage through the exposed discontinuities on slope surface can increase the hydrostatic pressure within the discontinuities causing increased chance of slides, topples, or falls of rock blocks. Heavy rainfall on a loose sediment cover can result in increased erosion, which can contribute of slope instability and increased the probability of landslide. When investigative the impact of rainfall on rock slopes covered by soil deposits, it is important to note that soil transportation may occur along with the rainfall infiltration process through open and interconnected joints. This could lead to the formation of soft infillings and, ultimately, alter the overall strength properties of the rock mass. None of the rock slope classification system considers rainfall as parameters in their rating system.

Several attempts have been made globally, regionally, and locally to develop models for rainfall thresholds, aimed at predicting the occurrence of landslides. Guzzetti et al. (2007) have proposed four subcategories of landslide thresholds that can be established by analysing precipitation data obtained from one or more rainfall events. These subcategories are:

(i) intensity-duration (ID) thresholds,
(ii) total event rainfall-based thresholds,
(iii) rainfall event-duration (ED) thresholds, and
(iv) rainfall event-intensity (EI) thresholds.

The ID thresholds, which are the most widely used type of threshold in the literature, are established based on the combination of rainfall intensity and duration. The general form of the ID threshold is formulated as follows:

$$I = \mathrm{c} + \alpha \times D^{\beta}, \tag{7}$$

where I and D represents the mean rainfall intensity and duration, respectively, while $\mathrm{c} \geq 0$, and α and β are the associated parameters.

Method of excavation

The stability of a rock slope is significantly affected by on the excavation method used to develop it. This is because it redistributes the shape, orientation, and distribution of rock blocks, as well as the creation and distribution of new discontinuities in the rock. These factors can impact the long-term stability and performance of the slope. Natural slopes tend to be relatively stable due to slow erosion over time and inherent protective mechanisms. Controlled blasting and presplitting methods can have minimal impact on slope instability. Normal blasting if performed correctly may also have little effect on instability. However, improper blasting practices, involving excessive explosives and improper detonation timing, can significantly reduce slope stability. Out of the 14 systems used for the classification of rock-cut slopes, 8 do not take into account factors related to the excavation technique. In contrast, six of these systems (SMR, CSMR, CoSMR, SSR, RDA, and SSPC) consider the excavation method in evaluating the stability of both existing and developing slopes. SMR was the first classification system that provides a rating system for various excavation techniques (Table 6). When assessing the stability of existing rock-cut slopes, this factor is used to determine the extent of damage caused by past excavation activities, which can be observed directly on site.

The GSI classification system does not consider the excavation method. However, when evaluating the strength and deformability properties of the rock mass using the Hoek and Brown failure criterion, additional rock mass damage associated with blasting or other excavation methods is taken into account through the parameter D.

Table 6 SMR rating adjustments for slope excavation methods

Method of excavation	Adjustment rating (F_4)
Natural slope	+ 15
Presplitting	+ 10
Smooth blasting	+ 8
Blasting or mechanical	0
Deficient blasting	−8

Table 7 SSR rating values for earthquake force (horizontal acceleration)

Earthquake force (Horizontal Acceleration)	Rating
0	0
0.15 g	− 11
0.20 g	− 15
0.25 g	− 19
0.30 g	− 22
0.35 g	− 26

Earthquake force (Horizontal acceleration)

The stability of rock slopes has significant impact of dynamic earthquakes, as it can trigger ground shaking and soil liquefaction, ultimately resulting in slope failure. Furthermore, earthquakes can alter the strength and stability of rock formations, leading to rock slides and landslides. The horizontal component of an earthquake is particularly dangerous, as it can cause lateral movement of soil and rock masses, potentially resulting in landslides and slope failure. Therefore, it is essential to consider the horizontal component of earthquakes when evaluating slope stability. The only classification system that takes earthquake forces into account when assessing slope stability is the slope stability rating (SSR) classification (Table 7). This system evaluates the effect of seismicity on slope stability, considering the horizontal component (horizontal acceleration) of earthquakes. The value of acceleration varies from 0 to 0.35 g, depending on the earthquake's categories, which is classified into six classes.

