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OPTIMAL PITWALL DESIGN FOR OPEN PIT MINES IN THE PRESENCE OF FAULTS

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Abstract

Slope Optimiser is a novel software tool that determines non-planar optimally shaped slope profiles which are featured by a depth varying inclination. These profiles are obtained as result of topological optimisation carried out in order to determine the slope profile featuring the maximum Overall Slope Angle (i.e. the overall slope inclination from crest to toe) for prescribed input ground strength parameters - Mohr-Coulomb (M-C) or Generalised Hoek-Brown (G-H-B) and a target Factor of Safety. Bench geometries (bench height, face inclination, minimum berm width) are prescribed in the optimisation as constraints constraining the maximum local inclination of the sought optimal profile, together with any other constraints stemming from any geological discontinuity that may influence slope failure.

In this paper a novel formulation to account for the effect of discrete faults on slope stability is introduced. The failure mechanism considered are mixed accounting for failure along intact rock and along the fault. To provide a rigorous quantification of the benefits brought by Slope Optimiser, we consider case studies of metalliferous open pit mines and performed two designs: one employing planar pit walls and another one adopting the optimal pitwall profiles determined by Slope Optimiser. Here, a new mine case study is presented where pitwalls have to be designed in a mine featured by several faults. The Factor of Safety of the optimal pitwalls determined by Slope Optimiser were independently verified by Finite Element analyses with shear strength reduction technique performed using Rocscience RS2 and Midas FEA NX.

***Keywords**: slope topological optimisation; discontinuities; optimal pitwalls; waste-rock reduction; carbon footprint reduction*

1. INTRODUCTION

Pitwall inclinations bear a very significant effect on mine environmental impact and profitability since they control to a large extent the amount of rockwaste to be excavated [1]. Consequently, ensuring pitwalls are as steep as possible is essential.

[2], [3] and [4] employed a novel geotechnical software, Slope Optimiser [5], that computes the slope optimal profile for any specified lithological sequence without unduly restricting the search to any predefined family of shapes to design the pitwalls of three open pit mines achieving important increases of NPV and carbon footprint reductions in comparison with the traditional design based on planar pitwalls. To be able to quantify the gains of NPV and carbon footprint reduction in a consistent way in [2-4] 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. Financial and environmental gains were calculated as the difference between the NPV, carbon footprint and

energy consumptions resulting from the two designs. Net Present Value increases and carbon footprint and energy consumption reductions obtained by the adoption of optimal pitwall shapes are rigorously quantified with gains up to 52.7% of Net Present Value and carbon footprint reductions averaging at 600,000 tonnes CO_2 equivalent.

