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OPTIMAL PITWALL SHAPES TO INCREASE THE FINANCIAL RETURN AND DECREASE THE CARBON FOOTPRINT OF THE OPEN PIT MINES

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Abstract

The steepness of the slopes of an open pit mine has a substantial influence on the financial return of the mine. This paper proposes a novel design methodology where the overall steeper pitwalls are employed without compromising the safety of the mine. In the current design practice, the pitwall profiles are often planar in a cross-section within each rock layer, i.e., the profile inclination across each layer tends to be constant. Here instead, a new geotechnical software, the OptimalSlope is employed to determine the optimal pitwall profiles of depth varying inclination. The OptimalSlope seeks the solution of a mathematical optimization problem where the overall steepness of the pitwall, from crest to toe, is maximized for an assigned lithology, geotechnical properties and Factor of Safety (FoS). Bench geometries (bench height, face inclination, minimum berm width) are imposed in the optimization as constraints which bind the maximum local inclination of the sought optimal profile together with any other constraints such as the geological discontinuities that may influence a slope failure. The obtained optimal profiles are always steeper than their planar counterparts (i.e. the planar profiles exhibiting the same FoS) up to 8 degrees depending on the rock type and severity of constraints on local inclinations. The design of a copper mine is first carried out employing the planar pitwalls, secondly adopting the optimal pitwall profiles, determined by the OptimalSlope. The adoption of optimal slope profiles leads to a 34% higher net present value and reductions of carbon footprint and energy consumption of 0.17 Mt CO_2 eq and 82.5 million MJ respectively due to a 15% reduction of the rock waste volume.

***Keywords**: optimal pitwalls, NPV optimization, carbon footprint reduction*

1. INTRODUCTION

The block model of the copper deposit, employed as a case study, has been provided by a mining company collaborating with the Delphos Mine Planning Laboratory at the University of Chile. All the parameters needed to perform the pit design were taken from [1]. From the site lithology and geotechnical properties, the two roughly uniform pit sectors were identified in [1]. In each sector, one representative cross-section was assumed to design the pitwall profile. The rock geotechnical parameters are reported in Table 1 together with the values adopted for the economic parameters and metallurgical recovery.

Table 1. *a) Geotechnical properties after [1]*

	UCS [MPa]	GSI [-]	m_i [-]	D [-]	γ [kN/m^3]
Pit sector S1	65	45	15	1	25.9
Pit sector S2	50	45	12	1	25.9

b) Economic parameters and metallurgical recovery taken from [1]

Copper price	[USD/t] 6000	[USD/lb] 3
Selling cost	[USD/t] 1700	[USD/lb] 0.85
Reference mining cost [USD/t]	3.4	
Processing cost [USD/t]	6.1	
Metallurgical recovery [%]	85	
MCAF [USD/t/bench]	0.13	
Discount rate (%)	10	
Processing method limit [mtpy]	5	
Mining limit [mtpy]	10	

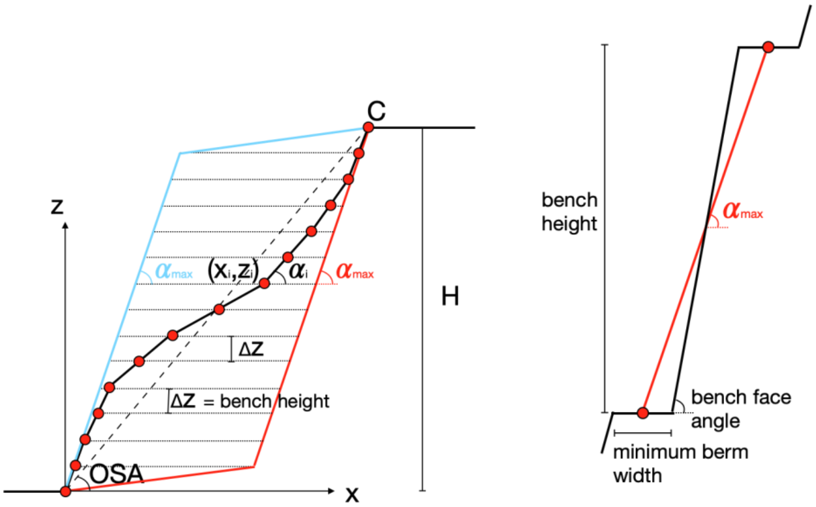
1.1 Pitwall Design

In the design of pitwalls, the standard practice of starting was followed with the design of benches and then moved to the overall pitwall profiles. The height of the benches, adopted for the whole mine, is 10m [1]. Then, the minimum berm width, b_w, was computed using the modified Ritchie's criteria.

