DOI: https://doi.org/10.68732/63db3539cabc82b7

ISBN: 978-9989-2053-6-1

Application of ARMR for rock slope design

H. Saroglou
NTUA&Geocon, Athens, Greece
saroglou@central.ntua.gr
0000-0002-5253-7972

N. Bar
Gecko Geotechnics, Kingstown, Saint Vincent and the Grenadines

Abstract

The engineering behaviour of rock masses is in many cases anisotropic due to the presence of either bedding, schistosity or joints and fractures. Anisotropic rock mass rating (ARMR) has been developed to assist in rockmass classification and design of structures in anisotropic rockmasses. A modified Hoek & Brown failure criterion, that incorporates ARMR rating, has been developed to calculate the strength of transversely anisotropic rock masses in various orientations with the context of rock engineering design. The paper presents the methodology of applying ARMR and the modified Hoek & Brown criterion to design a slope in an open pit in the Dominican Republic. Slope stability analysisis performed using anisotropic rock mass strength in 2D and 3D. It is demonstrated that the modified Hoek & Brown approach for anisotropic rock mass is slightly higher factor of safety compared to the Generalised Hoek & Brown criterion for isotropic rock masses.

Keywords

ARMR, Anisotropic, Hoek-Brown, Slopes.

1 Introduction

1.1 General

Directional shear strength models allow the application of different shear strengths to different slip surface orientations in numerical analyses. They can be applied in such a way so as to ubiquitously represent weaker bedding planes and foliations upon which shearing is expected to preferentially occur relative to the remainder of the rock mass. In order to apply such models, it is necessary to deter-mine the shear strength of intact rock or rock mass shear strength, the shear strength of the anisotropy plane and define the 'transition' from intact rock or rock mass shear strength to anisotropy plane shear strength (Bar & Weekes, 2017; Saroglou & Bar, 2020).

Linear approximations of non-linear shear strength envelopes derived from Hoek et al. (2002) or Barton& Bandis (1980) failure criteria can be used to predict the behaviour of rock masses and bedding in numerical analyses.

An alternative approach is to determine the strength of anisotropic rock masses for different orientations of the anisotropy plane by using the anisotropic rock mass rating system, ARMR (Saroglou et al., 2019), in conjunction with the Modified Hoek-Brown failure criterion (Saroglou & Tsiambaos, 2008). Using this method, both the shear strength of the intact rock and rock mass strength (in terms of Hoek-Brown or Mohr-Coulomb criteria) can be determined for any orientation of the anisotropy plane, while the least strength of the anisotropic rock mass occurs when the orientation of the anisotropy plane is such that failure takes place along the anisotropy plane, usually at an angle between 30 to 45°.

In this paper, a case study from a slope stability assessment of an open pit mine in the Dominican Republic is presented. The slope is dominated by weak anisotropic rocks and design of future mine slope in this geological environment requires careful consideration of rock mass anisotropy. The slope design is based on a 3D Limit Equilibrium Method (LEM) slope stability analysis using the modified Hoek-Brown criterion and ARMR for the anisotropic rockmass. This assessment is compared with conventional directional shear strength model and recommendations for design are discussed.

2 Anisotropic Rock Mass Rating (ARMR)

2.1 General

The behaviour of anisotropic rock masses is generally dictated by two key aspects – inherent strength anisotropy and structure anisotropy (Saroglou, 2025).Inherent strength anisotropy within the intact rock due to the variation of uniaxial compressive strength (UCS) with respect to the direction of loading relative to the plane of anisotropy (measured in degrees, β). The anisotropy of intact rock can be characterized by the strength anisotropy index (R_c). Structure anisotropy originates from the intensity of anisotropic structure (e.g. foliation, bedding etc.) and the quality or condition of the anisotropy surfaces.

Saroglou et al. (2019) developed the anisotropic rock mass rating (ARMR), specifically developed for anisotropic rock masses to account for the anisotropy of intact rock and rock mass structure anisotropy. Transversely isotropic rock masses, with one or two joint sets in addition to the foliation/bedding can be classified using ARMR, as these joint sets don't influence the persistence of the anisotropic structure. The rating approach of ARMR for each parameter is based on the Rock Mass Rating system (RMR) system by Bieniawski (1989), while the rating scores are modified as two new parameters are added, strength anisotropy index (R_c), and spacing of anisotropy. To account for the effect of confining stress, an adjustment of the rating of anisotropy degree is proposed following the stress classification proposed in Martin et al. (1999).