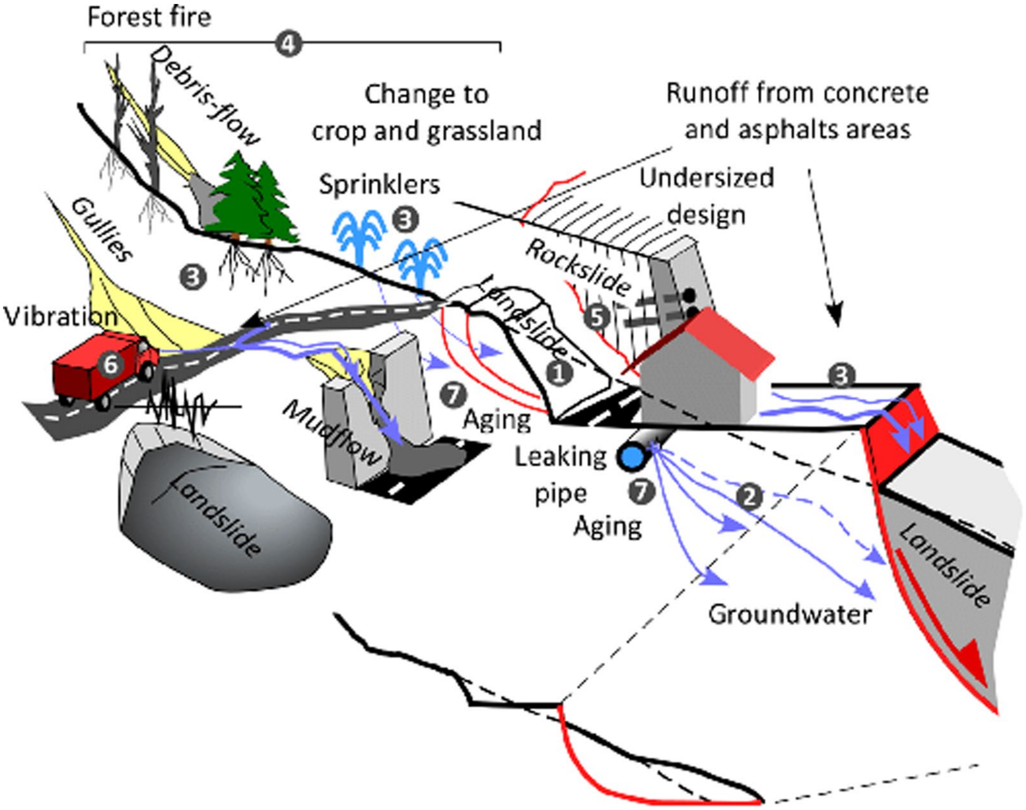


Fig. 8 Seven types of changes (Table 8) and some important features leading to slope instability (Reproduced from Sidle and Ochiai 2006)

Table 8 Seven changes or actions of humans which influence the stability of slopes

1. Slope re-profiling
a. Excavation work; b Construction work; c. Cut slopes; d. Fill slopes; e. Embankments; f. Tailing hills

2. Groundwater flow perturbation and fast pore pressure changes
a. Dam reservoirs; b. Pipe leaks; c. Pipe bursting; d. Leaks in old canalization networks

3. Surface water overland flow modifications
a. Diverting River; b. Deficient drainage system

4. Land-use changes and land degradation;
a. Urbanization; b. Forest fire; c. Deforestation

5. Inappropriate artificial structures
a. Infrastructure break; b. Inappropriate retaining wall

6. Vibration and explosive
a. Heavy traffic; b. Blasting

7. Ageing and degradation of infrastructure
a. Filling of torrential check dams; b. Weakening of terraced wall

Secondary entries were largely reproduced from Terzaghi's (1950) "modes of action"

Effect of anthropogenic activities

Anthropogenic activities have an adverse impact on slope stability, which can lead to landslides and other forms of slope failures. These activities include deforestation, construction, vehicle movement, and changes in land use. Deforestation results in the removal of vegetation that holds the soil in place, making the slope more susceptible to erosion and instability. Excavation and construction activities alter the slope angle and increase surface weight, which in response increase the probability of failure. Changes in land use, such as urbanization and agriculture, increase the weight and water content on the slope, leading to increased instability. Human activities also change the water balance of the slope by altering the drainage pattern of water through the soil and rock layers, causing the soil to become saturated and increasing the likelihood of slope failure. Furthermore, human activities have the potential to cause cracks and breaks in rock formations, which can lead to changes in their characteristics and increasing the chance of slope failure. Moreover, Terzaghi (1950) proposed a classification system that incorporates alterations caused by human activities and strives to provide a more pragmatic approach to addressing issues of instability. Figure 8 and Table 8 feature secondary entries outlining the seven types of human actions that impact slope stability, mainly inspired from Terzaghi's (1950) "modes of action."

