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Comprehensive three-dimensional geological–geostatistical–numerical model for open pit mining in competent rock

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Abstract

This paper combines the use of a three-dimensional geological model and geostatistical rock mass quality estimate in the numerical modelling of open pit mining in competent rock. The objective of the methodology is to identify macroblocks or structural controlled zones with high failure potential. The methodology is validated with an instability event that occurred at an open pit mine. Based on the results of the methodology, different zones with macroblock formation are identified during the life of mine and several recommendations are established related to the structural model, rock mass model and hydrogeological model.

Keywords: *open pit, competent rock, structural controlled, numerical analysis, optimisation*

1 Introduction

Three-dimensional analysis of potentially unstable conditions at inter-ramp and global scales is conducted due to unfavourably oriented major geological structures in relation to slope design for a life of mine (LOM) mining plan. For this analysis, a 3D numerical model is constructed at a mine scale, which includes assigning intact rock properties based on a lithological model and the spatial distribution of rock quality based on a geological strength index (GSI) block model. Geological structures are explicitly incorporated into the model through interfaces. This coupling of the rock quality and structural models enables the formulation of stress and strain and the identification of areas with complete structural control (e.g. outcropping wedges and planar faults) and partial structural control (e.g. non-outcropping wedges and mixed faults).

For stability analysis, Factors of Safety (FoS) are calculated using the strength reduction technique, which involves gradually reducing the properties of the rock mass and geological structures based on a strength reduction factor (SRF) (Cheng et al. 2007).

To validate the used mine-scale model, a historical instability case is employed. Based on the validation and forecast results of the model, geomechanically significant zones are identified. Geomechanically significant zones are defined as those exhibiting FoS below 1.3, indicating potential instability at the inter-ramp level.

2 Background

This section describes the main background information related to geology and geotechnics included in the analyses. The lithological model comprises 14 units, and the structural model includes a total of 69 geological structures.

Laboratory tests are available for intact rock core samples from each unit of the lithological model. The properties of intact rock are assigned to the lithological model units and include density (ρ), uniaxial compressive strength (UCS) , elastic deformation (E_i, vi), indirect tensile strength (σ_{tb}), and parameters for the Hoek–Brown peak strength envelope (Hoek et al. 1998, 2002, 2019) (σ_{ci} = unconfined compressive strength; m_i = material constant for the intact rock; σ_t = uniaxial tensile strength).

The UCS ranges from 150 to 250 MPa, while the modulus of deformation varies between 50 and 100 GPa, indicating a very strong intact rock.

The Mohr–Coulomb constitutive model is used to represent the mechanical behaviour of the geological structures, employing a perfect elastoplastic behaviour. The properties are obtained from laboratory tests, literature and the calibration process of the geomechanical stability analysis. The cohesion and friction are approximately 50–100 kPa and 20–25 degrees, respectively.

The stress condition to be used as the pre-mining condition in the numerical model is obtained from stress measurements conducted in nearby underground mines.

The spatial distribution of rock mass quality is derived from a block model of geotechnical parameters estimated through a series of Kriging interpolations using data from geotechnical logging of drill core samples. The model includes the following variables: fracture condition (FC) and rock quality designation (RQD) (Deere et al. 1967). For the analysis, the GSI is derived from the estimations in the block models of geotechnical parameters: $J_{con_{89}}$ and RQD through Equation 1 (Hoek et al. 2013).

$$GSI = 1.5 \cdot J_{con_{89}} + \frac{RQD}{2} \quad (1)$$

3 Procedure

3.1 Excavation stages

The excavation stages considered in the numerical model are as follows: the original topography (pre-mining) and the already excavated stages (10 steps). For the calibration model, the benches responsible for the instability event are modelled in detail (7 steps). Finally, the most relevant geometries of the LOM design are modelled annually (16 steps).

3.2 Mesh

The model is discretised into continuous tetrahedral elements. The size distribution is determined by the following factors:

- Geological structures: 5–20 m.
- Surface excavations: 10–15 m.
- Bench detail: 5 m.
- Model boundaries: 50 m.