2.2 ARMR rating

The Anisotropic Rock Mass Rating (ARMR) considers the following parameters:

- Strength anisotropy index, R_c.
- Uniaxial compressive strength of intact rock, σ_c, in which the loading direction is applied perpendicular to the anisotropy planes.
- Degree of structure anisotropy (spacing of anisotropy planes). Scale effects have an influence on the degree of structure anisotropy, so an appropriate scale must be used. For example, when planning a slope excavation of say up to 10 m, an appropriate scale for characterizing the degree of structure anisotropy would be in the order of 2 to 5 m.
- Corrected rock quality designation (RQD_c) whereby the principal anisotropy plane is omitted from calculations. This reduces the direction-dependence of RQD that can arise from sampling bias with 'higher values' when drilled parallel to anisotropy planes or 'lower values' when drilled perpendicular to anisotropy.
- Condition of anisotropy surfaces based on RMR_{89} (Bieniawski, 1989) considering discontinuity length, aperture, roughness, infilling and weathering.

The rating scores of each parameter and the classification to five rock mass quality classes, ranging between isotropic to very highly anisotropic, are presented in Figure 1.

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**	
UCS (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 – 200mm		< 40mm
Rating	**20**	**15**	**10**		**8**		**5**
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 <1mm, slightly weathered rock	Slighlty rough surfaces, separation <1mm, highly weathered rock		Slickensided surfaces or gouge < 5mm thick or separation 1 – 5 mm, continuous		Soft gouge > 5mm 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**
Adjustment of total rating based on confining stress range		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 anisotropy degree (+5, +4 or +3)		
		High in-situ stress	> 0.4		Move two cells towards left in the anisotropy degree		
ARMR Rating	**100 - 81**	**61 - 80**	**60 - 41**		**40 - 21**		**< 20**
Class number	I	II	III		IV		V
Description	Massive or isotropic rockmass	Slightly anisotropic rockmass	Moderately anisotropic rockmass		Highly Anisotropic rockmass		Very highly anisotropic to sheared rockmass

Fig. 1 Anisotropic rock mass rating (ARMR) classification.

2.3 Modified Hoek & Brown criterion for anisotropic rock mass

The generalized Hoek–Brown criterion (Hoek et al, 2002) is widely used nowadays for the estimation of rock mass strength. The criterion was proposed for isotropic conditions, but in many cases, it has also been applied in anisotropic conditions. The modified Hoek-Brown failure criterion for anisotropic rock (Saroglou et al, 2019) is used to estimate the strength of anisotropic rock masses at different orientations. The modified criterion has been linked with ARMR to derive a criterion for anisotropic rock masses. The total ARMR value is effectively used as a replacement of the GSI in the modified Hoek-Brown failure criterion as described in eq. (1).

$$\sigma_1 = \sigma_3 + \sigma_{ci\beta} \cdot \left(k_\beta \cdot \left(m_{b,an} \left(\frac{\sigma_3}{\sigma_{c\beta}} \right) + s_{an} \right) \right)^{\alpha} \quad (1)$$

Where, $\sigma_{ci,\beta}$ 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 parameter describing intact rock anisotropy

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

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

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

Based on the modified criterion, rock mass strength at different orientations can be calculated, which may be lower than the strength determined perpendicular to anisotropy planes by the generalized Hoek & Brown criterion.

3 Open pit slope design in anisotropic rock mass

3.1 Geotechnical conditions

An example from a large open pit mine (3 x 2 km) in the Dominican Republic is presented in which the pit slopes are up to 300 m in highly anisotropic and weak carbonaceous sediments (mudstones), overlying various, relatively isotropic volcanic and volcanoclastic rocks (Figure 2). The carbonaceous sediments are in the order of 100 m thick in the upper portion of the slopes and several instabilities were encountered, generally involving sliding on anisotropy planes and intact rock failure. Several of the instabilities within the carbonaceous sediments have been back analysed to derive and calibrate material properties using 3D LEM in Slide3 software (Rocscience Inc), with directional shear strength and 3D finite difference method (FDM) in FLAC3D software (Itasca, 2019) using the ubiquitous joint model considering φ' and c' of bedding and UCS of rock mass (Cancino et al, 2024). 3D LEM models were developed in Slide3 software to assess the stability of each different conceptual inter-ramp slope angle (IRA) design within the carbonaceous sediments (Bar, 2024).

