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ORIGINAL PAPER

ARMR, a new classification system for the rating of anisotropic rock masses

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Abstract
The engineering behavior of rock masses is strongly dependent on anisotropy, which is present at different scales, from the microscale in the intact rock due to the alignment of rock crystals (inherent anisotropy) to the macroscale in rock masses with anisotropic rock structure, characterized by distinct bedding or schistosity planes. This paper presents a new rock mass classification system, Anisotropic Rock Mass Rating (ARMR), specifically developed for the classification of anisotropic rock masses. ARMR considers the following rating parameters: (a) anisotropy strength index, R_C; (b) uniaxial compressive strength of intact rock; (c) degree of structure anisotropy; (d) corrected rock quality designation (RQD); (e) condition of anisotropy surfaces; and (f) groundwater conditions. Its use is illustrated and explained by application to specific case studies in anisotropic rock masses, and the advantages and limitations of the classification system are outlined. The strength of anisotropic rock masses is determined using the modified Hoek–Brown criterion (Saroglou and Tsiambaos, Int J Rock Mech Mining Sci 45:223–234, 2008), which is extended to rock masses with the use of ARMR.

Keywords Anisotropy · Rock mass · Classification · Rating · RMR

Introduction

In practice, rock mass classification systems have provided a valuable systematic design aid to many engineering projects, especially for underground constructions, tunneling, and mining projects. On the basis of the mode of characterization, these systems can be grouped as quantitative and qualitative.

Quantitative rock mass classification systems, such as RSR (Wickham et al. 1972), RMR (Bieniawski 1973), Q-system (Barton et al. 1974), MRMR (Laubscher 1990), RMi (Palmstrøm 1982, 1996), and RMQR (Aydan et al. 2014), take into account a number of rating parameters in order to assess the quality of the rock mass and attribute a total rating value. These parameters are usually rock quality designation (RQD), intact rock strength, discontinuity conditions, spacing and orientation, groundwater conditions, and stress field. The Geological Strength Index, GSI, initially proposed by Hoek et al. (1995), is based on the qualitative description of rock mass structure and quality of discontinuity surfaces. This index has been used for determining rock mass strength and deformability (Marinos and Hoek 2000).

Classification systems can also be classified on the basis of their aim, e.g., the Q-system and RMR system are used for stability assessment of underground openings. The Q-system, GSI, and RMR, to a minor extent, are also used to calculate the ground support design (liner thickness, bolt spacing, etc.).

Rock mass classification systems have been extended to weak rock masses, as in the case of the GSI (Hoek et al. 1998; Marinos and Hoek 2000). Sonmez and Ulusay (1999) and Hoek et al. (2013) proposed a quantitative GSI chart, while other similar approaches, i.e., the assistant tool based on GSI, were proposed by Osgoui et al. (2010) for a better characterization of poor and very poor rock masses.

The most widely used classification systems in rock engineering applications are the Rock Mass Rating (RMR), the Q-system, and the GSI, while the Basic Quality index (BQ; National Standards Compilation Group of People's Republic

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of China, GB 50218-94 1994) is widely used in China. Reviews of rock mass classification systems and their use and misuse are given by Singh and Göel (1999), Palmstrom and Broch (2006), and Cai and Kaiser (2006).

Current classification approaches, empirical design methods, and rock mass parameter estimation techniques do not specifically take into consideration the effects of anisotropic behavior due to the orientation of weakness planes (i.e., foliation). They do not account for anisotropy stemming from the presence of foliation planes or other anisotropic structural features encountered in a wide range of anisotropic rock masses, ranging from weak rock masses (phyllites, shales) to competent rock masses (gneisses). Nevertheless, the effect of foliation planes at the rock mass scale is implicitly accounted for the RMR correction for the orientation of discontinuities with respect to tunnel direction, if the main discontinuity set is considered to be foliation/bedding.

Hoek and Karzulovic (2000) proposed a GSI chart for schistose metamorphic rocks, in which lower GSI values are assigned to a rock mass with increasing degree of foliation and decreasing surface quality. Jakubec and Laubscher (2000) discussed the influence of rock strength anisotropy and its orientation in the revised MRMR system. Apart from these two cases, there is a lack of rock mass classifications in anisotropic rock masses.

For anisotropic rock masses, Marinos et al. (2007) pointed out that the main classification systems (i.e., Q-system, RMR, and GSI) do not properly account for rock mass behavior and strength reductions as a result of the directionality/anisotropic heterogeneous nature of the rock mass with respect to loading. They suggested that, in cases where anisotropic rock mass behavior is present, it would be necessary to develop an orientation-dependent rock strength based on an orientation-dependent uniaxial compressive strength. Accordingly, the GSI value would remain unchanged and the rock mass strength would be determined by the orientation-dependent uniaxial compressive strength value. Alternatively, an orientation-dependent GSI with a uniaxial compressive strength that is representative of the interstructural intact rock strength could be used to achieve the same effect.

The aim of the present study was to propose a new method of rock mass classification of anisotropic rocks masses and provide a methodology for its application in the design perspective. The system aims to provide an improved method of classification of anisotropic rock mass and to determine the anisotropic rock mass strength by extending a well-established failure criterion (Saroglou and Tsiambaos 2008). It is not intended to give recommendations for support, e.g., selection of temporary support measures in tunnels, through the total rating, as in the case of RMR, as that would not be appropriate. It is stated that the selection of temporary support in tunnels in anisotropic rock mass is often quite complicated due to asymmetric loading occurring in such conditions and, therefore, the support design requires modeling of the anisotropic conditions using appropriate methods. The application of this rock mass classification is illustrated with selected case studies in anisotropic rock masses. The selected case studies cover a wide range with varying degrees of structure anisotropy, thus demonstrating adequately the applicability of the classification in such conditions.

Anisotropy at different scales

General concept

The behavior of anisotropic rock masses is governed by two main aspects (Saroglou 2013):

1. Inherent strength anisotropy of intact rock due to the variation of uniaxial compressive strength ($\sigma_{c\beta}$), when loading occurs at different angles of loading, β, which is the angle between the principal loading axis and the plane of anisotropy. Anisotropy of intact rock is characterized by the strength anisotropy index (R_C), defined as the ratio between the maximum strength, occurring normal to the plane of anisotropy, to the minimum strength, occurring at an angle of 30–45° from the principal loading axis.
2. Structure anisotropy, which stems from the degree of anisotropic structure (foliation, bedding, etc.) and conditions of the anisotropy surfaces.

These aspects are described as a concept in Fig. 1.

Anisotropy of intact rock

Anisotropy of intact rock, characterized as "inherent" anisotropy, stems from the existence of bedding, foliation, and schistosity planes in intact rock. It is obvious at the macroscale (on the order of meters) and at the microscale (on the order of millimeters).

