Numerical Modelling for Improved Open Pit Optimization

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Abstract. Simple open pit optimization using industry standard approaches (e.g. Whittle or NPV scheduler) provides a range of pit shells for an engineer to evaluate and select an optimal pit, and/or interim push backs to which a mine design can be developed. The first optimization step requires the definition of an overall slope angle condition that must be met by any pit shell output by the software. The issue with this is that the inability to increase slope angles for smaller pit shells, may result in a suboptimal early production schedule. This paper outlines how the use of custom slope stability curves generated using numerical modelling techniques can be used to estimate slope angles for sequential pit shells, to generate a slope angle optimized 'pit-by-pit' graph. This would allow for maximum flexibility in mine planning focused on increasing revenue in initial push back designs.

Keywords: Slope Stability · Mining Engineering · Open Pit Optimization · Numerical Modelling

1 Introduction

Pit optimization has been widely applied to increase understanding of open pit project value; it is applied using software packages such as Dassault Systèmes, (Geovia) Whittle, or Datamine's NPV Scheduler. While more complex methodologies have been developed such as Whittle's simultaneous optimizer (SIMO) and the direct block scheduling approach to account for a greater number of variables during the pit shell optimization step. Currently a relatively basic approach is taken to select an optimal pit shell based on simple evaluation of individual blocks against a cut off criteria as defined by a set of economic parameters. In addition an assessment is made of material that must be removed as ore or waste to access the given block being evaluated without exceeding a specified maximum slope angle.

For the purposes of this paper, Dassault Systémes Geovia Whittle has been used for pit optimization for an example deposit. The standard optimization workflow is as follows:

1. Import geological block model
2. Define maximum slope angle

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3. Define simple economic parameters (for cut off calculation and nested pit shell generation)
4. Define time limits (mill throughput, mining capacity) to calculate time-value outputs
5. Define scheduling instructions to generate simple mining/processing schedule for evaluation

1.1 Geotechnical Input

The initial input to an optimization, is a definition for maximum overall slope angle, which the software must honor with the nested pit shells it generates. Geotechnical Engineering is one of the modifying factors of an Ore Reserve Estimate, although geotechnical study work is often limited during the stages of a project where initial optimization is undertaken, and no Ore Reserve is defined. However, pit optimization is used as an indication of economic potential from a very early conceptual stage. Given the geotechnical inputs required to carry out pit optimization there is a significant opportunity to introduce a small amount of engineering to increase confidence in ultimate pit valuations, and better understand potential project value at an early stage.

A number of approaches have been developed for the estimation of stable slope angles, which can broadly be separated into two groups: Generic, and Non-generic. Two of the most well-known generic approaches are presented in Hoek and Bray (1981) (later adapted by Read and Stacey (2009)) and Sjöberg (1999), while rock mass specific slope angle estimation tools have been developed by Carranza-Torres and Hormazábal (2018), (2020) or Li et al. (2008). This paper is intended to demonstrate the practical application for such an approach rather than focusing on the development of the tools. A more detailed summary of the available methods is provided by Styles et al. (2022).

1.2 Methodology

This paper presents three optimization cases, each following a different approach for optimization, economic parameters are identical for each, the method for deriving the slope angle constraints, and the method of application varies between cases.

Case One includes an optimization using the widely accepted empirical estimate of slope stability based on slope height presented by Read & Stacey (2009). The approach is commonly used for early optimization works where no or limited geotechnical information is available.

Case Two includes an optimization where the slope stability curve method as discussed by Styles & Vakili (2020), whereby a small amount of easily obtained geotechnical information, can be used to derive a set of rock mass specific slope stability curves based on iterative 2D numerical modelling. The purpose of this case is to demonstrate the economic significance that comes from a basic understanding of geotechnical conditions.

Case Three adds further complexity to case two, where the stability curves are used to define stable slope angles for the increasing pit depth, thus allowing steeper angles for smaller pit shells (termed 'dynamic angle optimization' herein). Treating the slope angle definitions as dynamic in the optimization process. The process of optimizing in this way is somewhat iterative, and manual, however much of the process can be automated for more detailed studies.

Table 1. Economic parameters applied for optimization

Parameter	Unit	Value
Mining Cost	\$/t	5
Mining Recovery	%	95
Mining Dilution	%	5
Processing Cost	$\$/t_{Ore}$	30
Processing Recovery	%	60
Selling Price	\$/t	6500
Discount Rate	%	10
Mining Limit	kt	8,000
Processing Limit	kt	4,000

2 Pit Optimization

Pit optimization has been carried out using Dassault Systèmes, (Geovia) Whittle, while much of the process is objective, the selection of ultimate pit shells is a subjective process and dependent on the engineer assessing results against desired project outcomes. For this study an approach has been taken to provide comparative results based on comparison between pit shells of equal revenue factor.

