A Parametric Study Illustrating the Effects of Moderately Anisotropic Rock Strength on the Stability of Large Slopes using Limit Equilibrium Analysis

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ABSTRACT: Accounting for moderately anisotropic conditions where one or more dominant structure sets affect slope stability analysis is challenging. Most analysis methods and software assume isotropic behaviour that better suits randomly jointed rock masses. Some methods for assessing anisotropic formations (bedding, schistosity, etc.) exist, but the computationally expensive Synthetic Rock Mass approach is the only method to capture moderately anisotropic behaviour. Therefore, guidance is needed to identify when a rock mass is moderately anisotropic. The limit equilibrium method software *Slide2* was used to perform a parametric study on the *Generalized Anisotropic* strength model for a hypothetical rock slope. The key contributors to determining if a rock mass is moderately anisotropic were the shear strength (cohesion only) of the weak plane was a quarter or less of the intact strength, the angular distance between two joint sets was approximately 30°, and the angle of anisotropy was within 15° of the slope face.

Keywords: Rock mass strength, Anisotropy, Slope Stability, Slide2.

1 INTRODUCTION

When multiple structure sets influence anisotropic rock mass behaviour instead of a single plane of weakness, accounting for the combined reduction in rock mass strength can be challenging. The orientation of single or multiple geological structures (e.g., bedding, schistosity, etc.) can drastically reduce the overall rock mass strength from the intact strength. Figure 1b illustrates how the orientation of joints to the axial load (α_j) and the joint friction angle (ϕ_j) both play a significant role in whether rock mass strength is driven by the intact rock failure or joint slip (Jaeger & Cook 1979). Numerical methods have been developed to estimate rock mass strength, which can be incorporated into a slope stability analysis. However, most tools for assessing rock mass strength are best suited for randomly jointed rock masses under isotropic conditions. Some methods exist for evaluating fully anisotropic (FA) rock masses where anisotropy exists at the grain scale (foliation) and the block scale (bedding), as seen in Figure 1c. Still, when multiple dominant structure sets at the block scale are present (Figure 1d), rock mass behaviour can be classified as moderately anisotropic (MA), and slope stability can be associated with a complex failure surface instead of a single weak plane.

Different analytical solutions have been developed to estimate anisotropic rock mass strength (Renani et al. 2019; Cylwik 2021). Still, the only method to capture the MA rock mass behaviour is the Synthetic Rock Mass (SRM) approach (Mas Ivars et al. 2011). While the SRM was the first to accurately capture the complexity of rock mass deformation and strength behaviour, the computational and engineering effort required can limit the broad use of the method. Classification systems for anisotropic rock mass have been developed (Saroglou et al. 2019; Maazallahi & Majdi 2021); however, guidance to determine when a rock mass should be considered MA is missing. Therefore, a standard rule-of-thumb to guide whether a rock mass is classified as MA would be beneficial.

In this study, we performed a slope stability analysis of a theoretical rock slope under different rock mass conditions using the LEM program *Slide2* (Rocscience 2021). The *Generalized Anisotropic Strength Model* (GAS) in *Slide2* will be used to perform a parametric study on the effects of different anisotropic input parameters. The safety factor (F) of a 500 m high theoretical slope will be analyzed due to changes in the input parameters. The effects of a range of anisotropic shear strength ratio (AR), the orientation of the axis of anisotropy (α_v), the angular range (θ_w) of the α_v, and the angular distance between joint sets (β_A) were examined. Through this parametric study, a suggestion for when a rock mass should be considered MA and more complex methods are required for simulating rock mass behaviour, such as the SRM, is discussed.

