Methodology for Estimating Hydrogeological Risk for Open Pits

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Abstract

Groundwater affects open pit slope stability by reducing effective stress and shear strength. To improve slope management, it is necessary to identify which areas of the pit may present stability issues triggered by groundwater.

This paper proposes a methodology for assessing hydrogeological risks to open-pit stability by integrating geotechnical and hydrogeological data through field measurements, numerical modeling (MINEDW and FLAC3D) and uncertainty analysis. This approach enables the generation of hydrogeological risk maps to support decision making on depressurization, monitoring, and mine design adjustments by quickly and efficiently identifying critical areas where groundwater affects stability, improving slope management, reducing failure risks and enhancing safety.

Keywords: Open Pit, Slope Stability, Numerical Modelling, Uncertainty, Reliability, Pore Pressure

Introduction

It is well documented that water presence can result in a loss of performance of the pit slopes (Read & Stacey 2009; Beale & Read 2013). Water pressure within discontinuities and pore spaces reduces the effective stress, leading to a decrease in shear strength of the rock mass (Sullivan 2007; Devy & Hutahayan 2021). As a result, slopes must be depressurized, designed with a lower factor of safety, or flattened to compensate for the reduced rock mass strength. When excess water pressures occur below the pit floor, groundwater pressure is the only geotechnical parameter in pit slope engineering that can readily be modified (Wyllie & Mah 2004). Therefore, it is crucial to have accurate hydrogeological characterization that enables the development of robust numerical models used to support decision making. An adequately calibrated groundwater model can provide reliable pore pressure predictions that combined with slope stability models can help understanding their impact in stability of open pit slopes.

This study outlines a new approach to quantify the risk linked to the hydrogeological component of slope stability in open-pit operations. It integrates geotechnical and hydrogeological data, focusing on the influence of pore pressure and water table variations on slope performance. Through the combination of field measurements, hydrogeological numerical modelling (developed using MINEDW software, Itasca Denver Inc 2019) and stability analysis (simulated by FLAC3D Software, Itasca Consulting Group Inc 2023), this methodology provides a comprehensive tool for evaluating potential risks and supporting the design of mitigation strategies.

As a result, a contour map is obtained that provides a quick and simple method to assess the implications of hydrogeology on slope stability. It identifies areas where depressurization is required, zones where improvements in hydrogeological characterization and monitoring are needed, and sectors where the mine planning design should be revised.

Background. Conceptual Hydrogeological Model of the Pit

The open pit used in this study has been excavated in a complex hydrogeological environment, characterized by a main aquifer hosted in alluvial materials and in the leached supergene unit which overlies an aquitard (low hydraulic conductivity medium with low storage) composed of andesitic rocks where porphyritic activity occurred forming the deposit. A 3D groundwater flow model has been developed for this open pit in MINEDW code, which is used to make seepage flows and pore pressure distribution predictions. A FLAC3D (Itasca Consulting Group Inc, 2023) model uses these pore pressure predictions to conduct slope stability analysis.

Methodology

The hydrogeological risk map aims to geographically identify sectors of the mine with higher geotechnical risk triggered by pore pressures, considering slope susceptibility to pore pressure variation, uncertainties in pore pressure modeling, hydrogeological data gaps, as well as regulatory safety requirements for maintaining operation.

Thus, a risk index (eq.1) was developed by combining information from field measurements, groundwater and slope stability numerical models, and safety standards for slope stability design. Specifically, it considers: (1) the density of hydrogeological data at the mine site, (2) the deviation of the pore pressures calculated by the groundwater model during calibration compared with field measurements, (3) the sensitivity of safety factors to pore pressure variations, and (4) compliance with pore pressure targets to maintain safety factors above required thresholds.

1. Hydraulic tests and groundwater monitoring databases were considered to calculate the information density, which reflects the existing knowledge of the hydrogeological regime affecting the site, the rock mass hydraulic properties and the groundwater level evolution during the mining operation (Eberhardt & Stead 2011). Furthermore, this knowledge is essential for effectively evaluating the performance of the slope design, including depressurization programs, and reducing uncertainties regarding pore pressure variations, which, in some cases could reach levels that compromise the slope stability (Dunnicliff *et al.* 2012; Brawner 1982). The data were georeferenced within the open pit. Subsequently, radial isocontours were generated from each data point, divided into 8 bands. These bands were categorized based on the greatest distance between a point and the excavation area not covered by hydrogeological information (800 m). As a result, 8 ranges of 100 m were created for each point. The information density map can be observed in the Fig. 1a.