The economic optimization parameters are summarized in Table 1, these have been applied to all cases, and are intended to provide a proof of concept, rather than accurate parameters relating to a specific project.

2.1 Case One

Case one has been analyzed using an overall slope angle selected from the empirical design chart shown in Fig. 1. As discussed in Styles et al. (2022) the graph does not capture rock mass specifics and provides an estimate of stable slope angle based on anticipated slope height. Initial analysis indicates the pit shell will reach an ultimate depth of approximately 400 m. Despite the empirical data showing a maximum height of 350 m, the curves trend towards vertical, and an estimate for an overall slope angle of 40° with Factor of Safety (FoS) of 1.6 has been applied for this case (Fig. 1).

Figure 2 shows a ‘pit-by-pit’ graph showing the ore and waste included in a series of nested pit shells generated by varying the selling price of the commodity by a given factors (revenue factors). The graph also shows a representative value based on extraction of material in a ‘best case’ sequence (each shell extracted sequentially) which should be used for comparative purposes only.

To assess a more practical indication of project value, it is necessary to develop a schedule. A number of inputs are required to develop a schedule, and at this stage interpretation and manipulation by an engineer carrying out optimization is required. However, to ensure consistency between the cases initial pushbacks equivalent to one and two years of production have been selected for the schedule, with two remaining

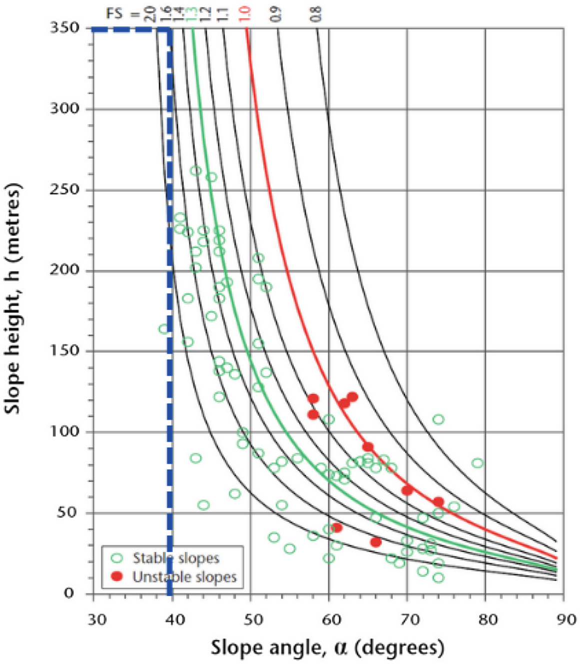

Fig. 1. Rock slope versus slope height, generic empirical database (Read & Stacey, 2009)

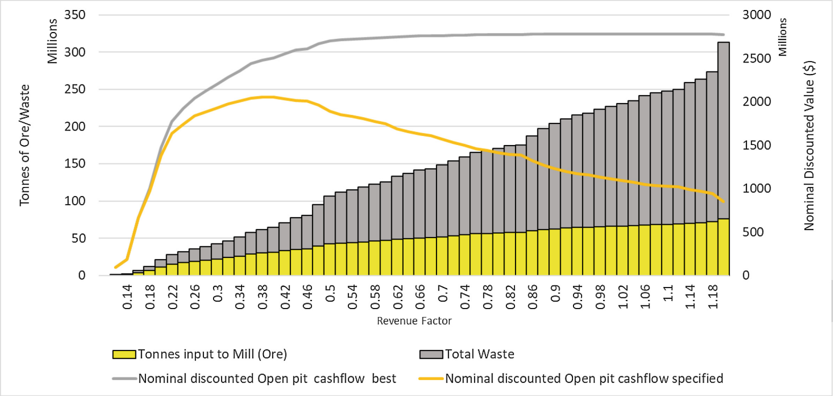

Fig. 2. Whittle output, pit by pit graph Case 1

larger pushbacks selected automatically using the Milawa Balanced algorithm built into Whittle (Table 2).