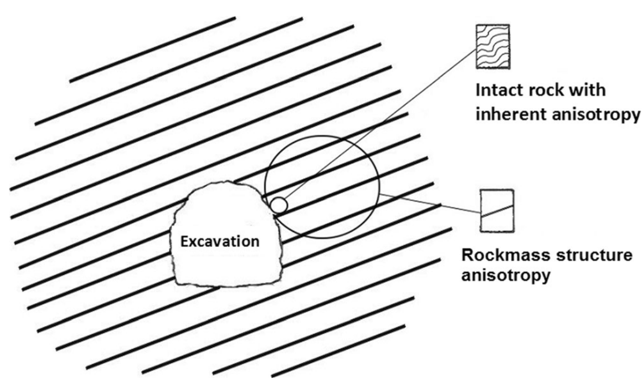


Fig. 1 Main aspects of the characterization of anisotropic rock mass at different scales (specimen scale within intact rock vs. bedding, foliation scale in a rock mass)

The variation of strength in uniaxial loading conditions of intact rock with respect to the loading direction, b, is defined as strength anisotropy. The degree of strength anisotropy (R_C) describes the anisotropy of intact rock (Saroglou and Tsiambaos 2008).

The minimum uniaxial strength is encountered, as expected, when loading is applied at an orientation between $\beta = 30°$ and 45° relative to the foliation planes. The variation of the uniaxial compressive strength of anisotropic rocks can be described by Eq. (1), initially proposed by Jaeger (1960) and modified by Donath (1961).

$$\sigma_{c\beta} = A - D[\cos 2(\beta_m - \beta)] \tag{1}$$

where β_m is the angle at which the uniaxial compressive strength is minimum (usually between 30° and 45°), and A and D are constants. The values of constants A and D can be determined given that the uniaxial compressive strength is known at least at three different loading angles, that of $\beta = 0°$, 30°, and 90°.

Saroglou and Tsiambaos (2007), based on a large number of tests in anisotropic metamorphic rocks (Saroglou 2007), proposed a classification system of rock anisotropy using the ultrasonic velocity index, uniaxial compressive strength index, and point load index.

The anisotropy of intact rock is taken into account by varying the Hoek–Brown strength parameters (σ_{ci}, m_i) according to the orientation of loading, β, by incorporating the parameter k, as proposed by the modified Hoek–Brown criterion (Saroglou and Tsiambaos 2008) given in Eq. (2).

$$\sigma_1 = \sigma_3 + \sigma_{c\beta} \cdot \left(k_\beta \cdot m_i \frac{\sigma_3}{\sigma_{c\beta}} + s \right)^{0.5} \tag{2}$$

where $\sigma_{c\beta}$ is the uniaxial compressive strength at an angle of loading β and k_β is the parameter describing the anisotropy effect.

According to these authors, the degree of strength anisotropy, R_C, relates well with the ratio k_{90}/k_{min}, practically with $1/k_{30}$, as shown Eq. (3).

$$Rc = \frac{k_{\beta=90}}{k_{\beta \min}} = \frac{1}{k_{\beta=30}} \tag{3}$$

where k_{90} is the value of the parameter k_β when loading is perpendicular to the foliation, equal to unity, and k_{30} is its value at the orientation of minimum strength, at $\beta = 30$–45°. This ratio is greater for the rocks with a high degree of anisotropy and reduces significantly for the rocks with a low degree of anisotropy.

In order to estimate the minimum failure envelope due to anisotropy, the parameter $k_\beta = 30°$ is determined as $1/R_C$, based on the previous equation.

Ismael et al. (2014) correlated the ratio k_{90}/k_{min} with R_C by fitting data from 15 anisotropic rocks (slates, shales, siltstones, schists, sandstone, gneiss). The same authors proposed a classification of the anisotropic strength index R_C based on the range of parameter k_{min}.

Rock mass structure anisotropy

Barton and Quadros (2015) mentioned that the appearance of rock masses is strongly dependent on their degrees of anisotropy, which stems from fundamental properties such as bedding or schistosity.

The degree of rock mass structure anisotropy stems from the intensity of the principal anisotropy planes (e.g., foliation) in a transversely isotropic rock mass, which is practically determined by the spacing of the anisotropy planes.

In this respect, the distance of the anisotropy planes, S, will be higher in a rock mass that has a lower degree of anisotropy (case A in Fig. 2) in comparison to that of a highly anisotropic rock mass (case B in Fig. 2).

Examples of such rock masses, with different degrees of structure anisotropy, are presented in Fig. 3a, b.

The proposed rock mass classification system takes into account the rock mass structure anisotropy by incorporating the intensity of the foliated/bedded structure, through the spacing of the foliation/bedding planes, into the rating system. The aim of the proposed rating system is to be able to differentiate two anisotropic rock masses with different degrees of structural anisotropy. Conceptually, this approach is comparable to the decreasing rock mass quality (thus, GSI value) with increasing foliation degree in the GSI chart proposed by Hoek and Karzulovic (2000).

Effect of confining stress

The effect of confining stress on the degree of strength anisotropy is very important and should be considered in the characterization of anisotropic rock masses. The degree of anisotropy, R_C, generally decreases with the confining pressure, σ_3. The effect of confining stress on the degree of strength anisotropy is described by Vutukuri et al. (1995), as shown in Eq. (4).

$$Rc = \frac{\sigma_{190^0}}{\sigma_{130^0}} = A \cdot \exp(-B \cdot \sigma_3) \tag{4}$$

where

$$Rc = I\sigma c = \frac{\sigma_{c90^0}}{\sigma_{c\min}} = A \tag{5}$$

when $\sigma_3 = 0$ MPa. The parameter B represents the gradient of decrease of the anisotropy index with increasing σ_3.

The decrease of the anisotropy degree with increasing confining pressure was studied in marbles, schists, and gneisses by Saroglou (2007). It is evident that rocks

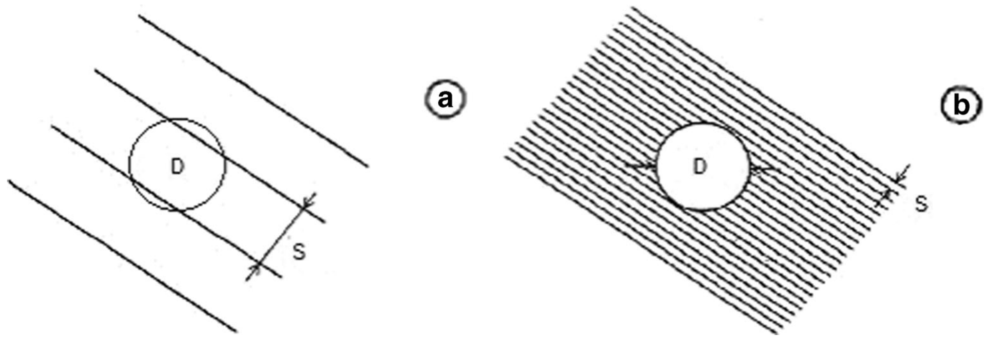


Fig. 2 Examples of the spacings of the major anisotropy plane in anisotropic rock masses

exhibiting higher anisotropy show greater decrease with increasing confining pressure.