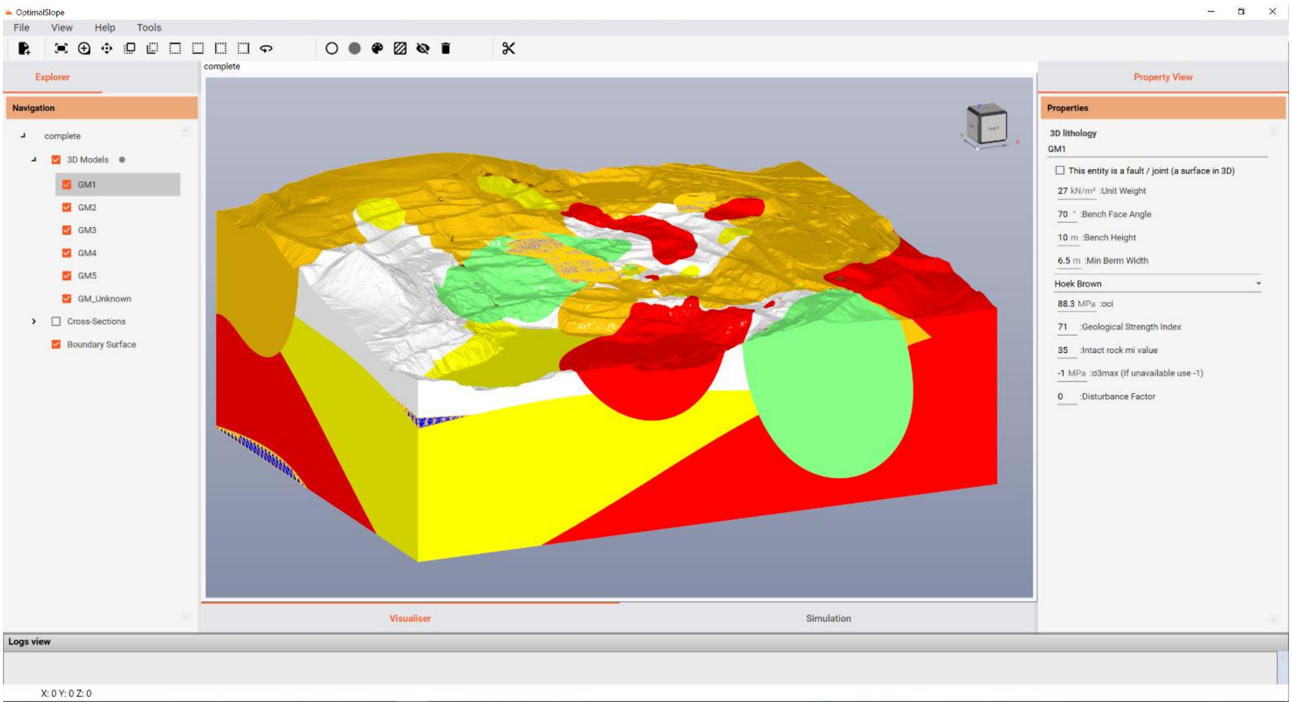
A fundamental limitation of the current topological optimisation is the non-consideration of discontinuities like faults. As the LOP guidelines [6-7] state faults are often encountered in the excavation of pitwalls and depending on their inclination they may severely reduce slope stability so their correct consideration in slope stability assessment is paramount. In this paper, we first describe and then showcase the extension of the current algorithm that seeks the Factor of Safety in 2D for a given slope profile to include faults.

The paper is structured as follows: in Section 2, the methodology adopted to include the discontinuity in the calculation of the FoS of a 2D cross-section are introduced; in Section 3 case studies of pitwalls of existing open pit mines employed to test the methodology are introduced; in Section 4 the results of the simulations performed using Slope Optimiser on the case studies are illustrated; in Section 5 conclusions are provided.