With the above considerations, the model consists of a total of 21 million elements. Figure 1 shows the mesh at the full model level and the surface excavation level.

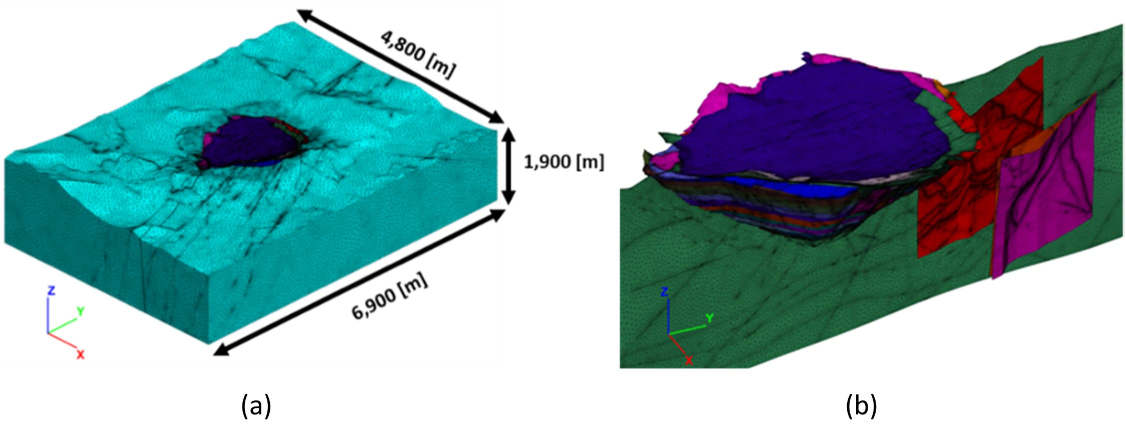


Figure 1 Mesh of the numerical model. (a) Dimensions; (b) Open pit phases and structural model

3.3 Assignment of geotechnical properties

The geotechnical properties are assigned to the numerical model mesh based on the spatial distribution from the lithology model and the GSI block model. Intact rock properties (σ_{ci}, m_i, E_i) are assigned according to the rock unit from the lithology model, while the rock mass quality is assigned from the GSI block model. The hydrogeology is included in the model as pore pressure in some of the geological structures.

Using the GSI distribution estimated from the block models, along with the previously assigned intact rock properties for each rock unit, the scaling of properties to the rock mass is generated using the methodology developed by Hoek et al. (1998, 2002, 2019).

$$\sigma_1^r = \sigma_3 + \sigma_{ci} \cdot \left(m_b \cdot \frac{\sigma_3}{\sigma_{ci}} + s\right)^a, m_b = m_i \cdot exp\left(\frac{GSI - 100}{28 - 14D}\right)$$

$$a = \frac{1}{2} + \frac{1}{6} \cdot \left(e^{-\frac{GSI}{15}} - e^{-\frac{20}{3}}\right), s = exp\left(\frac{GSI - 100}{9 - 3D}\right) \tag{2}$$

where:

σ_1^r	=	major principal stress from Hoek–Brown criterion (MPa).
σ_3	=	estimated minimum principal stress from the numerical model (MPa).
GSI	=	geological strength index (Hoek et al. 2002; Marinos & Hoek 2005).
D	=	damage disturbance factor due to blasting and stress relaxation (Hoek et al. 2002; Marinos & Hoek 2005).
s, m_b and a	=	parameters of the Hoek–Brown model.
σ_{ci} and m_i	=	parameters estimated from laboratory tests.
e and exp	=	exponential function.

The extent of the damage disturbance zone associated with the excavation process of the open pit during the pre-existing mining and LOM is estimated based on the scheme presented in Figure 2a. Depending on the height of the slope, a geometric region is assigned that defines the extent of the disturbed zone around the analysed wall. This region varies from a disturbance factor value (Hoek et al. 2002; Marinos & Hoek 2005), of D = 1 at the slope wall to D = 0 at the termination zone of that region (no disturbance). For analysis purposes, a linear function dependent on the distance from the slope wall is used to account for the degree of disturbance. Figure 2b shows a section of the result of the disturbance zone assignment process associated with the excavation of a phase of the open pit.