Based on this finding, the rock mass classification system for anisotropic rocks has to consider a correction of the rating of anisotropy degree with increasing confining stress.

Proposed rock mass classification

General

The application of the proposed classification refers to rock masses that are transversely isotropic and the inherent anisotropy stemming from schistosity or bedding planes is the principal structure that dominates the rock mass in the scale of the project.

The presence of one or two discontinuity sets in the rock mass does not influence the continuity/persistence of the anisotropic structure; thus, the rock mass can be classified using the Anisotropic Rock Mass Rating (ARMR). Such rock masses were presented in Fig. 3. The classification is marginally applicable when the anisotropic structure is damaged due to the existence of more than two discontinuity sets.

Rating parameters

The ARMR considers the following parameters:

(a) Strength anisotropy index, R_C
(b) Uniaxial compressive strength of intact rock
(c) Degree of structure anisotropy (spacing of anisotropy planes)
(d) Corrected RQD
(e) Condition of anisotropy surfaces
(f) Groundwater conditions

Additionally, an adjustment of the total rating is proposed based on the confining stress range of the project. A correction according to the orientation of the anisotropy planes with respect to the engineering work is not considered, as the effect of their orientation is already taken into account through strength anisotropy and parameter k_β.

The overall rating approach of ARMR and the rating scores of each parameter are based on the Rock Mass Rating system (1989 version) (Bieniawski 1989).

The overall rating approach and the rating scores of each parameter are summarized in Table 1.

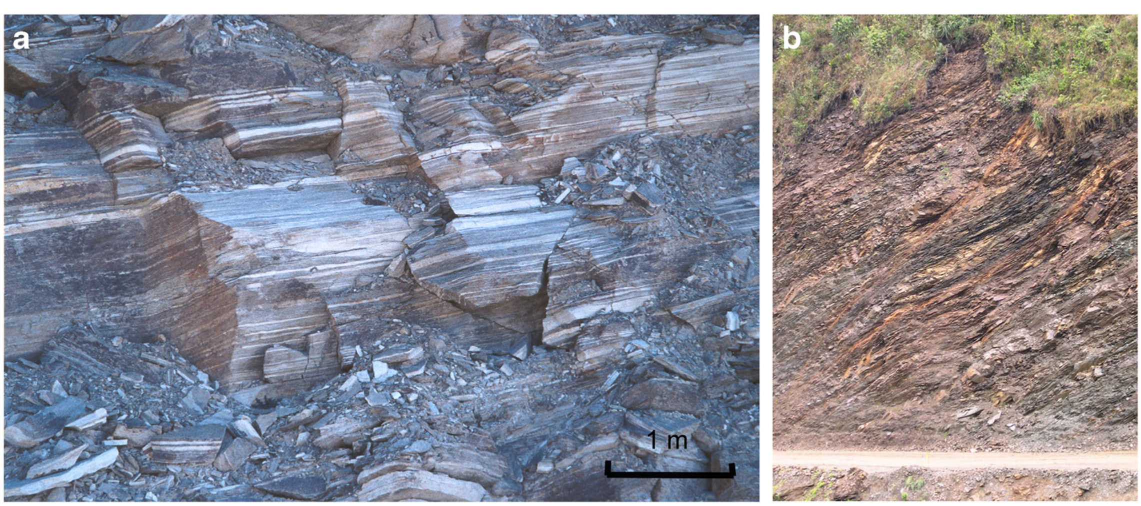


Fig. 3 **a** Gneiss rock mass with a low degree of structure anisotropy (Egnatia highway, Greece). **b** Phyllitic rock mass with a high degree of structure anisotropy (Mazar Dam, Ecuador)

Strength anisotropy index, R_C

The degree of anisotropy is rated according to the strength anisotropy degree, R_C. The value range of each category is based on the classification of uniaxial compressive strength rock anisotropy (Saroglou and Tsiambaos 2007), which follows from the anisotropy classification proposed by Ramamurthy (1993). The rating of anisotropy strength is presented in Table 1.

Strength of intact rock, σ_{ci}

The uniaxial compressive strength should be determined in the laboratory based on uniaxial compression or point load tests, in which loading is applied perpendicular to planes of anisotropy. When laboratory tests are not possible or a field estimate is needed, the International Society for Rock Mechanics (ISRM) proposed Tables (ISRM 2007) could be used to obtain estimates. The rating of intact rock strength is presented in Table 1.

Degree of structure anisotropy (spacing of anisotropy planes)

This parameter reflects the degree of structure anisotropy, which is well described using the spacing of the planes of anisotropy (i.e., foliation, bedding). The scale affects the degree of structure anisotropy, as it will have significantly different importance if, e.g., a tunnel has a diameter of 1 or 10 m. An appropriate scale for the characterization of the spacing is between 5 to 10 m. The rating of the degree of structure anisotropy is presented in Table 1.

Corrected RQD

It is well known that the RQD is not sensitive to the variation of discontinuity spacing greater than 1 m. Additionally, the RQD is direction-dependent, potentially showing high values if "drilled" parallel to the dominant anisotropy plane (a poor sampling strategy) and lower RQD values if "drilled" perpendicular to it (Barton and Quadros 2015).

In ARMR, when calculating the corrected RQD of the rock mass, the existence of the principle anisotropy plane should not be considered. This is due to the fact that the effect of the anisotropy planes is accounted for in the rating of the spacing of anisotropic structure. The RQD should be determined by core logging data (Lowson and Bieniawski 2013).

This parameter is incorporated in the classification in order to describe the possible fracturing degree due to existing discontinuity sets other than the main anisotropic structure. The rating of RQD is presented in Table 1.

Table 1 Classification parameters and their ratings for the Anisotropic Rock Mass Rating (ARMR)

Strength anisotropy degree, R_C	≤ 1.1	1.1 – 2.0	2.0 – 3.0	3.0 – 5.0		≥ 5.0	
Description	Isotropic	Low	Moderate	High		Very high	
Rating	20	17	13	8		3	
Uniaxial compressive strength (MPa)	> 250	100 – 250	50 – 100	25–50	5 – 25	1 – 5	< 1
Point load strength (MPa)	> 10	4 – 10	2 – 4	1–2	For this low range, uniaxial compressive strength is preferred		
Rating	15	12	7	4	2	1	0
Spacing of anisotropic structure	> 1.2 m	0.6 – 1.2 m	200 – 600 mm	40 – 200 mm		< 40 mm	
Rating	20	15	10	8		5	
Rock quality designation, RQD (%)	90 – 100	75 – 90	50 – 75	25 – 50		< 25	
Rating	15	10	7	4		2	
Condition of surfaces	Very rough surfaces, not continuous, no separation, unweathered wall rock	Rough surfaces, separation < 1 mm, slightly weathered rock	Slightly rough surfaces, separation < 1 mm, highly weathered rock	Slickensided surfaces or gouge < 5 mm thick or separation 1–5 mm, continuous		Soft gouge > 5 mm thick or separation > 5 mm, continuous	
Rating	15	10	7	4		0	
Groundwater	Completely dry	Damp	Wet	Dripping		Flowing	
Rating	15	10	7	4		0	

Condition of anisotropy surfaces

This parameter reflects the condition of the rock mass anisotropy surfaces and is calculated as the sum of five subratings, according to Bieniawski (1989), each related to a property of the planes, specifically, the length, the aperture, the roughness, the infilling, and the weathering. The rating for the surface condition of anisotropic structures is presented in Table 1. Generally, the principle follows that of the RMR_{89} system (Bieniawski 1989), but the values for each category are different.