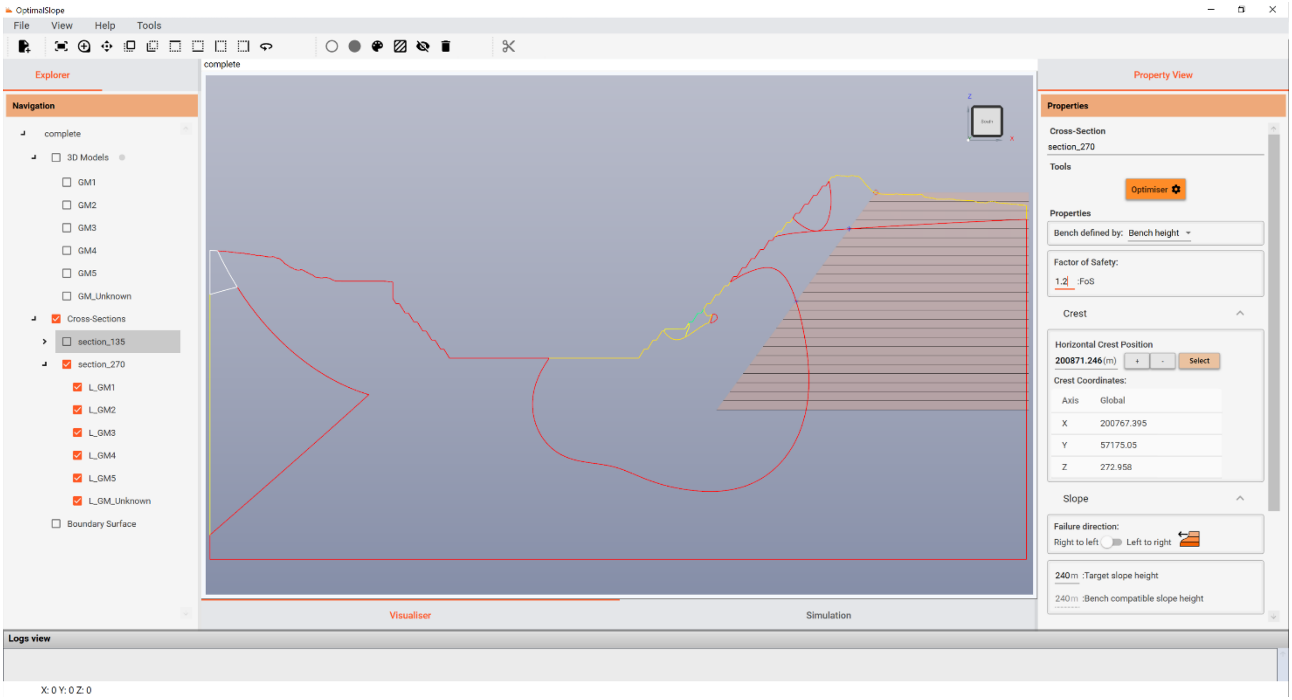
2. METHODOLOGY

2.1 Optimal pitwall design by slope optimisation

A detailed explanation of how slope profile optimisation works can be found in [2], therefore it will not be repeated here. The input data required are the rock mass strength (expressed as either Mohr-Coulomb or Generalised Hoek- Brown criterion), unit weight, and the geometries of benches, namely bench height, bench face inclination and the minimum berm width. Moreover, any ramps (roads) can be prescribed as a constraint for the slope to be designed together with any surcharge load as well. In Figure 1, typical input and output data for Slope Optimiser are reported.



a)

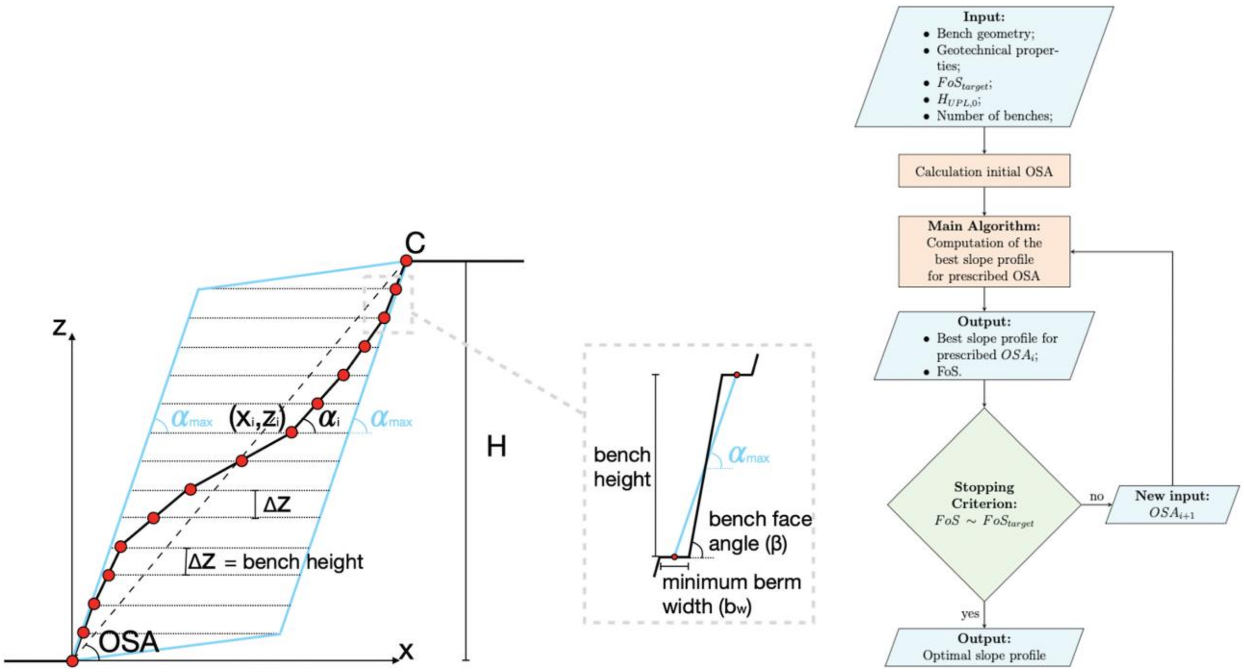


b)

Figure 1. Slope Optimiser graphical user interface: a) example of a 3D input stratigraphy. For each lithological unit, rock strength parameters - c and φ for the Mohr-Coulomb criterion or GSI, UCS and m_i for the Generalised-Hoek-Brown criterion - are specified together with unit weight. Bench and ramp geometries are specified also for each lithological unit. b) Example of a vertical cross section, obtained by slicing the 3D stratigraphy (it is also possible to import 2D section directly).

