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Empirical and Numerical Finite-Element-Based Model to Improve Narrow Vein Mine Design in Peruvian Mining

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Abstract. This paper proposes a numerical finite-element-based model aimed at optimizing narrow-vein stope stability. This model combines empirical and numerical methods to develop a sequence, which may determine an acceptable stope safety factor. A stope stability analysis was conducted through the Mathews stability graph method, which requires two factors: the hydraulic radius (HR) and stability number (N'). The Mathews stability graph method is used to assess the stability of an underground design. Variations in stope dimensions are estimated by changing the HR and Factor A within the N', which is determined through numerical methods. The results of the numerical simulation indicate that the HR increases with an increase in stope dimensions, while Factor A maintains an inverse relationship with the maximum stress induced on the excavation walls. This document demonstrates the potential of combining empirical and numerical methods in stope design optimization, especially when developed in small narrow vein mines.

1. Introduction

In recent decades, the depletion of near-surface mineral ore resources has prompted mining companies to invest more heavily in underground exploitation methods. In this context, underground work instability is inherent to the exploitation methods used and worsens based on mine depth [1]. In fact, mining companies have identified instability as one of the main issues that threaten mining operations. Some examples of instability issues are the 2010 collapse of the San José mine in Chile, where 33 miners were trapped for 70 days; the collapse in the Villa de la Paz mine in Mexico in 2015; and the collapse in the San José de Tacopilla mine in Chile in 2019, where three people died.

In general, most small and medium-scale mining companies design mining pits based on empirical and analytical criteria without support from scientific studies, which may lack accuracy, especially since the execution of empirical designs is based on the subjectivity of geomechanical engineers [2]. The instability issues are mostly due to various factors, such as mine depth; operations near blasting areas; water; geological discontinuities; ground stress; creep zones; relaxation zones; the physical and mechanical properties of the rock; rock mass qualities; earthquakes; regional, local, and structural faults; and inadequate geometric pit parameters [3][4].

This study seeks to combine empirical and numerical methods to propose better geometric stope design parameters and increase their stability.

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2. State of the art

2.1. Empirical Stope Design Methods

Some empirical methods such as the Mathews stability graph allow for stope design, while others such as the Q system provide recommendations as support [5]. The science of empirical design follows six steps: problem identification, end user identification, construction of a rock mechanics conceptual model, identification of key model parameters and values for each key parameter, and the development of new measures [6]. To verify design dimensions as well as the support systems implemented, the SF, which must be greater than 1.5 to guarantee work stability, is determined through numerical methods. In addition, empirical relationships between classification systems and the properties of intact rock are also used to determine rock mass properties [7][8].

2.2. Empirical and Numerical Methods in Stope Design

Sepehri, Apel, and Liu [5] validate this in their research studies, where they assess stope stability and the effect of the “k” ratio, which is the relationship between horizontal and vertical stresses, both in the creep and relaxation zones around the stopes. To address the issue, the authors first used the Mathews stability graph method to assess stope stability based on the N' and the HR. The authors conclude that the numerical model provides a better understanding of effort distribution and that the relaxation areas are easily identified. Other authors such as Iglesias Comesaña et al. [1]; Kozyrev et al. [4]; and Basarir, Su and Li [9] argue that design results from empirical methods must be validated through numerical results because both methods supplement each other.

3. Contribution

3.1. Proposed Model

The geomechanical characterization of the rock mass incurs in the use of classification systems such as Rock Mass Rating (RMR), Tunneling Quality Index (Q) System and Geological Strength Index (GSI) to determine rock mass quality. Stability analysis consists of using the Mathews stability graph method to determine whether the current design is located in a stable area or not. The empirical design is performed once the current design has been deemed unstable through the manipulation of the independent variables of the HR. The purpose of determining rock mass properties is to provide the input parameters required for the numerical model to perform simulations, which is achieved through the empirical relationships between the classification systems and the properties of the intact rock. The numerical model seeks to design dimensions and use them to provide the SF of the structure, which is assessed either with or without support. (Fig. 1)