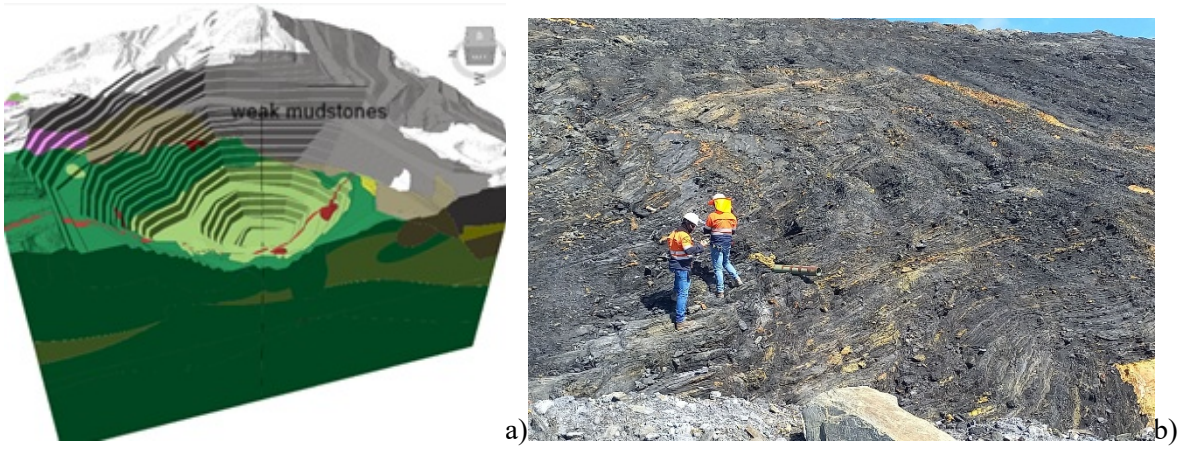


Fig.2 a) Open pit showing area of weak carbonaceous sediments (mudstones), b) exposure of sheared mudstones.

3.2 Slope stability analysis

Two methods of slope stability analysis (using 2D and 3D LEM) were used for future slope design:

a) Conventional anisotropic directional shear strength approach using the generalised isotropic Hoek & Brown criterion for the rock mass and the Mohr-Coulomb criterion with anisotropic linear transition for the bedding planes,
b) Modified Hoek & Brown criterion using ARMR classification with orientation dependent strength rock mass properties. The Hoek & Brown parameters are UCS = 8 MPa, m_i = 8, GSI=35, the bedding strength is c'= 6 kPa and φ'=18^0 (based on back analysis) and the anisotropic linear model transition parameters are A=5^0 and B=30^0. Based on ARMR classification the rock mass is characterized as highly anisotropic (Table 1).

A shear-normal function (non-linear failure envelope) is calculated for different bedding orientations using the modified Hoek & Brown criterion, considering a variation of uniaxial compressive strength and parameter k_β. The failure envelopes for the shear strength of the rock mass using the generalized and modified Hoek & Brown criteria are shown in Figure 3.

Table 1. ARMR classification of mudstone.

Rating parameter	**Description**	**Rating**
Strength anisotropy degree R_c	17/5.3= 3.2	8
Uniaxial compressive strength (MPa)	17	12
Spacing of anisotropic structure (cm)	5 -10	8
R.Q.D. (%)	30 - 50	4
Condition of surfaces	Slickensided, highly weathered	4
Groundwater	Damp	10
Total rating	Highly anisotropic rock mass	36
Stress adjustment	$\sigma_1 / \sigma_c < 0.14$	No