Slope Optimiser typically considers several thousands of candidate slope profiles, each defined by a discrete set of points in the vertical plane: see the (x_i, z_i) coordinates in Figure 2a, with z_i being values specified according to the bench height (Δz = bench height) input by the user, and x_i unknown variables to be determined. The search for the optimal profile is constrained to feasible profiles (which lie within the blue bounds of Figure 2a). A profile is feasible if $\frac{z_i - z_{i-1}}{x_i - x_{i-1}} \leq tan\alpha_{i\_max}$ for every *i* (i.e. the inclination of each segment of the profile is capped to α_{i_max}). The α_{i_max} values are determined by the software before the optimisation algorithm is called on the basis of bench height, bench face inclination, and minimum berm width provided by the user (see Figure 2b). If a ramp needs to be included as part of the pitwall profile, a lower α_{i_max} value is imposed for the profile segment corresponding to the vertical position of the ramp.

The optimal pitwall profile is defined as the overall steepest safe profile that meets the FoS design criterion (*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 2a). The logical steps used to calculate the optimal pitwall profile are summarised in Figure 2c. Firstly, an initial OSA is heuristically determined. The main algorithm then calculates the optimal pitwall shape for the assigned OSA and geometric constraints (bench height, bench face inclination, minimum berm width, and road width). The FoS_i associated with the optimal profile found at the *i*-th iteration is then compared to the FoS_{target}. If it is higher, a steeper OSA is prescribed at the next iteration; if it is lower, a flatter OSA is prescribed. The termination criterion is specified in terms of the percentage difference between FoS_{target} and FoS_i.



a) *b)* *c)*

Figure 2. After (Agosti et al., 2025): a) generic candidate slope profile. A uniform discretization along the z direction is adopted. The 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: $x_1, x_2, \dots x_{n-1}$. b) determination of α_{i_max} based on bench geometry. c) Flow chart summarizing the iterative procedure used to determine the optimal profile for a given pitwall.

2.2 Algorithm to include faults into calculation of the FoS

Discontinuities, eg. faults, are represented in a data structure (each fault as a vector of points) of their own since they are open polylines with their own strength properties: friction angle and cohesion. Every time intersection of the rotational mechanism under consideration with a fault is detected, a new failure mechanism is generated on top of the failure mechanism under consideration. This mechanism is made by a logspiral, which is the most efficient rotational failure mechanism in a homogenous rock layer, until the point A of intersection (see Figure 3) and then by the fault geometry which needs to be followed. There are two directions that can be taken along the fault, we want to follow the direction compatible with a feasible failure mechanism, hence from A upwards towards B. The algorithm can be described by the following steps:

1. Detect intersection of the rotational mechanism under consideration (logspiral) with any fault
2. Follow the fault until either of the two options occurs:
    a) The fault daylights on the slope face or exits at the topography
    b) The fault terminates inside a lithological unit (dangling fault)
    c) The fault re-intersects the composite logspiral

The external work (or the driving moment M_d) performed by the self-weight and surcharges are calculated as shown in [2] according to the limit analysis upper bound theorem or equivalently the limit equilibrium method for the case of a single rotating wedge [8]. In equations (1) and (2) below, both formulations are provided.

The calculation of the resisting moment involves two components: one along the rotational part of the rotational mechanism and one along the fault. $M_{res\,fault}$ is to be calculated as the sum of each piecewise linear segment multiplied by the lever arm to the Centre of Rotation (CoR).