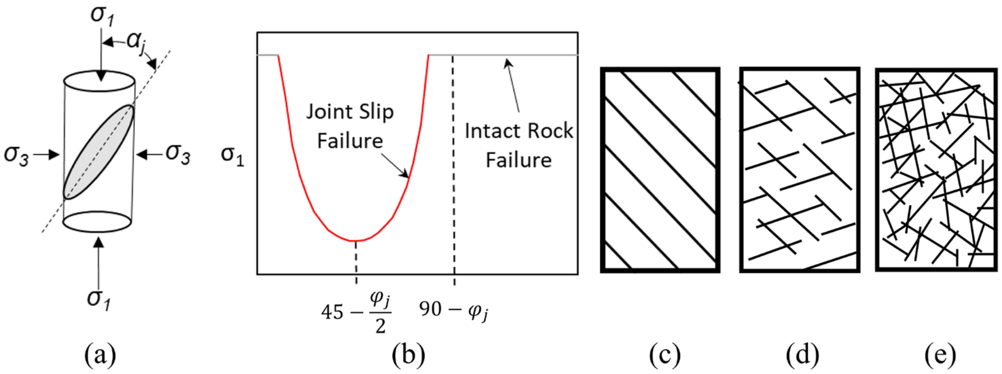


Figure 1. Illustrations of (a) Jaeger and Cook (1979) weak-plane theory curve; (b) a triaxial test with a single fully persistent joint; (c) randomly jointed rock mass; (d) MA rock mass; (e) FA rock mass.

2 LIMIT EQUILIBRIUM ANALYSIS

For the slope stability analysis, the commonly used LEM software *Slide2* was used to calculate F for a theoretical rock slope. *Slide2* can be considered an oversimplification of a complex issue cause a LEM cannot simulate displacement and deformation of the rock mass (Lorig & Varona 2000). However, using the GAS will provide insight into which input parameters have the most significant effect on F. This can help an individual implement better engineering judgement when determining whether a complex method, such as the SRM approach, is required.

2.1 Model Setup for Theoretical Slope

The theoretical rock slope for the study had a height (H_s) of 500 m with a slope angle (ψ_s) of 42°. The rigorous Morgenstern-Price method of slices was selected to calculate the F (Rocscience 2021). The model utilized a non-circular and optimized search routine with an iteration tolerance of 0.001 and a maximum concave angle of 2°. Additionally, a filter of a minimum failure depth of 100 m was used to ensure the F was based on the failure of the entire slope to produce more consistent results. Finally, the GAS was used to incorporate the effects of anisotropy into the slope stability analysis. If the base angle of a slice was within the θ_w of the joint sets' α_v, the strength anisotropy associated with the joint was applied.

2.2 *Rock Mass Properties for Parametric Study*

Four input parameters for the GAS were compared for the parametric study. The first parameter considers the ratio between the rock mass's strong (intact) and weak (anisotropic) rock mass strengths. For this study, the Mohr-Coulomb shear strength criterion was utilized for the model. A friction angle of 29° and a unit weight of 27 kN/m^3 were held constant for both the strong and weak materials. The two materials' strong (c_s) and weak cohesion (c_w) values are the only differing strength properties. Denoted as the *AR* and calculated using equation 1, the c_s was a constant value of 500 kPa, and c_w was reduced to assess the effects on *F* from *AR*.

$$AR = \frac{c_s}{c_w} \tag{1}$$

The remaining three parameters relate to the orientation and range of influence for a specific joint set. The rock mass was classified as FA if one anisotropic formation, i.e., bedding, foliation, etc., is present, and MA if multiple block scale anisotropic features exist in the rock mass. Figure 2 illustrates the input parameters for an MA rock mass and how the parameters relate to theoretical discontinuities in a rock slope.

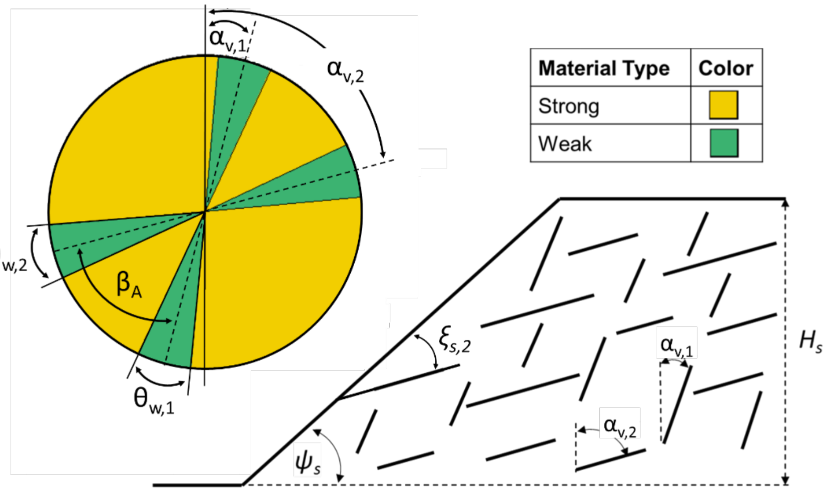


Figure 2. Illustration of different *Slide2* GAS input parameters for an MA rock mass.

