Optimal slope profiles for maximum mine pit-wall steepness in banded iron formation rocks

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ABSTRACT

The Overall Slope Angle (OSA) of pitwalls plays a crucial role in the financial return of an open pit mine. In current practice, pitwall profiles are designed to be planar in cross-section within each rock layer, ie the profile inclination across each layer tends to be constant. A new slope design software, OptimalSlope, has been recently proposed to determine the geotechnically optimal profile shapes for the pitwalls of mines. OptimalSlope seeks the solution of a mathematical optimisation problem where the overall steepness of the pitwall to be designed is maximised for an assigned stratigraphy, rock properties (unit weight and strength) and Factor of Safety. The geometry of the benches is provided as input to OptimalSlope. The results obtained so far on three mine case studies in isotropic rock masses (Utili *et al*, 2022; Agosti *et al*, 2021a, 2021b) show that optimal profiles are up to 5° steeper than their planar counterparts – ie the planar profiles exhibiting the same FoS – leading to realising significant saving on waste rock and as a consequence Net Present Value increments and carbon footprint reductions. OptimalSlope algorithms have been modified to deal with anisotropic rock masses characterised by direction dependent shear strength.

In the paper, the case of rock masses in banded iron formations (BIF) is tackled. A data set of anisotropic rock shear strengths typical of Western Australia is considered. The Snowden modified nonlinear model was employed to characterise the anisotropy of the rock mass shear strength.

From the OptimalSlope simulations performed emerges that optimal pitwall profiles can increase significantly the Overall Slope Angle in comparison with planar profiles featured by the same Factor of Safety. LEM stability analyses of all the profiles were also performed by Rocscience Slide 2 to independently verify the FoSs of the optimal profiles obtained.

INTRODUCTION

Anecdotal evidence that slope profiles nonlinear in cross-section, ie a profile whose inclination varies with depth, are better than linear ones was first reported as far back as 1890 (Newman, 1890). Almost a century later, Hoek and Bray, in chapter 12 of the second edition of Rock slope engineering (Hoek and Bray, 1977), analysed the stability of some concave circular slopes in cross-section. After that, the first systematic theoretical study on the mechanical properties of concave slope profiles for geomaterials exhibiting some cohesion, so applicable to all rocks and clayey soils, appeared in Utili and Nova (2007). By employing the upper bound theorem of limit analysis, they proved that logspiral profiles exhibit higher FoS than their planar counterparts for any value of c and φ considered. A fundamental limitation of the studies listed above is the assumption that the shape claimed to be optimal is found as the shape associated among curves belonging to a very restricted family and the assumption of uniform slope and no consideration of benches. More recently, a new geotechnical software, OptimalSlope (Utili, 2016), has been introduced which calculates the slope optimal profile for any specified lithological sequence without unduly restricting the search to any predefined family of shapes. To be able to quantify the gains of Net Present Value (NPV) and carbon footprint reduction in a consistent way in (Utili *et al*, 2022; Agosti *et al*, 2021a, 2021b) the open pit mines considered were designed twice employing the same pit optimiser software, economic parameters and optimisation strategy, with the only difference between the two designs being the pitwall profiles adopted. NPV gains of up to 53 per cent and carbon reductions of 600 000 t CO_2 were obtained.

In all the previous works the rock mass strength is isotropic as prescribed in the Generalised Hoek–Brown rock model whereas in this paper rock mass anisotropy is considered. Although the G-H-B is routinely employed by practitioners to characterise the rock mass behaviour, there is an increasing interest in the geotechnical community to account for rock mass anisotropy in the design of pitwalls.

In Agosti *et al* (2022) OptimalSlope was applied for the first time to anisotropic rocks employing an anisotropic model where both the cohesion and internal friction angle were prescribed as a function of angle of anisotropy to characterise the anisotropic behaviour of bedded sedimentary rocks with nine joint-sets. The model is very general since it can account for the presence of any number of joint-sets. Here instead OptimalSlope is applied to banded ironstone formations (BIF) of the Pilbara region and therefore a different anisotropic model was employed.