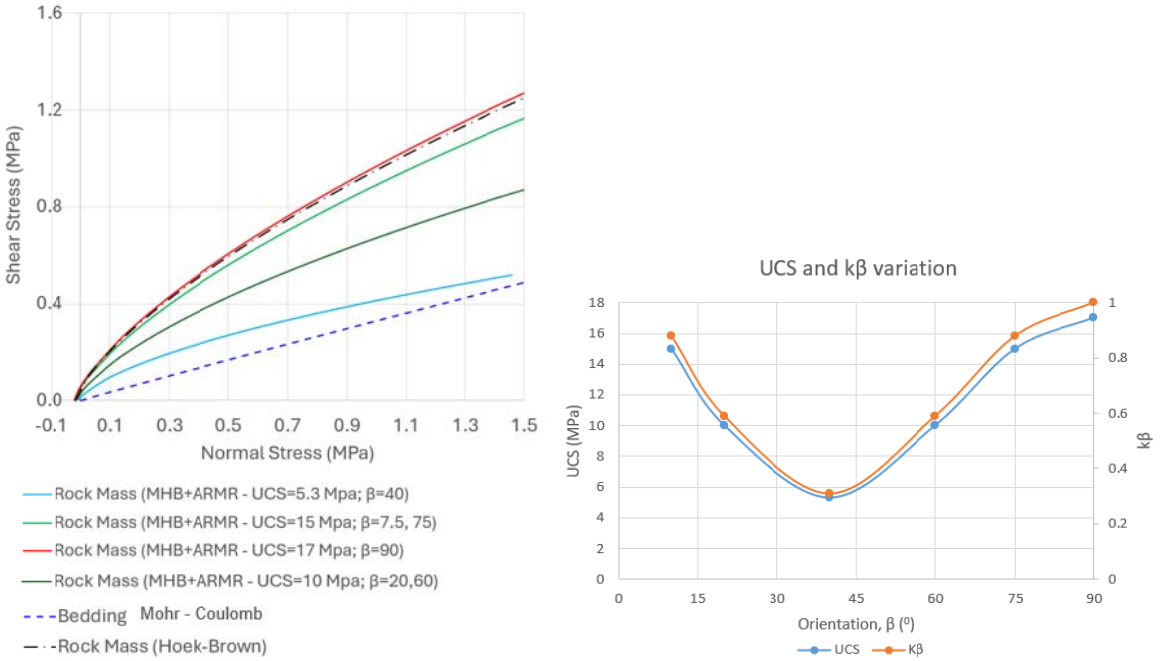


Fig.3 Shear strength of rock mass using generalized and modified Hoek & Brown criteria.

3.3 Slope stability results

The conventional anisotropic directional shear strength approach results to a critical slip surface, that is failing in the carbonaceous mudstones predicting a Factor of Safety (FoS) equal to 0.54 (Figure 4). The stability analysis using the modified Hoek & Brown and ARMR approach resulted in slightly higher FoS equal to 0.77 and the critical slope area is less extensive in relation to that predicted in the previous approach (Figure 5). It is noted that when using the modified Hoek & Brown with ARMR in the 3D LEM model, only anisotropic strength envelopes at minimum ($\beta=40^0$) and maximum ($\beta=90^0$) strength orientations were used due to limitations of Slide3 software.

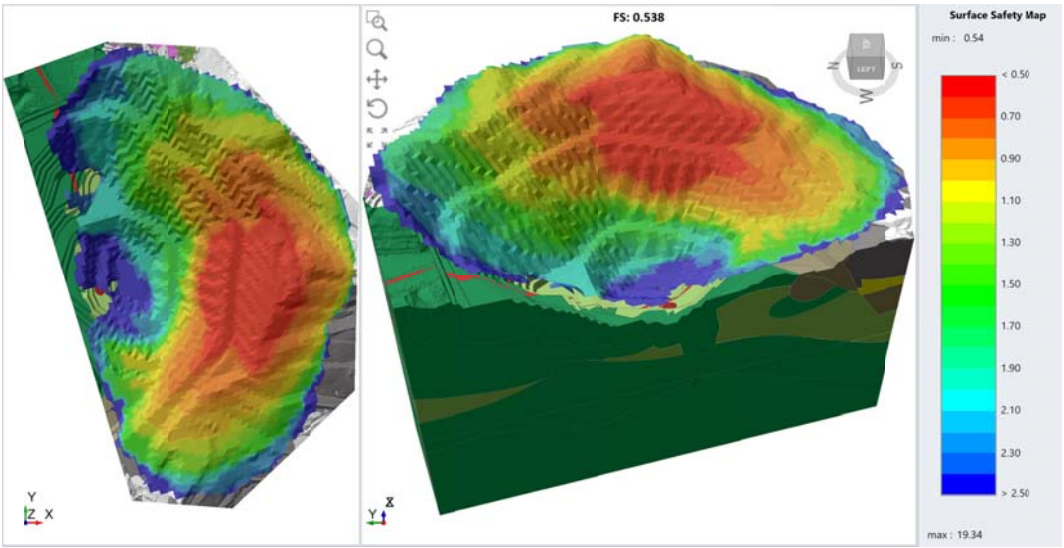


Fig.4 3D slope stability results using anisotropic directional shear strength.