Then, the geotechnically optimal slope profiles for the cross-sections of the mine, was computed using the proprietary code OptimalSlope [2]. The code requires the bench height, bench face inclination, minimum berm width and road width as the input. The optimal pitwall profile is defined as the overall steepest safe profile, i.e., OSA=OSA_{max}, with OSA being the inclination over the horizontal of the line joining the pitwall toe to the crest (see Figure 1). OSA_{max} is determined by the OptimalSlope iteratively. The main algorithm finds the optimal pitwall shape for an assigned OSA and geometric constraints ($\alpha_{i\max}$ values). An initial guess OSA value is first determined for the specified pitwall height, the geotechnical properties of all the layers and the specified FoS on the basis of a database of stability charts, built in the OptimalSlope. The FoS_i associated to the optimal profile, found at the *i*-th iteration, is then compared to the target FoS_{target}: if it is higher a steeper OSA is prescribed at the next iteration; if it is lower a less steep OSA is prescribed.

1.2 Pit Optimization

To assign the pitwall profiles into the pit optimizer Geovia Whittle, the block model was split into 'zones' (according to the Whittle terminology) using the Geovia Surpac and assigned a slope inclination to each 'zone'. Then, to compute the ultimate pit limit and pushbacks, first the Whittle was run to produce the discounted best case scenario curve in the pit-by-pit graph. Next, the so-called ‘Milawa NPV’ algorithm was employed to generate a specified case scenario curve for an initial set of pushbacks, chosen in correspondence of the sharp increases, exhibited by the best-case scenario curve. Finally, the UPL was chosen in correspondence of the highest point of the plateau, exhibited by the specified case curve.



a) *b)*

Figure 1. *a) A generic candidate slope profile. The toe of the profile is at the axis origin (x_0, y_0), point C is the slope crest. A uniform discretization along the z direction is adopted. The red and blue lines enclose the region where the profiles are sought. The profile is discretised in n Δz intervals so there are n-1 unknowns to be determined: x_1, x_2, …x_{n-1}. In the context of the open pit mines, a good choice of Δz is to assume Δz equal to the bench height. b) determination of $\alpha_{i\,max}$ based on bench geometry (input to the OptimalSlope)*

2. RESULTS

The pitwall profiles, obtained as result of the pit design process, are plotted in Figure 2a for the pit sector 1. The Factor of Safety of all the pitwall profiles was verified by performing a LEM analysis with the Morgenstern – Price method in Slide 2. The pitwall profiles employed in the Slide2 analyses are reported in Figure 2b for the pit design adopting planar profiles and, in Figure 2c for the pit design, adopting the optimal profiles together with their FoS. In all the cases, the FoS found is less than 1% from the target value of 1.3. For the optimal pitwall profiles, the additional stability analyses were performed by the FLAC3D 7.0 having assigned a unit length in the out of plane direction. The critical failure mechanisms, identified by Slide2 and FLAC3D, and the associated FoSs are reported in Figure 2c. In both mine sectors, the FoSs found are less than 1% from the target value of 1.30.

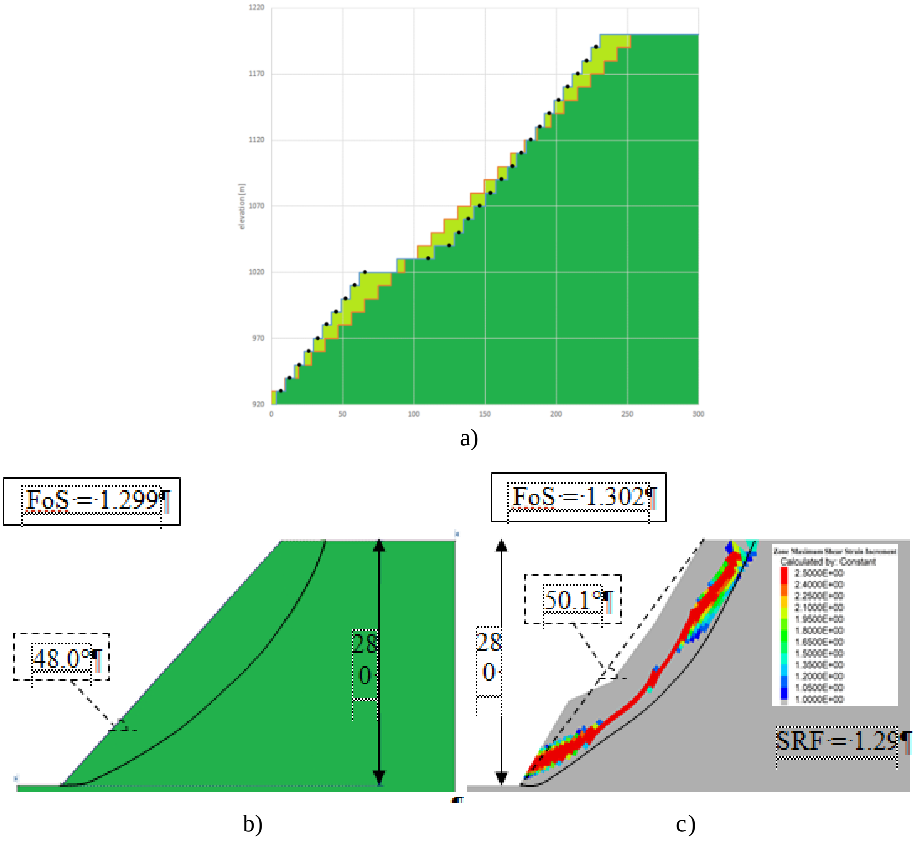


Figure 2. *UPL pitwalls for sector S1: a) comparison between the pitwall profile for traditional design (planar pitwall is in orange) and the optimal design (optimal pitwall is in blue, the black dots represent the x_i, z_i coordinates obtained as the output from the OptimalSlope); b) failure mechanism (black line) and Factor of Safety determined by the 2D Limit Equilibrium Method (Slide2) for the planar profile; c) failure mechanism (black line) and Factor of Safety determined by the 2D Limit Equilibrium Method (Slide2) and shear strain magnitude determined by the Finite Difference Method with the Shear Strength Reduction (FLAC3D) for the optimal profile*