ROCK MATERIALS AND GEOTECHNICAL MODEL

Anisotropic strength models are employed to capture the effect of discontinuities on the rock mass strength. Mercer (2012) defines:

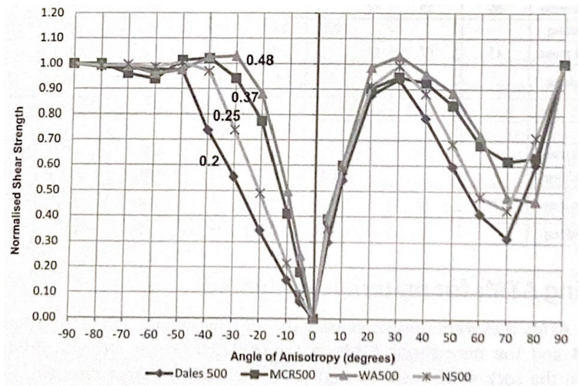
> *'An anisotropic strength model a constitutive model that describes the shear strength of an anisotropic rock mass in relation to the change in the angle between the plane of shear, and either the predominant plane of weakness of the rock fabric or the predominant orientation of major structural weakness.'*

The so called Snowden models were formulated and calibrated to capture the anisotropic behaviour of the banded ironstone formations (BIF) of the Pilbara region in Western Australia (Mercer, 2012, 2013; Bar *et al*, 2016). Here we employed an experimentally derived model to characterise the anisotropic shear strength of four BIF units in the Pilbara region (see Figure 1). The shear strength parameters for four types of rock from the Hamersley Group of the Pilbara region (see Figure 1a) were determined by Mercer (2013) on the basis of virtual shear box tests with input parameters such as GSI, UCS, JRC. Also Mercer (2013) provides the normalised shear strength – angle of anisotropy relationships experimentally determined at a normal stress of 500 kPa (see Figure 1b). Because the normal stress applied may affect the relationships due to the pressure dependency exhibited by rock shear strength, assuming a unit weight of 26.2 kN/m^3 we considered the design of a slope 195 m high so that the average confining stress in the slope is around 500 kPa. A typical bench height of 15 m was assumed so that 13 benches result.

To characterise the anisotropic rock strength for the simulations we performed in OptimalSlope and Slide 2 we calculated the cohesion and friction angle at every degree of the angle of anisotropy using the relationships provided in Figure 1b and assuming the same strength reduction with the angle of anisotropy for both cohesion and angle of internal friction, for instance for a normalised shear strength of 0.40 we calculated $c_{0.4} = (c_{max} - c_{min}) * 0.4 + c_{min}$ and likewise $tan\varphi_{0.4} = (tan\varphi_{max} - tan\varphi_{min}) * 0.4 + tan\varphi_{min}$.

Unit	Type	GSI	UCS (MPa)	m_i	JRC	JCS	Phi_b (°)	Cohesion (kPa)	Friction	Tau BB (kPa)	Tau HB (kPa)	Strength ratio
BIF Units												
Dales (DG)	Rock mass	50	33	10				385	53°		1037	0.20
Dales (DG)	Bedding				2.5	24	18	11	21°	204		
Newman (MN)	Rock mass	43	37	10				328	52°		961	0.25
Newman Shale Band	Bedding				3	4	23	14	25°	241		
Shales												
McRae (MCR)	Rock mass	44	15	7				223	41°		660	0.37
McRae (MCR)	Bedding				2.5	15	22	12	25°	241		
West Angela (WA)	Rock mass	26	12	6				140	30°		434	0.48
West Angela (WA)	Bedding				3	16	18	13	21°	207		

(a)