Groundwater conditions

Groundwater plays an important role in the mechanical response of rock masses and has been one of the most important parameters of rock mass characterization. The effects of groundwater on rock mass are described through adjectives such as dry, damp, wet, dripping, and flowing (ISRM 2007). The groundwater conditions are taken into account according to the rating presented in Table 1, which has the same rating as the RMR_{89} system (Bieniawski 1989).

Adjustment of the final rating

The final rating is adjusted according to the effect of confining stress on the engineering project.

Effect of confining stress

In order to account for the effect of confining stress, an adjustment of the rating of anisotropy degree is proposed.

The stress conditions are characterized as low, intermediate, and high in-situ stress, as suggested by Martin et al. (1999).

In general principle, a shifting to lower degree of strength anisotropy with increasing confining stress is suggested, as presented in Table 2.

Total rating index

ARMR provides a classification of the anisotropic rock mass in five classes of geomechanical quality, following the principle of the RMR_{89} index.

Higher total index values refer to rock masses with lower anisotropy degree, while low values refer to rock masses with high anisotropy degrees. The rock mass quality classes are shown in Table 3.

Application to case studies

In order to validate the proposed rock mass classification, specific case study sites were selected, according to the following criteria:

1. The strength anisotropy degree has a wide range
2. The intensity of structure anisotropy is different, ranging from slightly to highly anisotropic

Slate rock mass (China)

The foliated slate is encountered in a quarry in Jiujiang, Jiangxi Province in China, as reported by Chen et al. (2016). The slate is a metamorphosed Precambrian rock from sedimentary rocks, striking northwest and with a dip angle between 42° and 50° (Fig. 4). It has a well-developed slaty structure, with the bands displaying dark gray to light gray colors. The prevailing rock mass conditions in terms of spacing of foliation, RQD, and condition of surfaces are presented in Table 4. In terms of strength anisotropy, the intact rock is moderately anisotropic ($R_C = 2.66$).

The total ARMR value of the slate was calculated to be equal to 51–54 and the rock mass is characterized as moderately anisotropic.

Quartz schist rock mass (USA)

The site belongs to a former gold mine, at approximately 1500 m depth, in South Dakota, USA. A number of deep boreholes were drilled from within the existing mine drifts and data were collected for the in situ rock mass conditions. Sericite carbonate quartz schist is the most common lithology observed and foliation is the dominant rock mass fabric of the Poorman Formation within the project area (Fig. 5a). The rock is generally very thinly to intensely foliated and foliation is often wavy and/or contorted. Sulfides, including pyrite and magnetic pyrrhotite, generally make up 1–5% of sericite carbonate quartz schist and commonly occur disseminated within

Table 2 Adjustment of total rating based on confining stress range

Stress	σ_1/σ_c	Adjustment
Low in-situ stress	< 0.15	No change to rating
Intermediate in-situ stress	0.15 – 0.4	Move one cell towards left in the strength anisotropy degree (+ 5, + 4, or + 3)
High in-situ stress	> 0.4	Move two cells towards left in the strength anisotropy degree

Table 3 Rock mass quality classes according to ARMR values

Rating	100 – 81	80 – 61	60 – 41	40 – 21	< 20
Class no.	I	II	III	IV	V
Description	Massive or isotropic rock mass	Slightly anisotropic rock mass	Moderately anisotropic rock mass	Highly anisotropic rock mass	Very highly anisotropic to sheared rock mass

the rock or as blebs and stringers along foliation. Foliation is typically very well developed, but can be severely contorted in the vicinity of fold hinges.

The degree of foliation is also partially dependent on rock type. Foliation within the graphitic schist is typically the most pronounced and thinly spaced. Sericite carbonate quartz schist foliation is more variable and was typically less well developed where the carbonate content was highest. The prevailing rock mass conditions in terms of spacing of foliation, RQD, and condition of surfaces are presented in Table 5. In terms of strength anisotropy, the intact rock is slightly anisotropic ($R_C = 1.87$).

The total ARMR value was calculated to be equal to 63–67 and the rock mass is characterized as slightly anisotropic. The total rating was adjusted due to high stresses, and the final ARMR value is equal to 66–70.

Shale rock mass (Australia)

The bedded iron ore deposits in the Pilbara region of Western Australia are hosted by highly anisotropic rock masses of the Brockman Iron Formation (BIF) and Marra Mamba Iron Formation (Bar et al. 2016). These comprise strong-banded iron formation interbedded with weak shales and span hundreds of kilometers in the region. The study mine site is developed in Joffre Member, which is a banded iron formation interbedded with thin shales, highly weathered (Fig. 6a, b). The prevailing rock mass conditions in terms of spacing of foliation, RQD, and condition of surfaces are presented in Table 6. In terms of strength anisotropy, the intact rock is highly anisotropic ($R_C = 4.65$).

Fig. 4 Field outcrop of Jiujiang slate

The total ARMR value was calculated to be equal to 57–60 and the rock mass is characterized as moderately anisotropic, as presented in Table 6.

Gneiss rock mass (northern Greece)

The gneissic rock mass is encountered in northern Greece, where a number of tunnels of Egnatia highway were constructed. The gneiss is a muscovite-biotite-rich medium-grained gneiss, which has well-developed gneiss banding (Saroglou 2007), while the gneissic rock mass is slightly fractured by two discontinuity sets (Fig. 3a). The prevailing rock mass conditions in terms of spacing of foliation, RQD, and condition of surfaces are presented in Table 7. In terms of strength anisotropy, the intact rock is moderately anisotropic ($R_C = 3.8$).

The total ARMR value of the gneissic rock mass was calculated to be equal to 65–70 and it is characterized as slightly anisotropic.