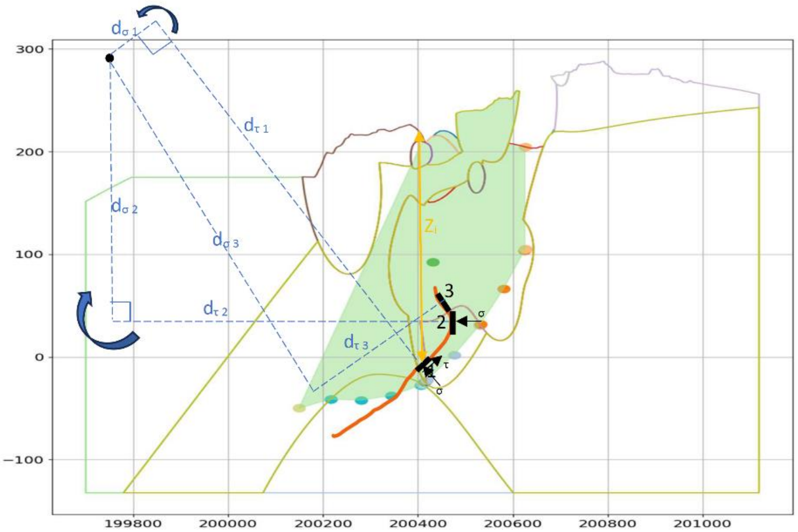


Figure 3. Calculations of resisting moment (or dissipated energy for the limit analysis upper bound method) along the fault (in red): the vector σ and τ indicate the normal and tangential stresses respectively along a fault segment.

$M_{res\ fault}$ is due to both tangential stresses, τ_{fault}, and normal stresses, σ_{fault} (see Figure 3). The fault is discretised into i segments, with the discretisation (length of the fault segment) being a function of the precision of the geotechnical model available. The moment is calculated from the summation of the stresses along each fault segment, so the following formula is derived:

$$M_{res\ fault} = \frac{W_d}{\Omega} = \sum_{i=1}^{N} \tau_i * l_i * d_{\tau\ i} + \sigma_i * l_i * d_{\sigma\ i} \quad (1)$$

with W_d the dissipated energy and Ω the rotational speed of the sliding mass, l_i being the fault segment length, $d_{\tau\ i}$ being the distance to the CoR of the segment i and $d_{\sigma\ i}$ being the distance to the CoR of the perpendicular to the segment *i*.

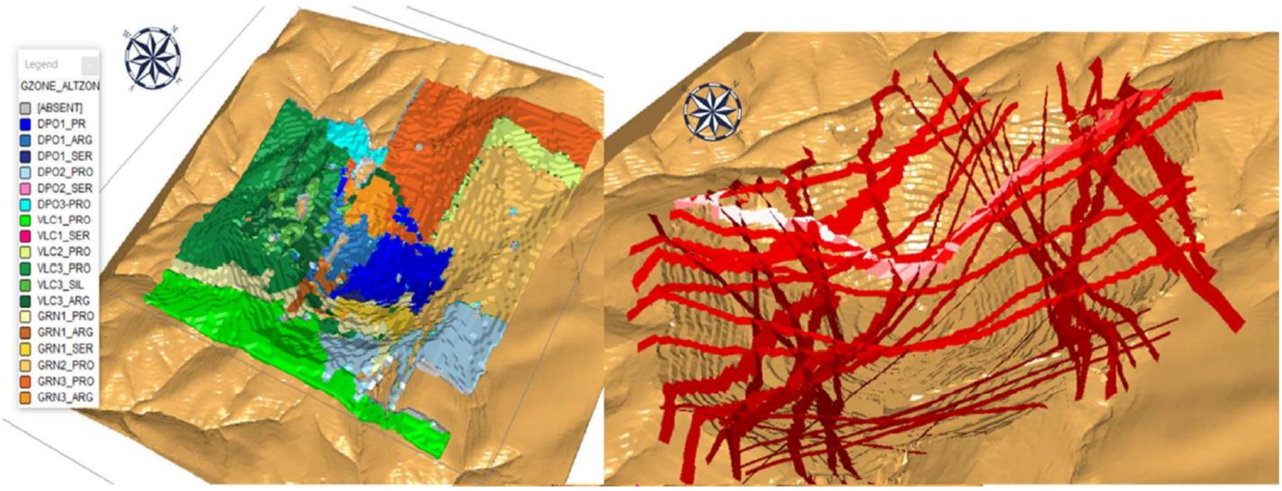
Then we substitute $\tau_i = \sigma_i tan\varphi_{fault} + c_{fault}$

$$M_{res\ fault} = \frac{W_d}{\Omega} = \sum_{i=1}^{N} (\sigma_i tan\varphi_{fault} + c_{fault}) * l_i * d_{\tau\ i} + \sigma_i * l_i * d_{\sigma\ i} \quad (2)$$

with c_{fault} being the cohesion and φ_{fault} being the friction angle along the fault (ideally measured by direct shear test).