Deviation between simulated (from model calibration) and observed (measured) pore pressures was also used to construct the index. An uncertainty analysis was conducted over predictive simulations of the groundwater model (Middlemis *et al.* 2019; Alvarez & Brown 2023; Gutierrez & Brown 2023). During the analysis, 100 realizations were executed with different hydraulic properties (conductivity, specific storage and specific yield) (Fig. 2a), covering the full conceptual range defined for each hydrogeological unit and adhering to the calibration standards established by groundwater modeling guides (SEA 2012; Barnett *et al.* 2012). In this analysis, the realizations are considered equiprobable, however, each model calibrates a particular monitoring well to greater or lesser degree. For the development of the map, the deviation marked by 80% of the models was associated with each monitoring point and isocontours were generated for the entire pit area, considering 8 bands, each representing a 10 meters deviation from 0 to 80. The deviation map is shown in the Fig. 1b.

2. Sensitivity analysis of the safety factors for different pore pressures distributions (higher or lower) is also considered. This variable was obtained using the geotechnical software FLAC3D to evaluate the safety factors of each sector of the pit with varying pore pressures as input. The evaluated pore pressures corresponded

to the base scenario obtained from the calibrated model, along with six additional scenarios with variations in the pore pressure field for the entire pit: ± 15, ± 30 and ± 45 m w.c. (i.e. ±147KPa, ±294 KPa and ±441 KPa). Fig. 3 shows a cross-section example of how pore pressures were modified in the base case ± 15 m w.c. As a result, the pit sectors where safety factor is most sensitive to pore pressure variations, were identified (Villa *et al*., 2024). For example, some sectors show no variation in their safety factor, indicating they are not susceptible to changes in pore pressures. In contrast, other sectors become unstable when pore pressures increase by 15 m w.c. or become stable when pore pressure decrease by 15 m w.c. To standardize criteria, sensitivity was divided into 8 bands, each corresponding to the variation in m w.c. required for the slope to lower its safety factor below the thresholds established by the operation. The sensitivity of the safety factors map can be observed in the Fig. 1c.

3. The final component of the index is compliance with pore pressure targets required to maintain the safety factors above defined thresholds. Compliance is measured as the difference between the target level and the current measured level. The target level is set by the operation based on depressurization targets, which are derived from geotechnical and hydrogeological numerical models, accounting for associated uncertainties and reliability criteria (Dowling *et al*. 2020; Rougier *et al*. 2020; Villa *et al*. 2024) (Fig. 2b). Once again, a map associated with this component was created, with isocontours divided into 8 bands. The targets map is illustrated in the Fig. 1d

To calculate the hydrogeological risk index, each of the four factors was divided into 8 classes (bands), which were assigned a rank from 1 to 8. The ranking depends on the nature

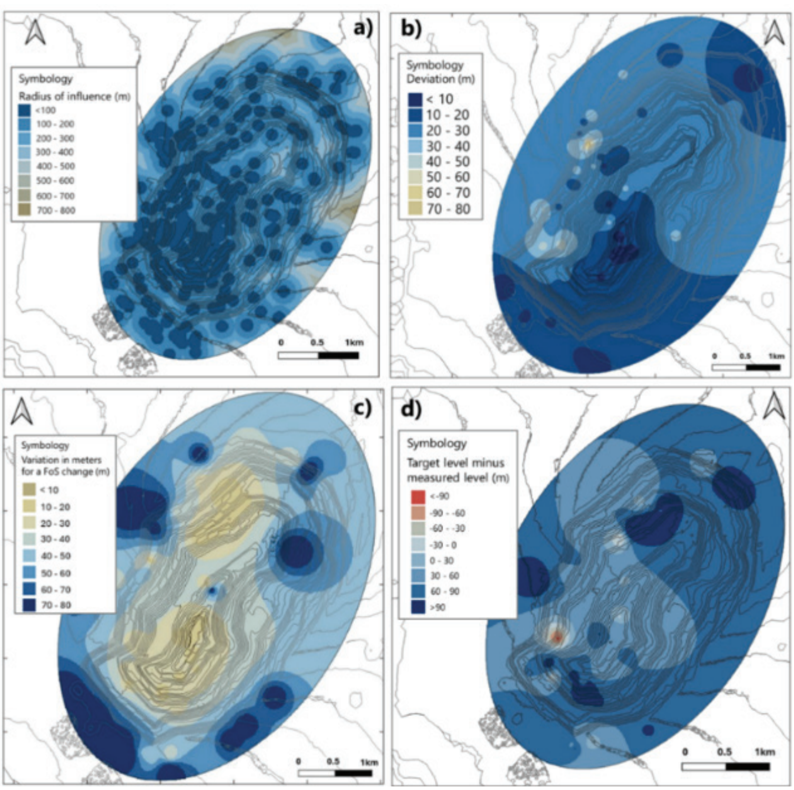

***Figure 1** Maps used to generate the Hydrogeological Risk Map associated with slope stability in the open pit. a) Information density map, b) Deviation level for 80% of the uncertainty models (P80), c) Slope stability sensitivity to the pore pressure and d) Difference between target level and measured level.*