2.2 Case Two

Case two follows the same approach as case one, except for the definition of overall slope angle. Based on the slope stability chart for 'Rock Mass A' defined by Styles &

Table 2. Case 1 Economic outputs summary

Measure	Value
Ore (Mt)	39.7
Waste (Mt)	55.3
Stripping Ratio	1.39
Nominal NPV ($,*000*)	2,420

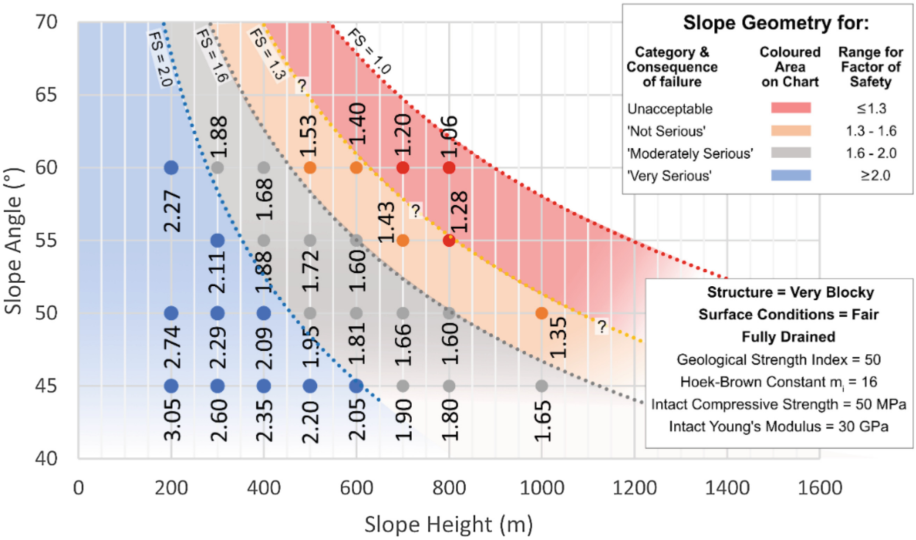

Fig. 3. Slope Stability curves for 'Rock Mass A', design curves for FoS 2.0 and 1.6 are confirmed (lower FoS are approximated) FoS values are labelled on each data point. (Styles et al. 2022)

Vakili (2020), an overall slope angle of 53° with an estimated FoS of 2 selected for the anticipated 400 m slope (Fig. 3). The slope stability chart is derived through a process of iterative modelling of 2D sections using the Improved Unified Constitutive Model (IUCM) with FLAC3D software as the solver.

The IUCM can more accurately predict the stress strain relationships of the rock mass, when compared to conventional constitutive models. Accounting for mechanisms such as transition from brittle to ductile response, confinement dependent strain softening, dilational response, strength anisotropy (where appropriate), and stiffness softening (Vakili, 2016), the IUCM is well suited to evaluating the overall slope stability for this study.

The required inputs to derive the slope stability curve are summarized in Table 3, each of which can be estimated through geotechnical logging of core and point load testing.

Figure 4 shows the pit-by-pit graphical output for case two pit optimization.

Table 3. Simple rock mass geotechnical parameters for 'Rock Mass A' (Styles & Vakili, 2020)

Rock Mass Description	
Structure	Very Blocky
Surface conditions	Fair
Basic IUCM Parameters	
GSI	50
m_i	16
UCS	50 MPa
Ei	30 GPa

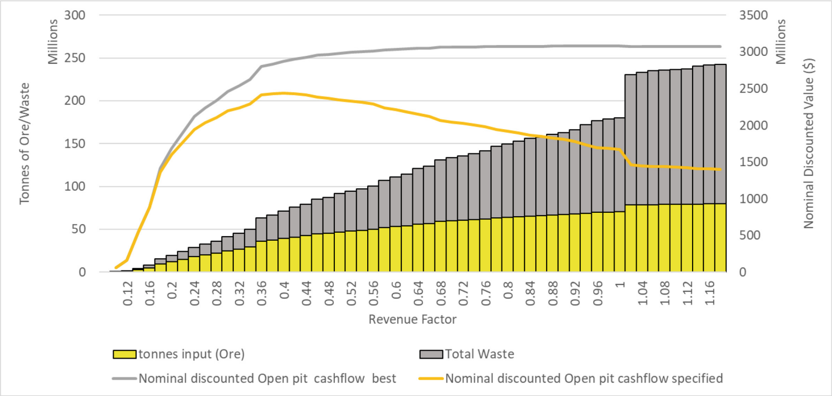

Fig. 4. Whittle output, pit-by-pit graph case two

Table 4. Case 2 Economic outputs summary

Measure	**Value**
Ore (Mt)	44.5
Waste (Mt)	41.5
Stripping Ratio	0.91
Nominal NPV ($,*000*)	2,749

A basic schedule using the same approach as in Case 1 has been developed, a summary of economic outputs is shown in Table 4.