3. RESULTS AND DISCUSSION

To test the new algorithm we considered an open pit mine located in Asia. For reasons of confidentiality we are unable to name it. The data were taken from the geotechnical reports of the mine. In Figure 4a the plan view of the lithological units is provided. The mine presents several faults which are also reported in red in Figure 4b each of them features by different strength values.



a) b)

Figure 4 lithological units and faults (in red); b) plan view with cross-sections.

3.1 Calculation of optimal pitfall profiles by Slope Optimiser

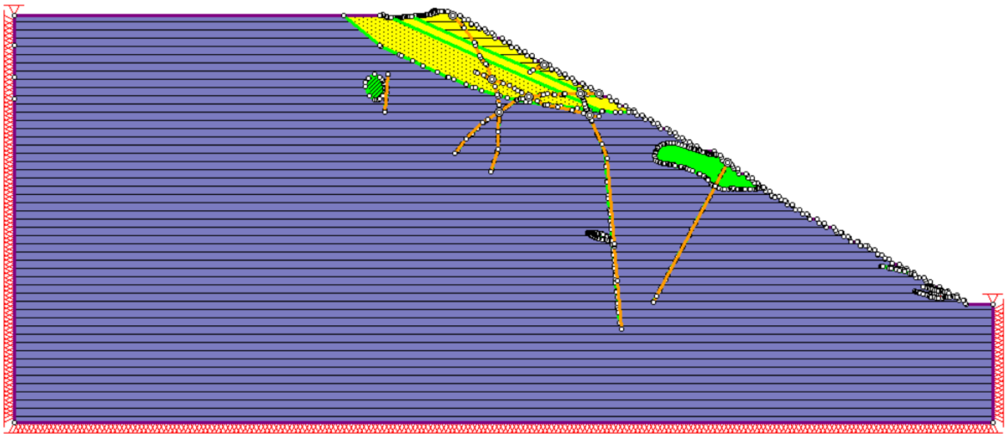
In the design of pit walls, we followed the standard practice of starting with the design of benches and then moving to the overall pitwall profiles [6]. The height of the benches to be adopted is a mine specific input parameter which often within the same mine, eg. higher benches in stronger rock layer. In Slope Optimiser, bench heights are to be specified for every lithological unit (rock layer) in the 3D stratigraphy. The properties are then inherited after slicing into any 2D cross-section made. The bench face inclination is another user specified input. In the 2 case studies here considered, bench face inclinations were calculated following a kinematic analysis at the bench scale.

The minimum bench width is the third geometric input required by Slope Optimiser which together with bench height and bench face inclination is used to calculate the angles α_{i_max} to be prescribed as geometric constraints in the search for the optimal slope (see Figure 2b). This geometric parameter depends on the type of mining equipment employed (eg. size of excavation machinery and type of blasting techniques) and the requirement to keep rockfalls under control.

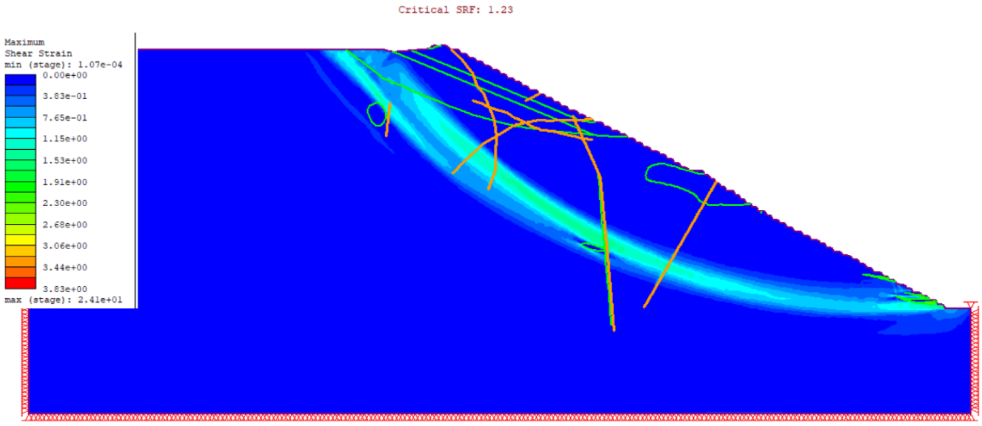
Then, we computed the geotechnically optimal slope profiles for the representative cross-section of the mine using Slope Optimiser.