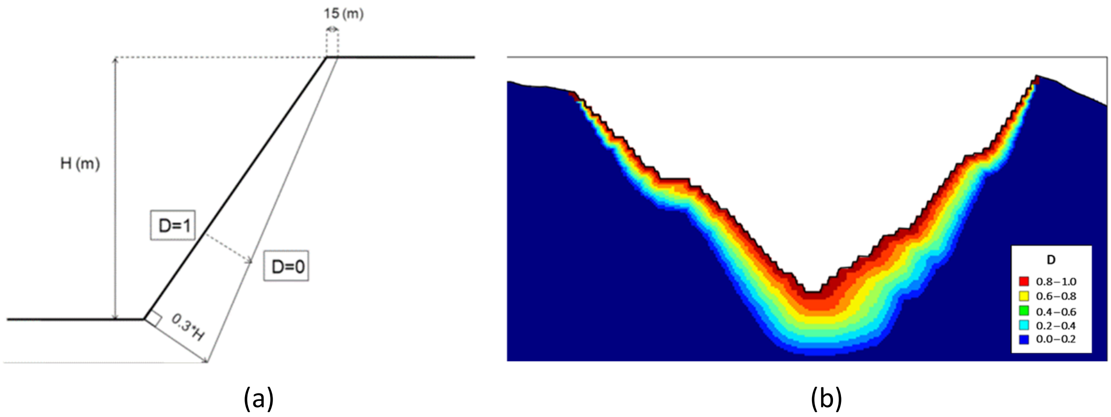


Figure 2 Disturbed zone at a global scale of a slope. (a) Conceptual model (Silva & Gomez 2015); (b) Assignment of the disturbance zone to the model

Figure 3 presents the methodology applied to the comprehensive 3D geological–geostatistical–numerical model for open pit mining. It can be observed that the values of intact rock and rock mass quality vary throughout the model.

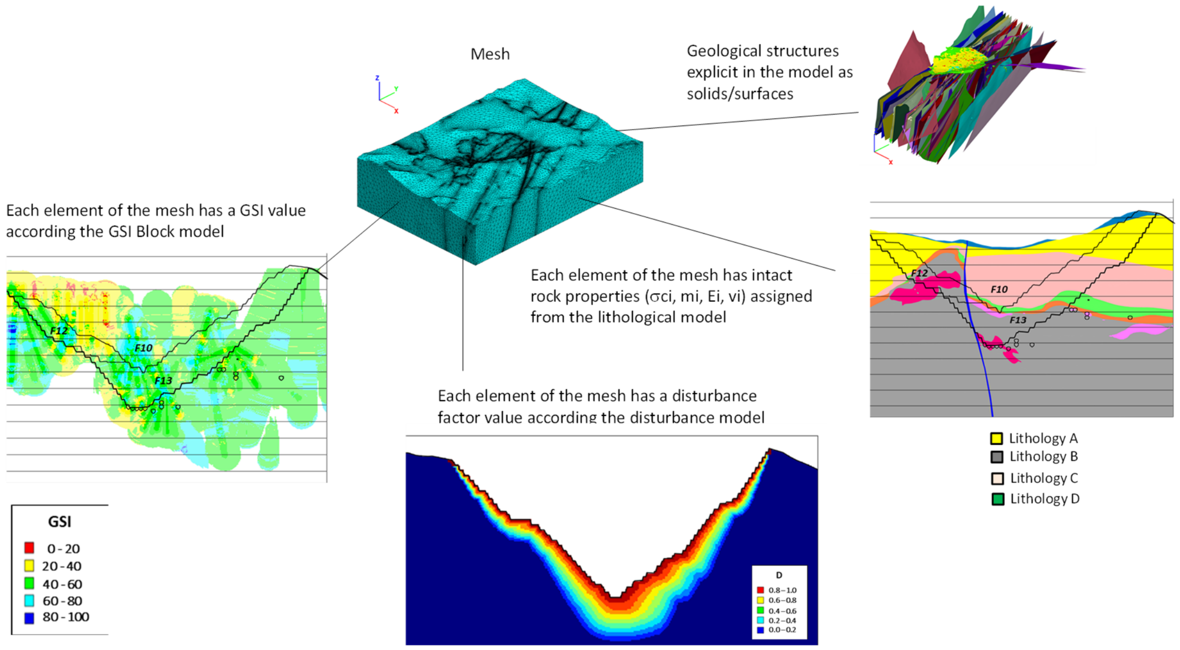
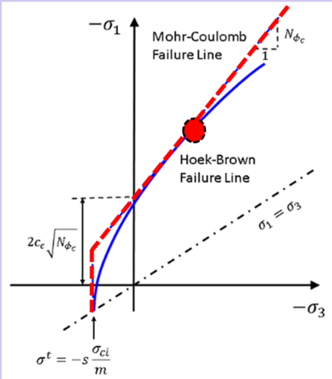