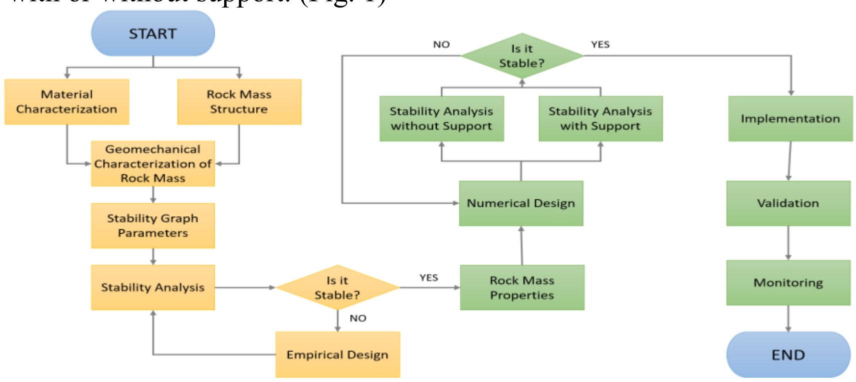

Figure 1. Proposed model

3.2. Proposed Method

Figure 2 depicts the proposed method.

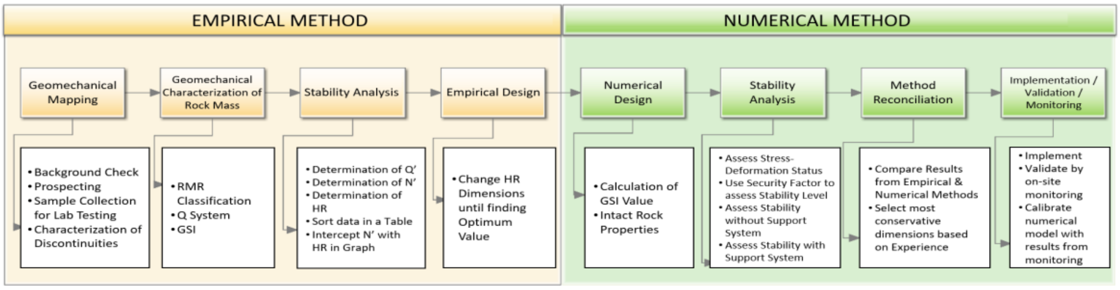

Figure 2. Proposed method

3.3. Indicators

3.3.1. Hydraulic radius

The HR allows modification of the pit's geometric dimensions so that this HR ratio may be entered into the Mathews stability graph to assess how stable the design is.

$$HR = \frac{Area}{Perimeter} = \frac{w \times h}{2w + 2h} \tag{1}$$

Interpretation: The higher the HR value, the greater the geometric dimension of the pit, but HR growth proportionality depends on the geometric shape of the design. For example, the HR ratio for a square shape is greater than that for a rectangular shape.

3.3.2. Stability number

The N' indicates the geological and geomechanical conditions of the land, and this value is used in the Mathews stability graph to assess the stability level of the geometric design.

$$N' = Q' \times A \times B \times C \tag{2}$$

Interpretation: a higher N' means that the ground conditions are more apt to support larger pit designs.

3.3.3. Security factor

The SF assesses the acting and resistant forces present in the excavation, which means that it is a pit design stability level indicator.

$$FS = \frac{Strength\ (MPa)}{Induced\ Stress\ (Mpa)} \tag{3}$$

Interpretation: If SF > 1, the stope is stable; if SF = 1, the stope is at its stability threshold; and if SF < 1, the stope is unstable. For security purposes, an SF ⩾ 1.5 is recommended.

4. Validation

4.1. Case Study

The model proposed seeks to assess, through numerical and empirical methods, stope instability at a narrow vein mine within the Eliana mining unit, Compañía Minera Escorpión S.A., located in the department of Ayacucho, province of Parinacochas, district of Pullo. As the mining unit could not provide any previous geomechanical studies, it was necessary to perform geomechanical mapping, laboratory tests and numerical modeling.

4.2. Initial Assessment

During the site walkthrough, it was found that stopes developed in the mining unit were 1.75 meters wide and 1.85 meters high, which means that their Hydraulic Radius (HR) was 0.45. (Fig. 3)
Regarding the calculation of the N´, first, as part of the empirical methods, rock mass classification was performed at the ceiling and floor cavities of the geomechanical stations.
Next, Factor A was calculated as per Equation 4. Thus, numerical methods are used to calculate the maximum effort induced on the stope.