3.2 Verification of optimal profiles by Strength Reduction Finite Element Analyses

In Figure 5, the optimal cross section determined for the mine is shown. The excavation goes through 4 different layers of rock (identified by different colours) and several faults in orange. The optimal cross section obtained from Slope Optimiser was exported as .dxf file and then imported into into Rocscience RS2 (Figure 5a). Then a Finite Element Analysis with Shear Strength Reduction (FEASSR) technique was run resulting in a Strength Reduction Factor of 1.23; a similar analysis was run in Midas NX resulting in a Strength Reduction Factor of 1.23. Note that the FEASSR is performed in RS2 and in Midas are performed according to two different methods: in RS2 bracketing and bisection is employed [9], ie several analyses are performed for different values of SRF each resulting in either convergence or non convergence of the analysis with the next value of SRF selected on the basis of bisection, whereas in Midas NX a single FEA is performed with SRF increasing monotonically [10] until displacements exceed a prescribed threshold, when failure is declared. In both techniques, the steps of SRF decrease can be prescribed as small as desired. The fact that the two methods give rise to very similar results is reassurance of the validity of the analyses performed.



a)



b)

Figure 5. Finite Element Analysis with Strength Reduction of the optimal slope profile determined by Slope Optimiser. a) geotechnical model (faults are visible in orange, each lithological unit is in a different colour); b) shear strain field from Rocscience RS2 with slope instability detected for SRF=1.23.

It is well known that Finite Element Analyses may be subject to mesh dependency and in case of non-normality of geomaterials to spurious results [11]. Therefore in order to ensure results are not unduly dependent on mesh size, 1) the normality rule, ie dilation angle chosen as equal to the internal friction angle φ, was adopted in all analyses, 2) simulations were performed for different mesh sizes until the mesh size was small enough not to affect the results in terms of both FoS values and geometry of the failure mechanism. Asymptotic convergence to the Strength Reduction Factor for decreasing size of the mesh adopted was observed in all cases.

An extra difficulty of these FEASSR analyses was about the selection of elastic stiffnesses for the faults in both normal and tangential directions for Midas FEA NX since the code requires these input parameters. In order to select these values, we ran several parametric analyses for an idealised case of a slope with a single oblique fault dominating its behaviour and selected the stiffnesses such that the displacements obtained were equal to those achieved from the same simulation run in Rocscience RS2.

4. CONCLUSIONS

A new methodology to extend topological optimisation of slopes to account for the presence of any number of discontinuities, eg. faults, is presented to determine geotechnically optimal profiles

– profiles that maximise the overall slope angle for a prescribed FoS, considering the geometry of benches and any ramps – for rock masses featuring several discrete discontinuities.

In current design practices, mines tend to be designed on the basis of planar pitwalls, i.e. with a constant inter-ramp angle (IRA) in each sector of the mine. However, looking at the final geometry of any pit cross-section, this is anything but planar due to the need to accommodate for benches, step-outs and roads, therefore the assumption of constant IRA adopted at the design stage is a simplification which can and should be removed if a better design can be achieved as result. It seems only natural to wonder whether pitwalls of non-linear shape could be used instead of planar ones. OptimalSlope' Slope Optimiser has been developed to find geotechnically optimal shapes for non-uniform slopes accepting any number of layers as input and geomaterials whose strength is described by either the Mohr–Coulomb criterion or the Generalised Hoek–Brown criterion.

In the presence of faults failure mechanisms end up being much more complex since they are determined by a combination of failure along the geometry of the discontinuity and rotational failure along a logspiral segment across the rock intact material. For each candidate slope profile considered, the critical failure mechanism, the one associated to the lowest FoS value, is found, then the best slope profile is found as the results of constrained optimisation and an iterative process where different OSA inclinations are trialled. The new formulation was demonstrated on an open pit mine case studies in the presence of several distinct faults. The Factor of Safety values and the failure mechanisms identified were verified by running Finite Element simulations with Shear Strength Reduction using two state-of-the-art commercial software packages for slope stability analyses: Rocscience RS and Midas NX.

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