2.3 Case Three

The process of including variable slope angles dependent on depth requires significant manual intervention in the standard optimization process. To simplify the approach for

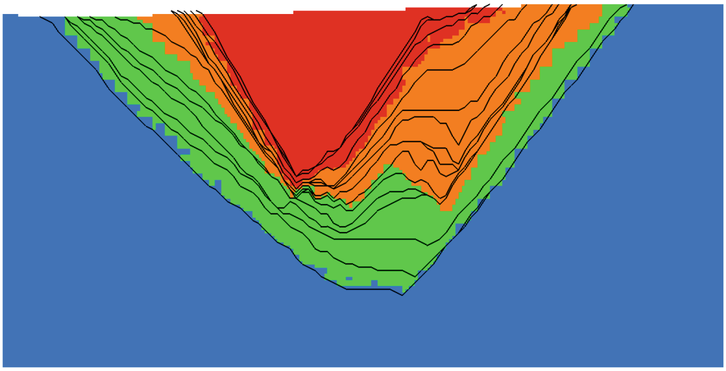

Fig. 5. Cross section of sequential pit shells, with slope angle zones colored

this proof of concept, a set of three discreet slope angles have been used based on the data points included in the slope stability chart, and the approximate maximum pit depth of 400 m.

- Pit shells with a depth $\leq$ 200 m must honor a maximum slope angle of 60°
- Pit shells with a depth $>$200 m and $\leq$300 m must honor a maximum slope angle of 57°
- Pit shells with a depth $>$300 m and $\leq$400 must honor a maximum slope angle of 53°

To achieve this initial optimizations must be processed without depth limits for each of the slope angles, and the geometries for the generated pits exported. The largest pit that does not exceed the specified maximum depth for each angle can then be extracted. Three pit shell geometries are generated in this case, the shells are used to code the geological block model into zones. The coded block model is then imported into Whittle and slope angle definitions for optimization are based on the coded zones. Figure 5 shows a cross section of the block model, colored by slope angle zones, the generated dynamic angle optimization shells are shown for reference. Figure 6 shows the pit-by-pit graph for the dynamic slope angle optimization. Table 5 shows the economic outputs summary for the case three schedule.

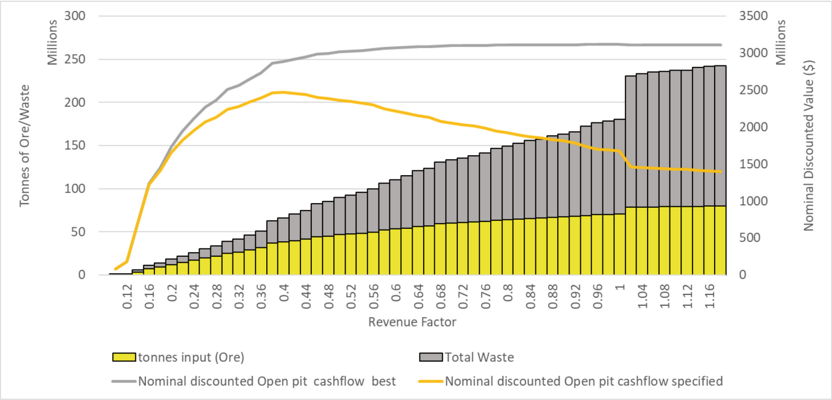

Fig. 6. Whittle output, pit by pit graph case three

Table 5. Case 3 Economic outputs summary

Measure	Value
Ore (Mt)	44.0
Waste (Mt)	38.5
Stripping Ratio	0.87
Nominal NPV ($)	2,871

3 Approach Comparison

To enable objective comparison between the methods, a number of graphs can be used to review the stripping ratio, and nominal value for each of the cases. The use of generic slope angle estimation demonstrates a significant disparity between the expected optimal pit shell. Demonstrating the requirement to increase basic understanding of geomechanical properties in a rock mass during early-stage studies (Fig. 7).

Comparison between cases two and three demonstrates some financial gains can be made by introducing the dynamic angle approach to guide early production scheduling. The ultimate pit contents are the same, and values tend to closely match one another in this case when the schedule has been generated to targeting a smooth ore/waste feed over the life-of-mine.

The dynamic approach may be most applicable when an aggressive mining approach must be taken. In such cases, some compromise can be made on the ‘smoothness’ of a mining schedule. For this example, the use of dynamic slope angles demonstrates an incremental improvement in discounted project value above the single angle approach (Fig. 8 and Fig. 2).