Figure 3 Comprehensive three-dimensional geological–geostatistical–numerical model for open pit mining

3.4 Stability analysis procedure

Next, the considerations and procedure for the stability analysis for the validation case and the LOM periods are presented. This procedure is carried out after obtaining the equilibrium models in the elastoplastic stage (Table 1). The analysis was performed using a combination of the finite element Abaqus software and the finite difference FLAC3D software.

Table 1 Considerations and procedures for stability analysis

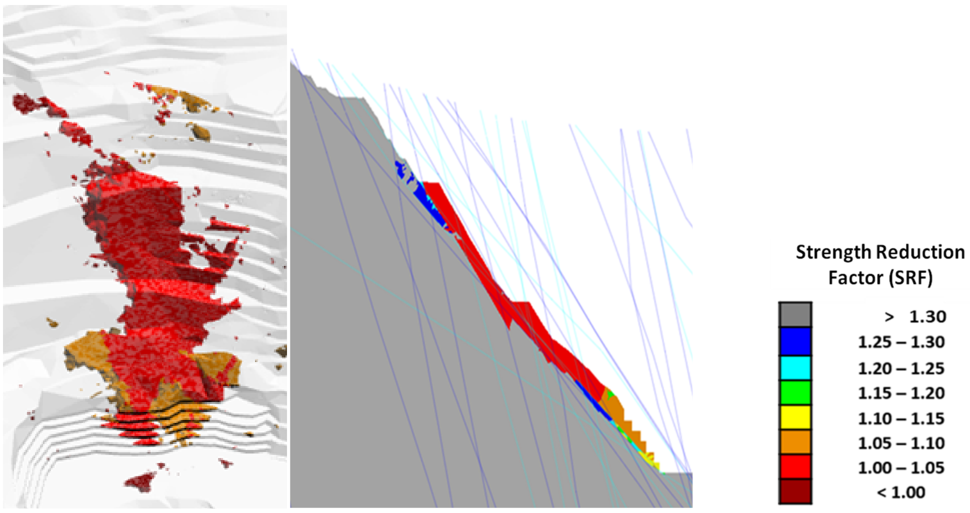
Element	Description
1. Conversion from Hoek–Brown model to Mohr–Coulomb model	For the conversion to a Mohr–Coulomb model, a linearization of the Hoek–Brown envelope is performed based on the minor principal stress (σ_3) of the numerical model at that moment. The parameters of the Mohr-Coulomb envelope, friction angle (ϕ_c) and cohesion (c_c), are described by Equation 3 and are directly obtained from the software.  $$c_c = \frac{\sigma_c^{UCS}}{1 - \sin\phi} \quad \phi_c = \sin^{-1}\left(\frac{N_{\phi_c} - 1}{N_{\phi_c} + 1}\right) \quad N_{\phi_c} = 1 + a \times m_b\left(m_b\frac{\sigma_3}{\sigma_{ci}} + s\right)^{a-1} \quad \sigma_c^{UCS} = \sigma_3(1 - N_{\phi_c}) + \sigma_{ci}\left(m_b\frac{\sigma_3}{\sigma_{ci}} + s\right)^a \qquad (3)$$ where: c_c = cohesion for the Mohr-Coulomb model. ϕ_c = friction angle of the Mohr-Coulomb model. a, m_b, s, σ_{ci} = parameters of the Hoek–Brown model. σ_3 = minor principal stress from the numeric model (MPa). N_{ϕ_c} = slope of the strength envelope.
2. Resetting variables of the numerical model	The velocities, displacements and plasticity of the numerical model are reset in order to be recalculated based on the current stress state of the model and its new resistance properties.
3. Application of the strength reduction method and calculation of the safety factor	For stability analysis, the strength reduction method (Cheng et al. 2007) is utilised. This method involves a progressive process of reducing the strength of the rock mass and geological structures. For each reduction step, the fulfillment of the equilibrium criterion at each node of the model is checked. The SRF is determined at the point where the equilibrium criterion is no longer satisfied. The reduction in the strength of the rock mass and geological structures is based on an SRF. The reduction according to SRF is defined by Equation 4. $$c_r = \frac{c_0}{SRF} \quad T_r = \frac{T_0}{SRF} \quad \varphi_r = degrees\left(atan\left(\frac{\tan(radian(\varphi_0))}{SRF}\right)\right) \qquad (4)$$