The effects on the theoretical rock slope's stability as α_v changes from vertical to horizontal were examined to determine the most problematic orientations of a weak plane. The value θ_w, to some degree, represents spatial variability, incorporating a range of influence for multiple weak planes with an average orientation of α_v. Examining the deviation in *F* as θ_w increases can provide insight into the combined effects of numerous weak planes interacting. However, it should be mentioned that a LEM cannot simulate intact rock failure and sliding/shear mobilization along discontinuities leading to a complex failure surface, such as step-path failure.

For an MA rock mass, the β_A was assessed to determine the effects on *F* when two dominant sets are close. While *Slide2* cannot develop a complex failure surface due to rock bridge failure and crack propagation, the results of different magnitudes of β_A can still provide some level of insight into a more complicated problem. At what point are two structure sets close enough to consider complex failure mechanisms?

Different combinations of the four input parameters were evaluated and are listed in Table 1 below. To compare the results to an equivalent isotropic model, an isotropic cohesion (c_{iso}) was calculated using equation 2, a weighted average of the c_s and c_w based on θ_w. This value was considered the reduced rock mass strength due to anisotropy for the entire model.

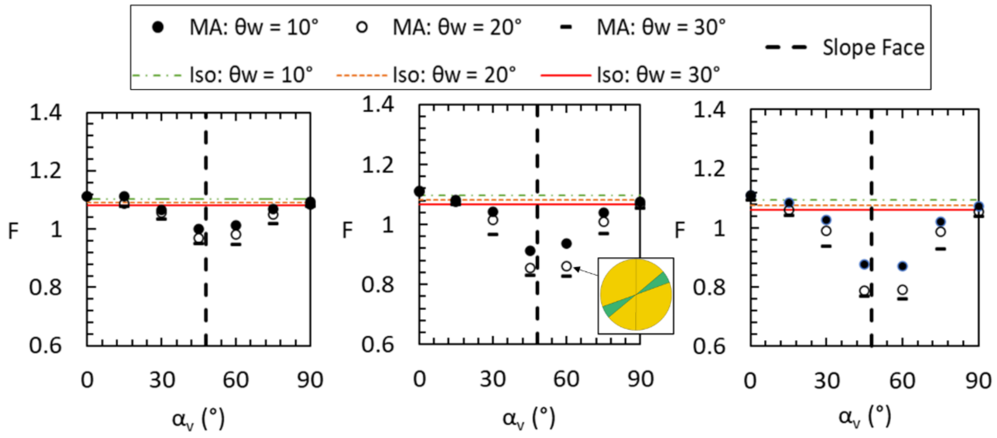
$$c_{iso} = \frac{360 - 2\theta_{w,1} - 2\theta_{w,2}}{360} c_s + \frac{2\theta_{w,1} + 2\theta_{w,2}}{360} c_w \tag{2}$$

Table 1. GAS input parameters for LEM model of theoretical rock slope.

GAS Property	Units	Values used for parametric study
AR		2, 4, 8
θ_w	[°]	10, 20, 30
β_A	[°]	0, 30, 60
$\alpha_{v,1}$	[°]	0, 15, 30, 45, 60, 75, 90