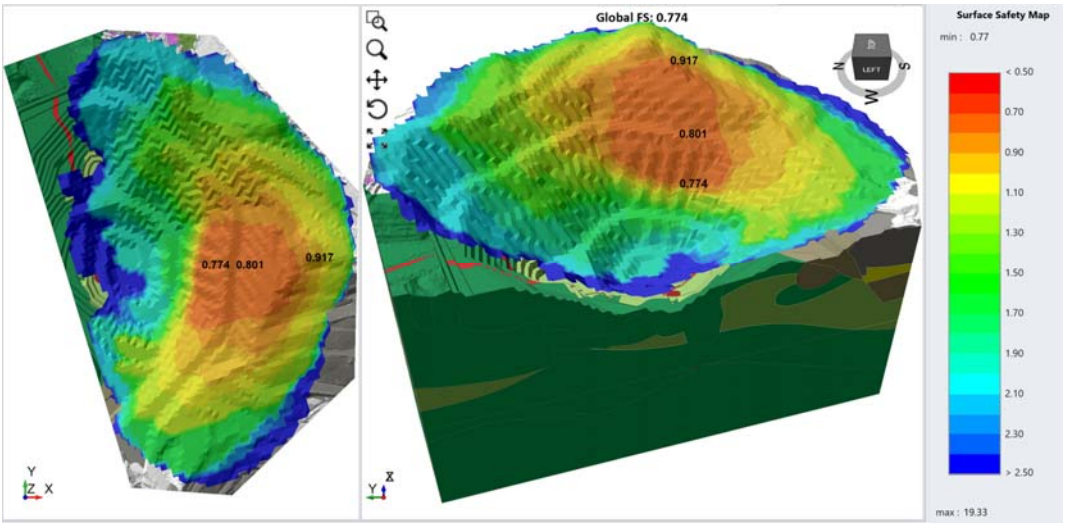


Fig.5 3D slope stability results using the modified Hoek & Brown criterion and ARMR.

4 Conclusions

The advantage of ARMR is that it can be used jointly with the modified Hoek & Brown criterion to determine the rock mass strength in different anisotropy orientations. Based on the results of the 3D slope stability analysis performed in the open pit case study this approach provides a slightly higher factor of safety but generally compares well to the anisotropic directional strength approach. Slope stability of anisotropic rock masses is very sensitive to orientation and strength anisotropy and more analysis is necessary to model the behaviour of anisotropic rock masses. Continued improvement of understanding anisotropic rock masses is key to reliably predicting the stability of slopes.

References

Bar N, Weekes G (2017) Directional shear strength models in 2D and3D limit equilibrium analyses to assess the stability of anisotropicrock slopes in the Pilbara Region of Western Australia", AustralianGeomechanics Journal, 52(4), pp. 91–104.

Bar N (2024) Digital Twin Concept for the Safe and Economic Design and Management of Rock Slopes. Proc. 6thRegional Symp on Landslides in the Adriatic-Balkan Region, ReSyLAB2024. Vol. 6, 11, p. 89–97.

Barton N, Bandis S (1980) Some effects of scale on the shear strengthof joints", International Journal of Rock Mechanics and MiningScience & Geomechanics Abstracts, 17(1), pp. 69–73, 1980.

Bieniawski ZT (1989). Engineering Rock Mass Classification; Wiley: New York, NY, USA.

Cancino C, Lorig L, Bu J, Bar N (2024). Back-analysis for more reliable mine plans at Pueblo Viejo Gold Mine. Proc. Slope Stability 2024.

Hoek E, Carranza-Torres C, Corkum B (2002) The Hoek-Brown failurecriterion – 2002 edition", In: Proc. of the 5th NorthernAmerican Rock Mechanics Symposium and 17th Tunneling Association of Canada Conference (NARMS-TAC), Toronto,Canada, pp. 267–271.

Itasca Consulting Group, Inc. (2019). FLAC3D – Fast Lagrangian Analysis of Continua in Three Dimensions (Version 7.0). Minneapolis: Itasca.

Martin CD, Kaiser PK, McCreath DR (1999). Hoek–Brown parameters for predicting the depth of brittle failure around tunnels. Can. Geotech. J. 36: 136–151.

Saroglou H, Tsiambaos G (2008). A modified Hoek–Brown failure criterion for anisotropic intact rock. Int. Journal of Rock Mechanics & Mining Sciences, 45: 223–234.

Saroglou C, Qi S, Guo S, Wu F (2019). ARMR, a new classification system for the rating of anisotropic rock masses. Bull Eng Geol Env. 78: 3611-3626. https://doi.org/10.1007/s10064-018-1369-4

Saroglou C, Bar N (2020). The ARMR classification system and the modified Hoek-Brown failure criterion compared to directional shear strength models for anisotropic rock masses. Periodica Polytechnica Civil Engineering, 64(1), pp. 14–19.

Saroglou C (2025). The challenge of Rock Mass Classification of anisotropic rockmasses. Rock Mechanics and Rock Engineering https://doi.org/10.1007/s00603-025-04681-8.