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$$A = 0.1125 \times \left(\frac{UCS}{\sigma_{max}}\right) - 0.125 = 0.1125 \times \left(\frac{45}{5.62}\right) - 0.125 = 0.78 \tag{4}$$

Then, Factor B is calculated based on the orientation of the most unfavorable discontinuity (72°) on the stope surface. This figure depicts the interpolation of Factor B calculation: $\alpha = 90° \rightarrow B = 1.0$ and $\alpha = 60° \rightarrow B = 0.8$. Hence, B is found for $\alpha = 72°$, then *B=0.88.*
Factor C is given by the following equation:

$$C = 8 - 7 \times \cos(\theta) = 8 - 6 \times \cos(90°) = 8 \tag{5}$$

Once all the factors have been obtained, the N´ is 31.57 in the floor cavity and 60.73 in the ceiling cavity.
Finally, to calculate the SF through numerical methods, laboratory tests had to be performed.
For these purposes, representative samples were taken from the ceiling and floor cavities, which were prepared in the Rock Mechanics Laboratory at the Peruvian University of Applied Sciences and were tested for uniaxial compression, indirect traction, triaxial compression, and physical property determination. (Fig. 4). The numerical model analysis was performed through the Examine 8.0 and UnWedge 7.0 software using the parameters depicted in Table 1.

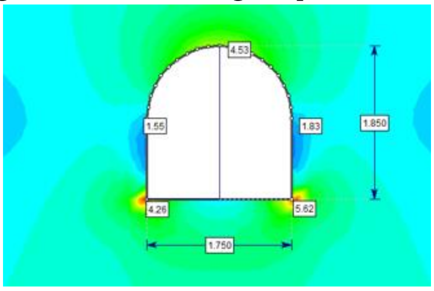

Figure 3. Initial Numerical Analysis of the Stope

Figure 4. Sample Preparation and Testing

4.3. Numerical Model Application

For application of the numerical model, the only values that will be modified will be the dimensions of the stope, which now is 1.85-meter-wide and 2.4 meters high, with a HR of 0.52. Other values that were modified are Factor A of the N´ and the SF. From (4), *UCS=45,* $\sigma_{max} = 6.23$, then A=0.69
Regarding the new dimensions, the numerical analysis was performed again using the Examine 8.0 software to obtain the new value for the maximum stress induced.
Once the values of the HR and N' were obtained, the stability graph method proposed by Mathews (1981) was applied. (Fig. 6).
Finally, the SF was calculated again through the Examine 8.0 and UnWedge 7.0 software.

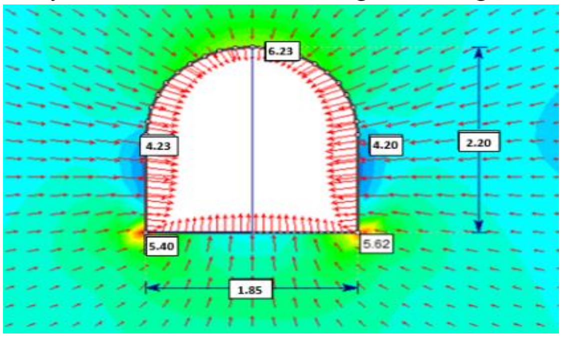

Figure 5. Final Numerical Analysis

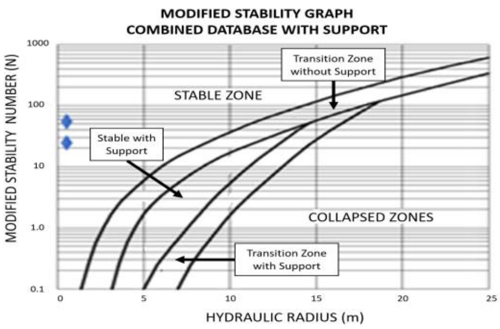

Figure 6. Mathews Stability Graph

The final indicator values are shown below (Table 2).

Table 1. Initial Indicator Value

	Hydraulic Radius (HR)	Stability Number (N´)	Safety Factor (SF)

Table 2. Final Indicator Value

	Hydraulic Radius (HR)	Stability Number (N´)	Safety Factor (SF)

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Footwall	0.45	31.57	1.22	Footwall	0.52	27.83	2.27
Hangingwall	0.45	60.73	1.35	Hangingwall	0.52	53.53	2.34

5. Conclusions

The objective of the present study was complementary to the empirical method with the numerical methods in order to obtain better geometric parameters of the design of the cuttings that increase its stability. The results showed that both the motivation and the objective of the research were achieved.
The proposed model was based on the assumption that the empirical method can analyze in narrow veins, since it was only used in large-scale exploitation methods.
The use of numerical methods for the structural control in mines of narrow veins guarantees a support system and size of cut appropriate to use appropriately the resistance of the rock mass.
The TJ 55 N mineralized block of the Eliana mining unit evidences its safety factor went from 1.35 to 2.34, representing a 73% increase in the design.

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