Calcschist rock mass (Italy)

Saint-Martin-La-Porte tunnel is 2.3 km long and belongs to the Lyon–Turin base tunnel. The tunnel was mostly excavated in heavily foliated calcschist (Fig. 7a), and its overburden was 300 m. Significant problems of the support system developed when the calcschist was encountered in the tunnel, resulting in very large deformation problems (Fig. 7b), which necessitated reprofiling of the tunnel (Rettighieri et al. 2008). The problems appeared to be associated with the complex distribution of axial and shear forces in the support shell as a result of the response of the highly anisotropic rock mass to high in situ stresses (Bonini and Barla 2012). The prevailing rock mass conditions in terms of spacing of foliation, RQD, and condition of surfaces are presented in Table 8. In terms of strength anisotropy, the intact rock is moderately anisotropic ($R_C = 3.5$).

The total ARMR value for the foliated calcschist was calculated to be equal to 35 and the rock mass is characterized as highly anisotropic. The total rating was adjusted due to high stresses, and the final ARMR value is equal to 40.

Table 4 Rating of slate rock mass

Rating parameter	Description	Rating
Strength anisotropy degree, R_C	2.66	13
Uniaxial compressive strength (MPa)	104.9	7
Spacing of anisotropic structure (cm)	40 – 200 mm	8
RQD (%)	25–50	4
Condition of surfaces	Slickensided, slightly rough	4 – 7
Groundwater	Completely dry	15
Total rating	Moderately anisotropic rock mass	51 – 54
Stress adjustment	$\sigma_1/\sigma_c < 0.15$	No

Using ARMR to determine rock mass strength

Introduction

According to Hoek and Brown (1997), if the 1989 version of Bieniawski's RMR classification is used, then the GSI can be calculated as: GSI = $RMR_{89} - 5$ for $RMR_{89} > 23$ and where RMR_{89} has the groundwater rating set to 15 and the adjustment for joint orientation set to zero. Marinos et al. (2005) proposed that these correlations between GSI and other rock mass classification systems should not be used.

Truzman (2009) investigated the applicability of the GSI for the classification of foliated metamorphic rocks and proposed the following correlating relation between the GSI and RMR for such rocks: GSI = 1.0122 × RMR, which shows that the values of GSI and RMR in schistose metamorphic rocks are almost equal (Truzman 2009).

In this perspective, it is proposed that the total value of ARMR is used without any correction in the modified Hoek–Brown failure criterion, proposed by Saroglou and Tsiambaos (2008), when determining the rock mass strength.

Fig. 5 Quartz schist outcrop in the mine

Proposed failure criterion for anisotropic rock mass

The proposed failure criterion, which is linked with ARMR, is based on the modified Hoek–Brown criterion of anisotropic rock (Saroglou and Tsiambaos 2008) and takes into account:

1. The orientation of anisotropy in rock mass (through parameter k_β) and
2. The anisotropy degree of the rock mass (through ARMR classification)

According to the approach described earlier, the anisotropy of rock mass is characterized by the strength anisotropy of the intact rock and the structure anisotropy. The first is determined by the variation of intact rock strength relevant to the orientation (considering k_β in the failure criterion), while the second is described by the ARMR value of the anisotropic rock mass. Once the ARMR total rating is calculated, the failure envelope of the rock mass can be determined by incorporating this in the proposed modified Hoek–Brown failure criterion. The procedure for using parameter k_β and ARMR in the modified Hoek–Brown failure criterion is presented in Fig. 8.

The proposed modified Hoek–Brown failure criterion for use in anisotropic rock masses is described by Eq. (6).

$$\boldsymbol{\sigma_1} = \boldsymbol{\sigma_3} + \boldsymbol{\sigma_{ci\beta}} \cdot \left(\mathbf{k_\beta} \cdot \left(\mathbf{m_{b,an}} \left(\frac{\boldsymbol{\sigma_3}}{\boldsymbol{\sigma_{c\beta}}} \right) + \mathbf{s_{an}} \right) \right)^{\alpha} \tag{6}$$

where:

σ_1	Major principal stress at failure
σ_3	Minor principal stress at failure
$\sigma_{ci,\beta}$	Uniaxial compressive strength of intact rock at orientation of anisotropy, β
$m_{b,an}$	Reduced value of m_i parameter for anisotropic rock mass
a, s_{an}	Constants
k_β	Constant related to the orientation of anisotropy

Table 5 Rating of quartz schist rock mass

Rating parameter	Description	Rating
Strength anisotropy degree, R_C	100/53.4 = 1.87	17
Uniaxial compressive strength (MPa)	100	7
Spacing of anisotropic structure (cm)	< 40 mm	5
RQD (%)	95–100	15
Condition of surfaces	Smooth planar, some hard mineralization (qtz and pyrite), minor iron oxide. JRC = 4–6	4 – 7
Groundwater	Dry. Water table is kept below mine level by pumps. Only very minor seeps from surface during heavy rains	15
Total rating	Slightly anisotropic rock mass	63 – 67
Stress adjustment	$\sigma_1/\sigma_c = 0.37$	+ 3
Final rating		66 – 70

The parameters of the criterion are determined according to the generalized Hoek–Brown failure criterion (Hoek et al. 2002) by incorporating the total ARMR value, using Eqs. (7) to (9).

$$\mathrm{m_{b,an}} = m_i \cdot \exp\left(\frac{ARMR-100}{28-14D}\right) \tag{7}$$

$$\mathrm{s_{an}} = \exp\left(\frac{ARMR-100}{9-3D}\right) \tag{8}$$

$$\alpha = \frac{1}{2} + \frac{1}{6}\left(e^{-ARMR/15} - e^{-20/3}\right) \tag{9}$$

The strength of the anisotropic rock mass, $\sigma_{cm,an}$, is given by Eq. (10).

$$\sigma_{\mathrm{cm,an}} = \sigma_{\mathrm{ci},\beta} \cdot \frac{\left(\mathrm{m_{b,an}} + 4\mathrm{s_{an}} - a\left(\mathrm{m_{b,an}} - 8\mathrm{s_{an}}\right)\right) \cdot \left(\mathrm{m_{b,an}}/4 + \mathrm{s_{an}}\right)^{a-1}}{2(1+a)(2+a)} \tag{10}$$

Application to case studies

The proposed Hoek–Brown failure criterion was applied to the studied anisotropic rock masses.

The uniaxial compressive strength and anisotropy degree of the studied intact rocks (σ_{ci}, R_C) were determined based on uniaxial compression tests perpendicular to the anisotropy planes and at the orientation of minimum strength. The parameter m_i of the intact slate, quartzitic schist, and gneiss was determined from triaxial tests perpendicular to the anisotropy planes, while for the calcschist and shale, it was based on the values proposed by Hoek et al. (2002).

The proposed criterion was applied for the case where anisotropy planes are considered perpendicular to the major principal stress; therefore, the value of the parameter k_β was equal to unity. The disturbance factor, D, was considered equal to zero in all cases.