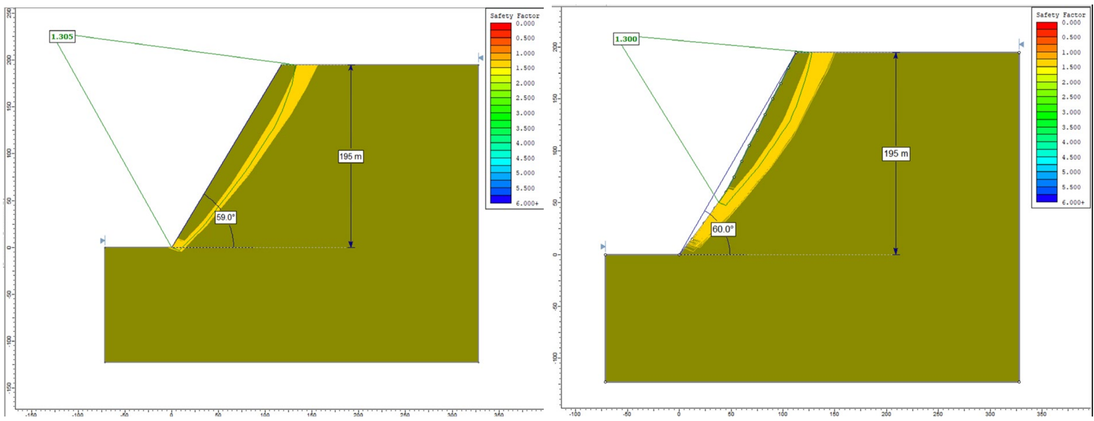
(b)

FIG 1 – (a) strength parameters for the rock mass and bedding of the four BIF units considered (after Mercer, 2013); (b) experimentally determined normalised shear strength versus angle of anisotropy of the BIF units (after Mercer, 2013).

RESULTS

Albeit OptimalSlope can be applied to any complex stratigraphy made of different rock layers (see for instance Agosti *et al*, 2021a), for sake of model simplicity we considered only uniform slopes in this exercise. We considered the two BIF units at the extreme of the spectrum in terms of the strength difference between rock mass and bedding, ie the Weathered Dale Gorge (Dales in Figure 1a) and the West Angela shale, exhibiting the highest and lowest difference respectively. A bedding orientation of 90 degree to the horizontal was chosen for the simulations so that slope stability is affected by both bedding and rock mass strength.

To quantify the benefit provided by the adoption of optimally shaped pitwalls, first we designed planar pitwalls by trial and error by changing the inclination of the slope until the target Factor of Safety of 1.3, calculated by performing Slide 2 simulations with the Morgenstein-Price method, was met (Figure 2a). Then we ran OptimalSlope to determine the optimally shaped pitwall for that same Factor of Safety (Figure 2b).



(a) (b)

FIG 2 – Designed pitwalls for the Weather Dale Gorge with a target FoS of 1.30: (a) planar pitwall; (b) optimally shaped pitwall calculated by OptimalSlope. Note benches are not included in the image but their geometry has been accounted for in determining the optimally shaped pitwall.

In the case of Weathered Dale Gorge, the optimally shaped profile exhibited a gain of 1.0° steepness whilst in the case of West Angela shale, the gain was of 1.6° (31° inclination for the optimal profile instead of 29.4° for the planar one). In previously analysed case studies of open pit mines (Utili *et al*, 2022; Agosti *et al*, 2021a, 2021b), a one degree gain in steepness corresponds to a cost saving of USD15 million on average.

CONCLUSIONS

Pitwalls were designed for a data set of anisotropic banded iron formations (BIF) typical of Western Australia is considered whose anisotropic strength was characterised by an experimentally derived nonlinear model.

Optimally shaped pitwalls were calculated by the software OptimalSlope (Utili, 2016) for two BIF formations featured by the highest and lowest difference between rock mass and bedding strengths so at the ends of the spectrum of values presented in Mercer (2013), see Figure 1a. From the calculations it emerges that optimal pitwall profiles can meaningfully increase the Overall Slope Angle in comparison with planar profiles featured by the same Factor of Safety. LEM stability analyses of all the profiles were also performed by Rocscience Slide 2 to independently verify the FoSs of the optimal profiles obtained.

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