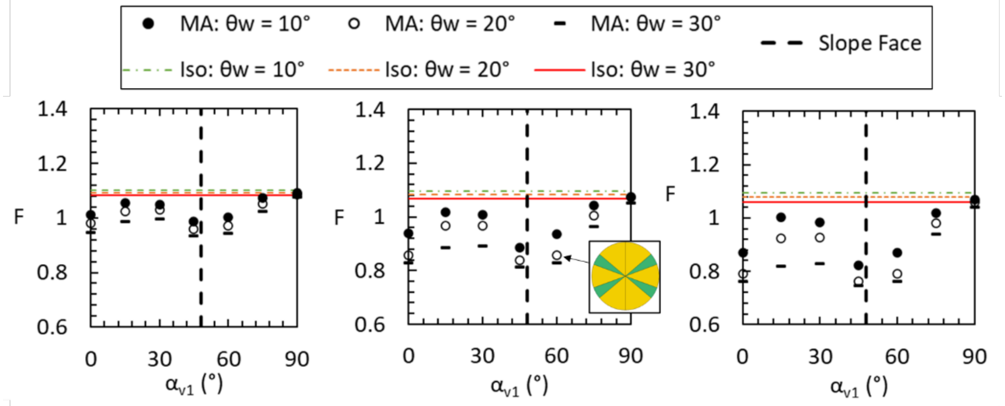
3 RESULTS

Figures 3, 4, and 5 present the results from *Slide2* for the FA and MA rock masses considering the four input parameters. For the FA case, the relationship between α_v and F produces a U-shape curve, with the lowest value of F occurring when α_v was nearly parallel to the slope face. Furthermore, all simulations, FA and MA, produced a failure surface resembling block slumping in *Slide2*. However, when the α_v was near parallel to the slope face, the failure surface was less curved and was more planar. The inset figure in all three plots present the GAS model setup for the FA and MA cases where $\boldsymbol{\alpha}_{v1}$ and θ_w were 60°and 20°.



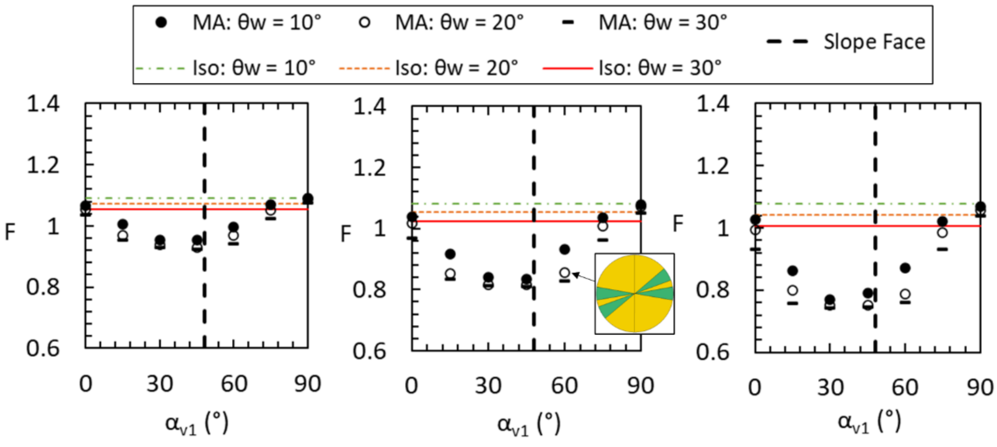
(a) (b) (c)

Figure 3. Effects of the orientation of α_v on F for an FA rock mass (a) AR = 2; (b) AR = 4; (c) AR = 8.



(a) (b) (c)

Figure 4. Effects of joint orientation on F for an MA rock mass with two structure sets with a β_A = 60° (a) AR = 2; (b) AR = 4; (c) AR = 8.



(a)
(b)
(c)

Figure 5. Effects of joint orientation on F for an MA rock mass with two structure sets with a βA = 30° (a) AR = 2; (b) AR = 4; (c) AR = 8.

For the MA cases when β_A was 30° and 60°, the lowest value of F was when $\alpha_{v,1}$ or $\alpha_{v,2}$ was 45°. Illustrating the most adversely oriented structures were when the angular distance between the α_v and the slope face (ξ_s) approached zero. In all three plots, the c_{iso} was used to calculate the F of the slope considering isotropic conditions. It was observed that the F of the FA and MA models was lower than the isotropic model unless the α_v was nearly vertical ($\alpha_v \approx 0°$) or horizontal ($\alpha_v \geq 75°$). Additionally, F decreased as the AR increased (i.e., reduced c_w), with the most significant drop seen when $AR \geq 4$.

$$\xi_s = \alpha_v - \left(90^\circ - \psi_s\right) \tag{3}$$

The value of θ_w represents the outer limit of the zone of influence for a particular set with orientation α_v. As expected, as θ_w increases, the F decreases, with the most significant drop seen when θ_w changes from 10° to 20°. When θ_w and β_A are larger values, the likelihood of one of the structure sets being adversely oriented increases. Still, once one set was near horizontal, $\alpha_{v,1} \geq 75°$, and the other dips away from the face, i.e., $\alpha_{v,2} > 90°$, the F was close to the isotropic condition.