Element	Description
	where: SRF = reduction factor. For the purposes of this study, the SRF is the value of the safety factor. c_r, c_0 = reduced cohesion and original cohesion of the Mohr–Coulomb model, respectively. T_r, T_0 = reduced and original tensile strength, respectively. φ_r, φ_0 = reduced and original friction angle of the Mohr–Coulomb model, respectively. The equilibrium criterion is defined based on the velocities of each node in the analysed sector and is described by Equation (0). $velocity_{nodal} < 1 * 10^{-5}$ (0) The reduction process used in the analysis consists of a total of nine steps, starting with a reduction factor of 0.90 and increasing in intervals of 0.05 until a reduction factor of 1.30 is reached.
4. Stability analysis	Based on the FoS results obtained using the SRF technique for each analysis period, all geomechanically significant zones are identified and each zone is analysed independently

4 Results

4.1 Validation

The results of the validation process are presented in Figure 4, where it can be observed that the model is able to successfully reproduce the instability event for a FoS of 1.05. On the other hand, the system of geological structures identified in the instability and forming of the macroblock consists of a set of semi-parallel structures with an angle similar to the inter-ramp, and another set of high-angle, semi-parallel structures.



(a) (b)

Figure 4 Results of the calibration case. (a) Plan view distribution of the Factor of Safety; (b) Section with limiting geological structures (strength reduction factor = 1.00–1.05)

4.2 Life of mine design

Figure 5 presents examples of stability analysis results for the LOM design analysis periods with the SRF for two expansion phases of the LOM design. Two geomechanically significant (potentially unstable) zones are identified, along with the limiting structures of each macroblock.