Recommendation to improve the existing classification system

Rock mass classification is a unique method for evaluating the engineering properties of rock mass. Such systems integrate empirical relationships between the rock mass characteristics and its behaviour for a specific engineering application. This integration allows for the development of established methodologies to design engineering structures. It took more than a century to formalize the first empirical approach for tunnel design when the first rating system was proposed by Ritter (1879) and Wickham et al. (1972). During this time, only two significant rock mass classification systems were introduced by Terzaghi (1946) and Lauffer (1958), both of which were also proposed for tunnel design. The efficacy of the rating system as a tool for categorizing rock formations was promptly realized, leading to the development of several novel classification systems. These systems were founded on the rating concept initially put forth by Wickham et al. (1972) which was originally devised for mining and tunnelling purposes, and also found extensive application in addressing slope stability concerns. During the evaluation of rock slopes along highways, the classification of rock formations necessitates an approach that is unambiguous, expedient, and provides reliable outcomes.

Most of the empirical classifications were first proposed for tunnels and their further modifications were proposed for slopes such as GSI classification system, which is strictly related to the Hoek and Brown failure criterion, was originally developed for underground projects and subsequently extended to rock slope stability problems (Hoek and Brown 1997). Furlani et al. (2022) conducted an analysis of the rock mass classification system on flysch rock slopes; it revealed that the GSI classification system alone cannot accurately depict the actual stability of the slope. The study found that the rock masses with the lowest GSI values did not experience slope failures, whereas rock masses with higher GSI values were associated with various slope failure processes. This highlights the inability of the GSI to characterize unstable rock masses. Additionally, the study emphasizes that relying solely on rock mass classification systems cannot replace the need for engineering judgment based on comprehensive field observations, which should encompass factors beyond simple rock mass structure and discontinuity surface conditions.

In the past few decades, several different slope stability classifications have been proposed, which utilise varying parameters in their rating system to classify the vulnerability of rock slopes. However, even when some similar parameters are used, different weightages are assigned to them, leading to different vulnerability classifications for the same slope. This can be attributed to the fact that none of the existing classifications consider all the critical parameters necessary for accurately evaluating the stability of a rock slope. Some classifications focus on a few critical parameters, while others consider different ones. Due to these limitations, researchers are required to assess the slope condition using multiple classification systems to evaluate the effect of all the critical parameters on the stability of rock slopes. However, relying on existing classification systems alone can lead to overestimation or underestimation of a slope's stability, leading to significant safety and economic consequences. Recent technological advancements and the availability of new data and information may enable the development of a more accurate and comprehensive classification system. This can improve our understanding of rock slope stability and reduce the chance of slope failures. The new classification system may need to consider additional factors such as the impact of climate change, rainfall, seismicity, and human activities.

Summary and conclusion

Several systems have been proposed for evaluating the stability of rock excavations since Bieniawski's (1979) seminal work. A comparison of these systems reveals both similarities and differences. The main factors in these systems typically relate to the overall condition of the rock mass, the characteristics of discontinuities in orientation, shape, and condition, as well as groundwater movement. The RMR_{basic} system's five rating components serve as a basis for developing other systems. However, it should be noted that most of the existing classification systems only consider groundwater, and neglect the negative impact of surface water on stability. Infiltration of surface water through exposed discontinuities or the displacement of small rock blocks and stones can occur, depending on the rock mass state.

While 9 out (RQD, RMR_{1989}, RMS, SRMR, GSI_{1995}, GSI_{2002}, GSI_{2013}, SSR, and Q-slope) of 14 classification systems do not consider the mode of slope failure, some classifications (RDA) only refer to non-structurally governed failures. In contrast, other classification (SMR, CSMR, CoSMR, and SSPC) examine the combination of both structurally and non-structurally controlled failures. Rainfall and seismic factors are common triggering parameters for failure, especially in hilly regions. However, these factors received limited consideration or are usually ignored in the existing classification systems, which assess the stability of rock slopes on the static of condition of rock slope cuttings. Additionally, two rock slopes with similar rock mass conditions may have different failure probabilities due to exposure to different climatic conditions or diurnal temperature variations, leading to inaccurate stability assessments. Therefore, it is recommended that existing rock mass classification systems be improved in reliability or new classification systems be developed. The number of rating parameters can also be reduced by amalgamating factors to increase the reliability of the system. These integrated or new classification systems should be able to incorporate the influence of all the critical parameters responsible for causing slope instability and examine each parameter independently. Additionally, these systems should consider the influence of triggering factors such as precipitation and earthquakes.

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Declarations

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