Figures 4 and 5 show the effects of β_A for a MA rock mass compared to an FA case in Figure 3. A similar trend to the anisotropic strength curve presented by Renani et al. (2019), when β_A was 60°, a W-shape curve was produced, while for a β_A of 30° most values of α_v sit at the bottom of the saddle of the U-shape curve. These results highlight the importance of the α_v of a single joint set and the β_A when multiple dominant structure sets are present. When $\beta_A \geq 60°$, the stability of the slope was driven by the most problematically oriented geological feature. However, a complex failure mechanism should be considered when two structure sets are close ($\beta_A \approx 30°$). Further analysis with different values of β_A revealed a relationship where the W-shape curve becomes U-shaped when equation 4 was met.

$$0^\circ < \beta_A - \left(\frac{\theta_{w,1}+\theta_{w,2}}{2}\right) \leq 15^\circ \tag{4}$$

4 DISCUSSION

In this study, all input parameters for the GAS in *Slide2* affected F. In order to establish a rule of thumb to classify a rock mass as MA, some threshold must be identified. The key to determining if the rock mass was MA is whether the F is affected by both structure sets instead of a single adversely oriented set.

The value of θ_w, to some degree, represents an aspect of spatial variability, modelling a range of weak planes associated with an average α_v. Still, the value was a range of influence for a particular weak plane, and a θ_w of 30° could be considered too large. In Figures 3 to 5, the most pronounced drop in F occurred when θ_w increased from 10° to 20° compared to 20° to 30° where the reduction in F was significantly less. Based on these results, for assessment of a rock slope in *Slide2* using GAS, a design limit should be $\theta_w \leq 20°$.

Based on the F calculated in *Slide2*, when the β_A was low (~30°), there was a higher chance that both sets were adversely oriented; therefore, the rock mass was more likely to be MA (two-set system) instead of isotropic or FA. However, when β_A was large, as seen in Figure 4, a W-shape curve was developed, and F was predominately influenced by the geological feature with the more problematic α_v. Furthermore, one geological feature must be able to daylight for planar failure to occur or to dip in the same direction as the slope for block slumping (Sjöberg 1999). Considering this, in a rock mass with two dominant structure sets, $\xi_{s,1}$ or $\xi_{s,2}$ needs to be between -15° and 15°. The decrease in F was found more significant when the AR increased from 2 to 4 compared to 4 to 8. Based on these results, an AR of 2 was not as detrimental to the stability of the slope, but an $AR \geq 4$ should flag the potential to consider MA rock mass behaviour when multiple sets are present. These points create the initial guidance for classifying a rock mass as MA and the potential need for a method such as the SRM to assess complex failure mechanisms expected to affect a rock slope's stability.

5 CONCLUSION

This study investigated different input parameters for the GAS in the commonly used LEM software *Slide2* to guide when a rock mass should be classified as MA. The parametric analysis showed the effects on the F of a 500 m high theoretical rock slope for different rock mass shear strength ratio combinations and orientation of dominant structure sets. As a general rule-of-thumb, a rock mass should be considered MA if equation 4 is met, $AR \geq 4$, and $-15° \leq \xi_{s,1}$ or $\xi_{s,2} \leq 15°$ while $\theta_w \leq 20°$ should be considered as a model criterion for the GAS. The current results provide insight into a potential solution for determining when a rock mass is identified as MA, and a complex numerical method should be considered. Still, sensitivity analysis testing more values of β_A, assessing the AR values for both cohesion and friction angle, and more complex numerical models for validation are required for a definitive answer to the problem.

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