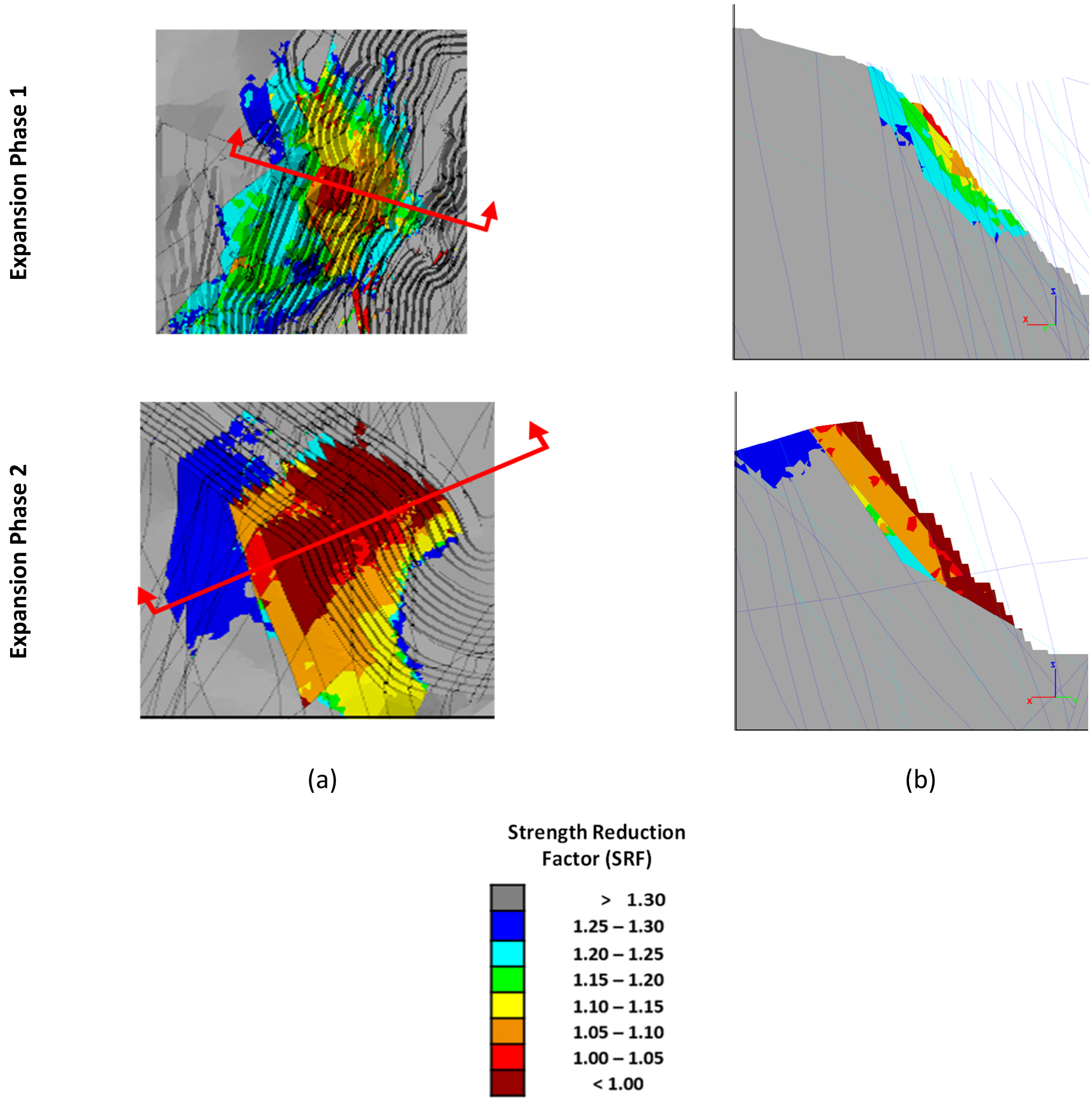


Figure 5 Results of the life of mine design. (a) Plan view distribution of the SRF; (b) Section with limiting geological structures defining the SRF of the macroblocks

5 Conclusion

The stability analysis procedure using the calculation of the FoS (based on the SRF technique) allowed an accurate reproduction of the validation case corresponding to the instability recorded in an open pit wall.

For the LOM forecast analysis it was possible to identify different geomechanically significant zones with potential for sliding. For the identified zones, it is recommended to carry out the recognition, verification and validation of the structures that constitute the potential instability.

The stability analysis results showed a dependence of the mining design on the structural geological model as they largely influence the geomechanically significant zones. Therefore, it is recommended to validate the interpretation of the structural model, both in terms of continuity and geometry of these structures, defining different degrees of reliability. Emphasis should be placed on the most relevant geological structures that define the zones with potential instability.

One of the major sources of uncertainty for the analyses conducted in this study is the estimation of pore pressure. It is recommended to validate the conceptual model (the presence of water in faults) with a model based on information from a hydrogeological characterisation program and the development of a numerical model. This requires implementing an instrumentation system and a monitoring plan that includes vibrating wire piezometers and piezometric wells. For future studies, the results of these models should inform the pore pressure in each stability analysis section, including the base case (most probable condition) and its respective variations.

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