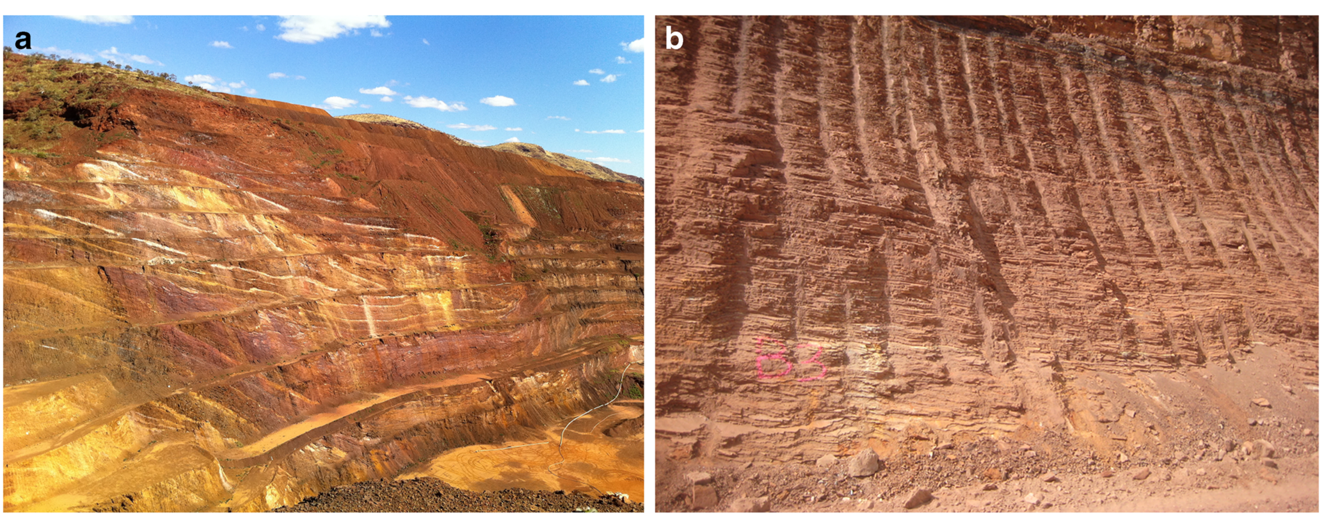


Fig. 6 **a** Mine in the Dales Gorge Member (Brockman Iron Formation [BIF] interbedded by distinct shales, lighter colored). **b** BIF bench face of Joffre Member at a different mine

Table 6 Rating of shale rock mass

Rating parameter	Description	Rating
Strength anisotropy degree, R_C	151/32.5 = 4.65	8
Uniaxial compressive strength (MPa)	151	12
Spacing of anisotropic structure (cm)	5 – 20	8
RQD (%)	50 – 75	7
Condition of surfaces	Undulating-rough; iron staining rarely < 1 m silty-clay infilling	7 – 10
Groundwater	Completely dry, above water table	15
Total rating	Moderately anisotropic rock mass	57 – 60
Stress adjustment	$\sigma_1/\sigma_c < 0.15$	No

The Hoek–Brown rock mass parameters ($m_{b.an}$, s_{an}, α) were calculated based on the proposed criterion and are given in Table 9.

It is evident that, as the degree of rock mass structure anisotropy increases, the ARMR value decreases and the failure criterion parameters (s_{an}, $m_{b.an}$) also decrease, as reported in Table 9. The highest strength was determined for the gneiss and quartzitic schist rock mass, as their ARMR values were the highest, being 65 and 68, respectively. The lowest strength was determined for the calcschist rock mass as the ARMR value was the lowest, being equal to 40, and its intact rock strength was also the lowest. The failure envelopes of the examined rock masses are presented in Fig. 9. It can be seen that, as the ARMR value decreases, the failure envelope of the rock mass decreases accordingly, in the case of principal stress perpendicular to anisotropy planes.

Based on the validation of the modified criterion in the case study sites, it was found that the failure envelope of an anisotropic rock mass is dependent on the orientation of anisotropy planes in relation to the principal loading axis, essentially incorporated through parameter k_β, and the degree (intensity) of structure anisotropy of the rock mass, incorporated through the ARMR value.

The minimum failure envelope of a given rock mass occurs when the orientation of anisotropy planes is considered at the minimum strength angle (30–45°); thus, parameter k_β has its minimum value ($k_{\beta min}$). This is true irrespective of the degree of structure anisotropy and, thus, the ARMR value of the rock mass.

In order to demonstrate the effect of the orientation of anisotropy planes on the rock mass strength, the failure envelopes of the quartzitic schist rock mass were determined for different orientations of the structure anisotropy ($\beta = 0°$, 15°, 30°, 45°, and 90°). The parameter k_β was calculated for each orientation based on the triaxial tests performed on intact rock. The failure envelopes of the quartzitic schist rock mass, at different orientation of anisotropy planes and rock mass quality ARMR equal to 68, are presented in Fig. 10. As expected, the maximum strength envelopes are perpendicular and parallel to the planes of anisotropy and the minimum envelopes are when the orientation is at 45°.

Modeling of anisotropic rock mass

Anisotropy in a rock mass resulting from preferentially orientated structural features around the boundary of an underground opening affects the extent and shape of low confinement zones and directly influences the location and depth of stress-driven rock mass degradation (Bewick and Kaiser

Table 7 Rating of gneissic rock mass

Rating parameter	Description	Rating
Strength anisotropy degree, R_C	3.8	8
Uniaxial compressive strength (MPa)	85	7
Spacing of anisotropic structure	0.6 – 1.0 m	15
RQD (%)	75 – 90	10
Condition of surfaces	Rough, fresh to slightly weathered	10
Groundwater	Completely dry	15
Total rating	Slightly anisotropic rock mass	65
Stress adjustment	$\sigma_1/\sigma_c < 0.15$	No

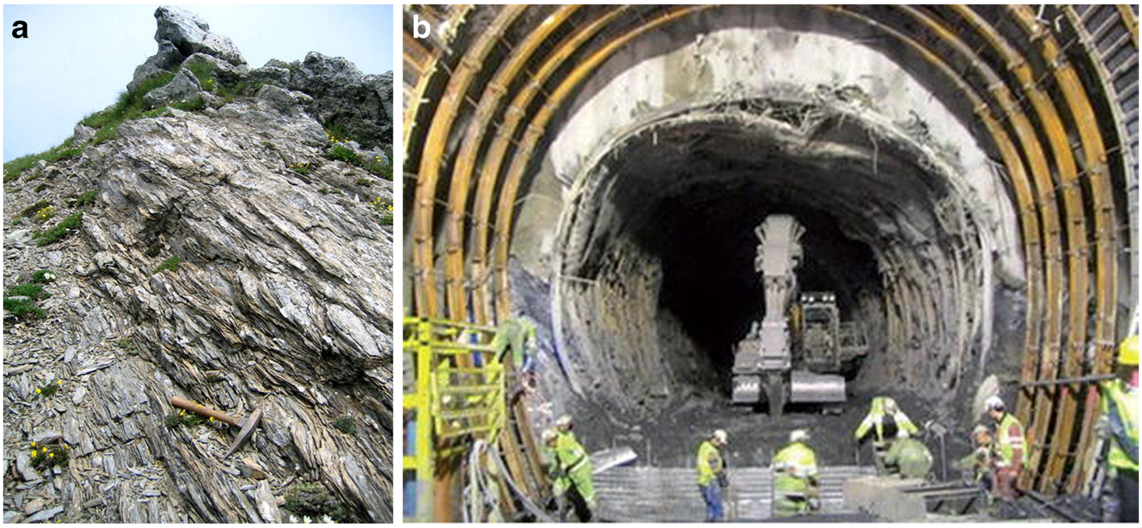


Fig. 7 **a** Heavily foliated calcschist (photo from M. Diederichs). **b**) Saint-Martin-La-Porte access adit, Lyon–Turin base tunnel (Rettighieri et al. 2008)