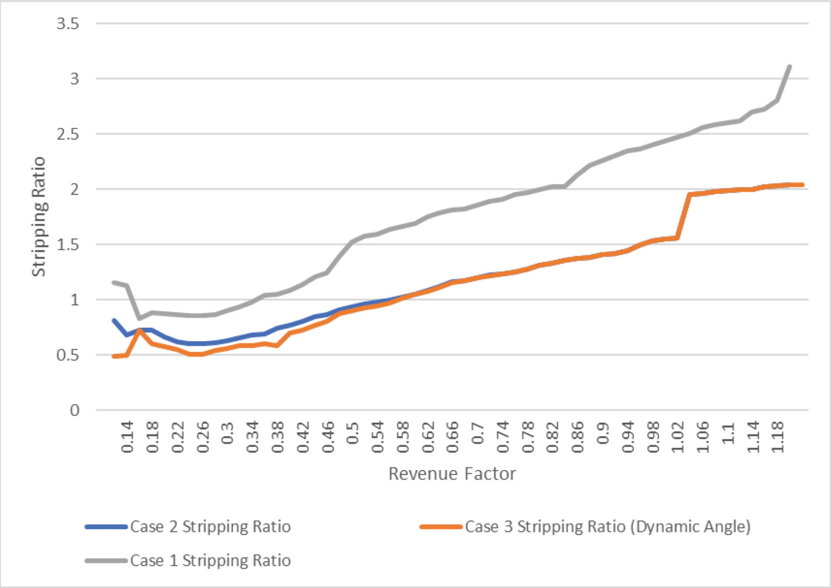

Fig. 7. Ore to Waste Stripping ratio for each slope angle optimization approaches

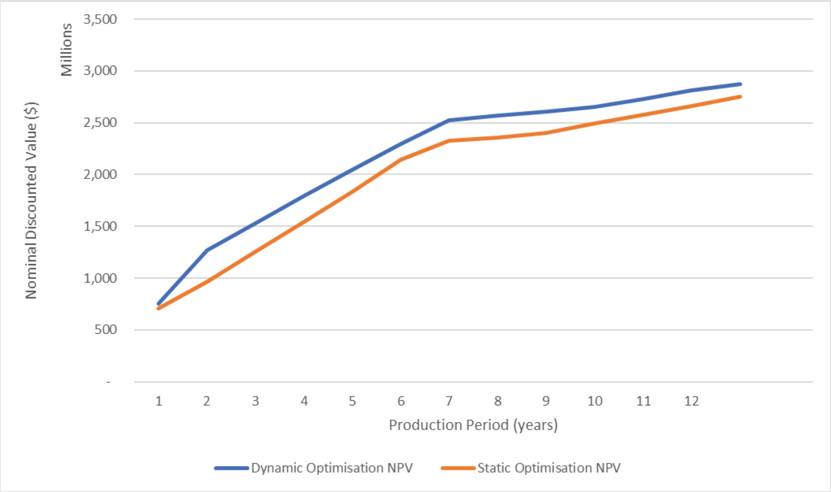

Fig. 8. Nominal Discounted Value for schedules from cases two and three

4 Discussion

Comparison between each case demonstrates the variation in outputs that are achieved by using a rock mass specific slope stability estimation method. While this example shows a significant increase in value due to the high strength rock mass allowing steeper angles than the generic chart suggests, it is equally likely that with a different rock mass the opposite may be achieved where a more accurate appraisal of slope stability could indicate a shallow angle is required.

The introduction of numerical modelling derived slope stability curves, to estimate a non-dynamic angle for optimization provides a confidence increase, while the additional analysis to develop a dynamic slope angle in the optimization provides relatively small increases in final project value for this case study. However, the approach does introduce the ability to increase early project revenue where cash flow is crucial to the initial stages of operation. By applying steeper angled, shallow pit shells as initial pushbacks, lower stripping ratios are demonstrated, reducing the size of an initial mining fleet, thus further limiting capital expenditure, mining costs, and waste production in the initial years of a project where capital recovery is most critical.

The introduction of new optimization methods may allow a more seamless approach for the inclusion of slope angle variability based on pit depth as part of optimization, rather than the current approach where a fixed value must be applied before ahead of the optimization step. Developments in slope stability inputs for open pit optimization such as the optimal slope profiles presented by Agosti et al. (2021) for generating varying slope profiles with depth may be used to further optimize early pushbacks in mining schedules.

The methodology proposed in this paper allows a gap to be bridged allowing inclusion of geotechnical inputs for improving optimization outcomes with relatively minor manual input. The use of rock mass specific slope stability versus slope height tools such as those developed by Styles & Vakili (2020), Li et al. (2008), and Carranza-Torres and Hormazábal (2020) provide a basis from which a more reliable estimation of stable slope angles can be introduced. The advantages of applying the dynamic angle approach outlined, will depend on the project specifics, namely the size and depth of the low revenue factor pit shells.

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