Figure 2a allows a visual comparison between the planar pitwall profile of a traditional design, demarcated by the orange line, and toptimal pitwall profile, demarcated by the blue line. The optimal profile is clearly steeper than the planar one. The FoS of the entire UPL was verified performing a 3D FDM analysis with the FLAC3D 7.0. Throughout the entire mine, the minimum FoS found was 1.67. This value is significantly higher than the FoS values, obtained by the 2D FLAC analyses of Section 1.1, of ~1.30 and ~1.31, respectively.

The key output data for the two design cases are provided in Table 2. The net present value (NPV) for the design, based on the optimal pitwalls, is around 12 million USD higher than the NPV of the design, based on the planar pitwalls. Therefore, the adoption of the optimal profiles would lead to an increase of the NPV of 34%. Such an increase is to be ascribed to a very substantial decrease of rock waste volume, around

15%, from $23.7 \cdot 10^6$ tons to $20.7 \cdot 10^6$ tons, whilst the amount of the ore extracted is similar.

Table 2. *Pit optimisation economic and metallurgical results*

UPL output	Planar pitwalls		Optimal pitwalls	
	S1	S2	S1	S2
Overall Slope Angle [deg]	48	43.8	50.1	51.3
H_{UPL} [m]	270	220	280	150
Waste [tons]	23,707,500		20,651,462	
Ore [tons]	59,314,446		59,232,285	
Stripping Ratio [-]	0.40		0.35	
NPV [USD]	34,561,747		46,231,284	
IRR [%]	13.9		15.8	
Life [year]	12.22		12.12	
Payback [year]	3.89		3.57	
NPV increase [%]	33.8			

The energy was computed that was requested to the mine, i.e., both orebody and waste rock together with the associated carbon footprint for both design types (with planar and with optimal pitwalls), based on [3]. The energy consumption was calculated for each mined block of the UPLs. The adoption of the optimal pitwalls leads to the reductions of carbon footprint and energy consumption of 0.17 million tons CO_2 eq and 82.5 million MJ, respectively over the mine life. To provide some context, a reduction of 0.17 million tons CO_2 eq is equivalent to the carbon sequestered by 2.8 million tree seedlings grown for 10 years.

3. CONCLUSION

Considering the mine case study, the adoption of geotechnically optimal profiles led to a 34% higher net present value and very significant reductions of carbon footprint and energy consumption, 0.17 million tons CO_2 eq and 82.5 million MJ respectively, due to a 15% reduction of waste rock volume in comparison with the traditional design based on the planar pitwalls.

The FoS values of the pitwall profiles, determined by the OptimalSlope, were independently verified by two most popular geotechnical software, employed for the geotechnical verification of the open pit mines, Slide2 and FLAC, confirming that the pitwall profiles, determined by the OptimalSlope, are as safe as their planar counterparts.

The OptimalSlope was also employed in the design of other two case studies: a contemporary mine being developed by Kinross [4], and the well-known case of the McLaughlin mine, where a publicly available block model was used [5]. In both cases, employing the optimal pitwall profiles in the mine design led to the significant increases of the NPV, up to 52.7%, and substantial decreases of energy consumption and carbon footprint.

REFERENCES

[1] Parra A, Morales N, Vallejos J, Nguyen PMV (2017) Open Pit Mine Planning Considering Geomechanical Fundamentals. *International Journal of Mining, Reclamation and Environment* 32 (4):221-238.

[2] OptimalSlope (2021): Software for the Determination of Optimal Profiles for Slopes and Pitwalls. www.optimalsope.com

[3] Munoz J., Guzman RR., Botin JA. (2014). Development of a Methodology that Integrates the Environmental and Social Attributes in the Ore Resource Evaluation and Mine Planning. *Int J Mining & Mineral Engineering* 5:38-58. doi:10.1504/IJMME.2014.058918

[4] Agosti, A., Utili S., Gregory D., Lapworth A., Samardzic J., Prawasono A. (2021) Design of an Open Pit Goldmine by Optimal Pitwall Profiles. *CIM Journal*, **12**(4): 149-168.

[5] Agosti, A., Utili S., Valderrama, C., Albornoz, G. (2021) Optimal Pitwall Profiles to Maximize the Overall Slope Angle of Open Pit Mines: The Mclaughlin Mine. *ACG Proceedings of Slope Stability in Mining Conference 2021*, 69- 82, Perth (Australia). doi:10.36487/ACG_repo/2135_01