2009). Different approaches can be used in order to model anisotropic rock masses, either continuum or discontinuum methods. Modeling using continuum methods are commonly used, where rock mass anisotropy is introduced through anisotropic constitutive models (e.g., transversely isotropic model) using finite element codes (Martin et al. 2016). An alternative approach is the ubiquitous-joint model, used in finite difference code, which can be employed to describe the behavior of rock mass with one closely spaced anisotropy plane (Papavasiliou et al. 2010). The presence of the joints (anisotropy planes) in the rock mass can be simulated by using a ubiquitous joint model. In the ubiquitous joint model, failure can occur either in the rock material or along the joint or even in both, depending on the stress field, the joint orientation, and the strength parameters of rock and joints. Marinos et al. (2007) mention that it is possible to model anisotropy using the continuum modeling approach by superimposing a large number of discontinuities on an isotropic rock mass. These discontinuities can be assigned shear strength and stiffness characteristics that simulate the properties of the schistosity and bedding planes in the rock mass.

Another approach is using discontinuum models in distinct element codes, which consider explicitly modeled joints while the rock material between the joints is usually isotropic (Schubert and Mendez 2017).

In the present study, it is proposed to model anisotropy by superimposing joints on an anisotropic rock mass. The parameters of the anisotropic rock mass, between the explicitly modeled joints (anisotropy planes), are determined using the modified Hoek–Brown criterion and the ARMR classification, as presented in the section entitled "Proposed failure criterion for anisotropic rock mass".

Nevertheless, depending on the type of the anisotropic rock mass (degree of anisotropy and ARMR value), different modeling approaches can be used, either continuum or discontinuum, as presented in Table 10.

The main modeling approaches, depending on the type of anisotropic rock mass, can be summarized as follows:

Table 8 Rating of calcschist rock mass

Rating parameter	Description	Rating
Strength anisotropy degree, R_C	3.5	8
Uniaxial compressive strength (MPa)	35	4
Spacing of anisotropic structure	< 40 mm	5
RQD (%)	25 – 50	4
Condition of surfaces	Slickensided	4
Groundwater	Damp	10
Total rating	Highly anisotropic rock mass	35
Stress adjustment	$\sigma_1/\sigma_c = 0.21$	+ 5
Final rating		40

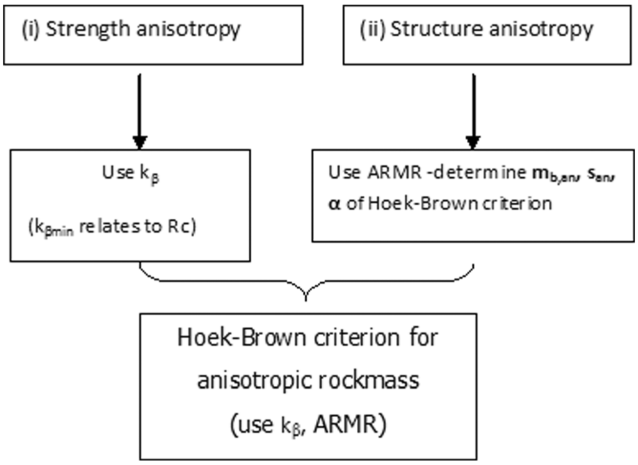


Fig. 8 Procedure for determining the anisotropic rock mass strength

– Continuum (isotropic) for massive isotropic rock mass (ARMR > 80)
– Discontinuum or anisotropic continuum (explicitly modeled joints or ubiquitous-joint model) for slightly and moderately anisotropic rock mass (41 < ARMR < 80)
– Discontinuum and anisotropic continuum (use the ubiquitous-joint model between explicitly modeled joints) for highly anisotropic rock mass (21 < ARMR < 40)
– Anisotropic continuum for very highly anisotropic to sheared rock mass (ARMR < 20)

In massive isotropic rock masses, a continuum approach can be adopted using the rock mass strength determined from the modified Hoek–Brown criterion.

In slightly to moderately anisotropic rock masses, it is preferable to model anisotropy using explicit joints, as the spacing of anisotropy planes allows their implementation in the model. The strength of the rock mass between joints is determined from the modified Hoek–Brown criterion.

In the case of highly anisotropic rock mass, it may be necessary to use the combination of a discontinuum model for explicitly modeled foliation/bedding joints and a continuum ubiquitous-joint model for blocks between joints, as the spacing of anisotropy planes is very small (less than 20 cm).

Finally, in very highly anisotropic to sheared rock masses, the difference in the strength of the rock and that of the anisotropy planes within it is often small (Marinos et al. 2007) and, thus, it is proposed to use an anisotropic continuum model. In this case, the overall rock mass strength can be calculated from the modified Hoek–Brown criterion.

Additionally, in this rock mass, if the anisotropy planes have no preferred orientation due to shearing and tectonic disturbance, it is proposed not to consider anisotropy orientation in the application of the modified criterion (thus, parameter $k_\beta = 1$).

The main advantage of the proposed approach is that the anisotropic strength of the rock mass can be determined using the ARMR classification and the modified Hoek–Brown criterion. Eventually, this can be directly used in modeling using the appropriate method according to the type of anisotropic rock mass.

Conclusions and discussion

A new rock mass classification system, called the Anisotropic Rock Mass Rating (ARMR), specifically designed for anisotropic rock masses, has been developed based on the Rock Mass Rating (RMR) (Bieniawski 1989). The system follows the approach that the behavior of anisotropic rock masses is

Table 9 Properties and calculated parameters

	Slate (China)	Quartz schist (USA)	Shale (Australia)	Gneiss (Greece)	Calcschist (Italy)
σ_{ci}	104	100	151	85	35
$\sigma_{c\beta}$	39	53.4	32.5	22	10
R_C	2.67	1.87	4.65	3.86	3.5
ARMR	52	68	58	65	40
D	0				
k_β	1				
m_i	8.5	9.6	6	23	9
$m_{b.an}$	1.531	3.061	1.339	6.5896	1.056
s_{an}	0.0048	0.0286	0.0094	0.0205	0.0013
α	0.5050	0.5016	0.5033	0.5020	0.5114

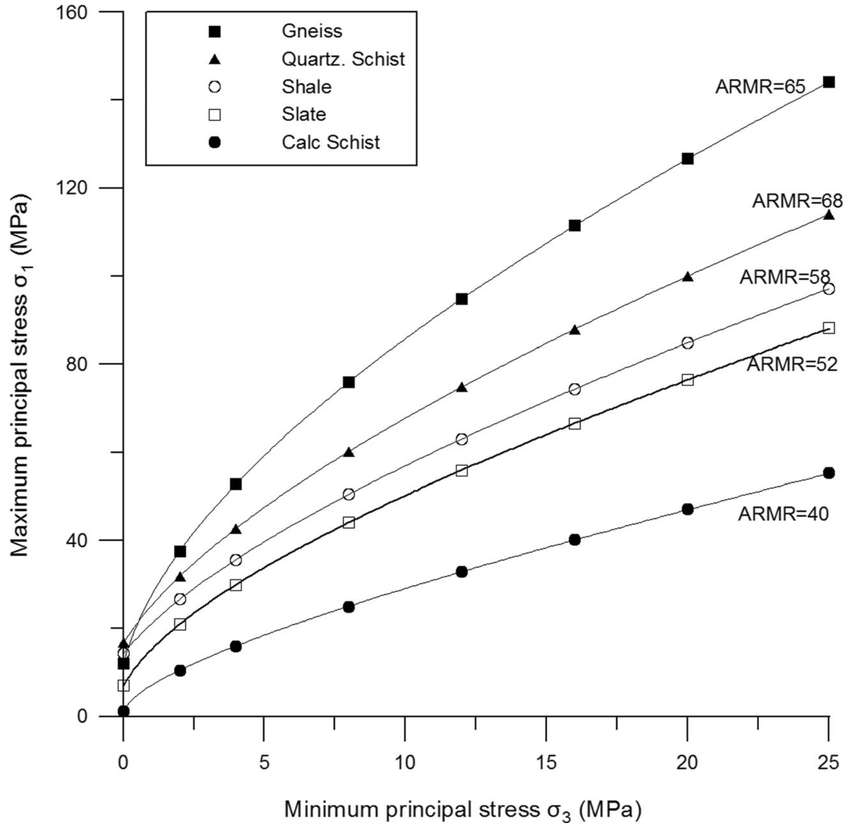


Fig. 9 Failure envelopes of studied anisotropic rock masses

governed by (a) the inherent strength anisotropy of intact rock and (b) the structure anisotropy, which stems from the intensity of anisotropic structure (foliation, bedding, etc.) and quality of the anisotropy surfaces. Considering this, it was evident that a rating approach was necessary, instead of a graphical chart, in order to take into account both of these factors.

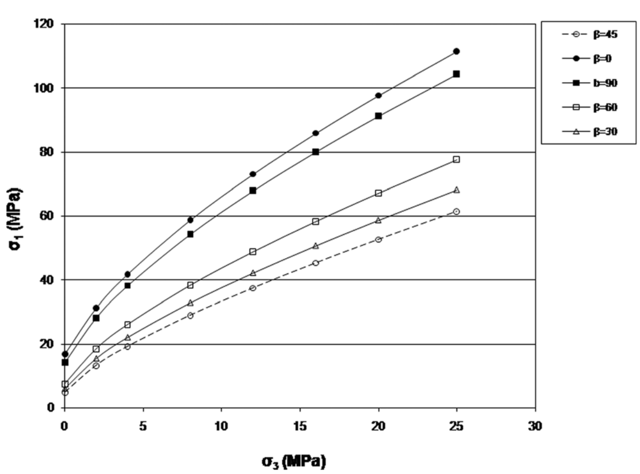


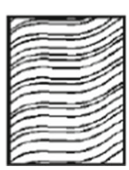
Fig. 10 Failure envelopes of quartzitic schist rock mass at different orientations of foliation

The system considers the following parameters: (a) strength anisotropy index, R_C; (b) uniaxial compressive strength of intact rock; (c) degree of structure anisotropy (spacing of anisotropy planes); (d) corrected rock quality designation (RQD); (e) condition of anisotropy surfaces; and (f) groundwater conditions.

It is noted that the ARMR should not be used in cases where the failure of the rock mass is exclusively controlled by structural features, i.e., anisotropy planes (foliation, bedding). Therefore, it is not directly applicable in slope stability problems, where the anisotropy planes are dipping towards the slope and failure of the rock mass occurs along these planes. In highly anisotropic rock masses with tectonic disturbance (e.g., shearing along planes of anisotropy), when failure occurs partially through the rock mass and partially along the planes of anisotropy, the classification should be used with caution.

Based on the application of the system to specific case studies, ARMR was validated and the expected behavior of the rock masses, in terms of geomechanical quality, was assessed. It was evident that ARMR can incorporate the effect of degree of structure and strength anisotropy on the behavior of the rock mass very effectively. ARMR classification would

Table 10 Proposed approach of analysis for different rock masses

Description of rock mass*		Analysis	Classification
	Massive/ isotropic rockmass S > 1.2 m	Continuum (FEM, FDM)	ARMR > 80
	Slightly anisotropic rock mass S = 0.6 – 1.2 m	Discontinuum (DEM) or anisotropic continuum	ARMR = 61 - 80
	Moderately anisotropic rock mass S = 0.2 – 0.6 m		ARMR = 41 - 60
	Highly anisotropic rock mass S = 0.04 – 0.2 m	Discontinuum (DEM) and anisotropic continuum	ARMR = 21 - 40
	Very highly anisotropic to sheared rock mass S < 0.04 m	Anisotropic continuum	ARMR < 20

*Sketches adapted from Hoek and Karzulovic (2000); S spacing of anisotropic structure

result in different rock mass index in the case of a tunnel excavated in two rock masses with similar intact rock strength and field stress conditions but with different degrees of structure anisotropy, as presented in Fig. 2, which reflects the importance of assessing their different geomechanical quality. The design of excavation and support of these two different tunnel cases would rely on the ARMR value and the overall rock mass strength determined using the modified failure criterion.

The ARMR system was also linked with the modified Hoek–Brown failure criterion for anisotropic rocks (Saroglou and Tsiambaos 2008), thus extending the criterion to rock masses. Based on the validation of the modified criterion in the case study sites, it was found that the failure envelope of an anisotropic rock mass is dependent on the orientation of the anisotropy planes in relation to the principal loading axis, essentially incorporated through parameter k_β, and the degree (intensity) of structure anisotropy of the rock mass, incorporated through the ARMR value. It was also evident that the higher the degree of anisotropy of the rock mass, the lower the ARMR value and, thus, the rock mass strength, as depicted by the respective failure envelope.

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