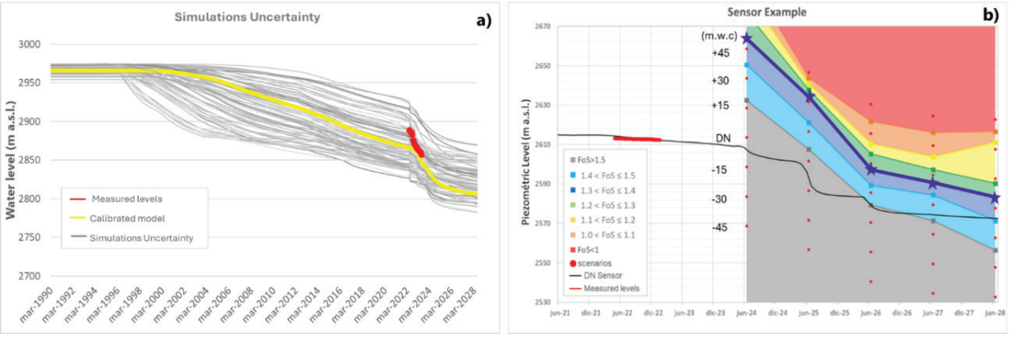

Figure 2 *Uncertainty analysis and impact of pore pressure on slope stability: a) Uncertainty simulations, measured level, and best-calibrated model. b) TARP chart linking the water table level to the Factor of Safety.*

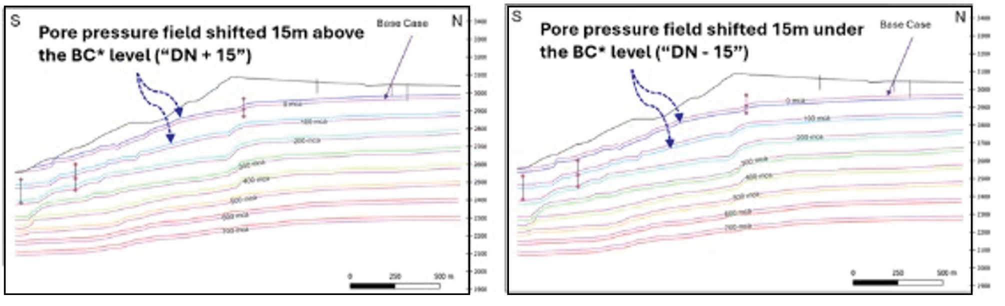

Figure 3 *Example of additional scenarios with a ±15% variation in the pore pressure field.*

of the variable: for favorable variables such as data information density and compliance with pressure targets, higher values (e.g., more data, better compliance) received higher ranks. In contrast, for variables representing higher uncertainty or risk – such as model deviation or safety factor sensitivity – the ranking was inverted, assigning lower ranks to higher-risk conditions (e.g., larger deviations = lower rank).

Finally, for each 10 × 10 m grid cell, the hydrogeological risk index was calculated by multiplying the four ranked values according to Equation 1, allowing spatial identification of sectors with higher or lower hydrogeological risk within the pit.

Hydrogeological Risk = Data Density × Model Deviation × Safety Factor Sensivity × Compliance (eq.1)

In Fig. 1, the four generated isocontours maps can be observed, which serve as the basis for creating the hydrogeological risk index of the open pit. The risk index was conceptualized as a simple combination of equally weighted factors.

Results

The calculated risk index for every 10x10 m is plotted to create the hydrogeological risk map Fig. 4. The map illustrates the risk arising from non-compliance with the operational targets and slope stability susceptibility to pore pressure variations, integrating the uncertainty due to hydrogeological data gaps and numerical modeling of pore pressures.

To ease interpretation, the risk map has been divided into three categories, although it could consider further discretization if more detailed information were needed. In this case study, the pit exhibits overall intermediate risk, with low-risk sectors mainly on high slopes, and high-risk sectors concentrated in the west and northwest.

The map supports decision making regarding sectors that require additional hydrogeological characterization such as pore pressure monitoring and new hydraulic tests, that inform the hydrogeological model and can serve as an input to interpret other numerical models used in the slope design

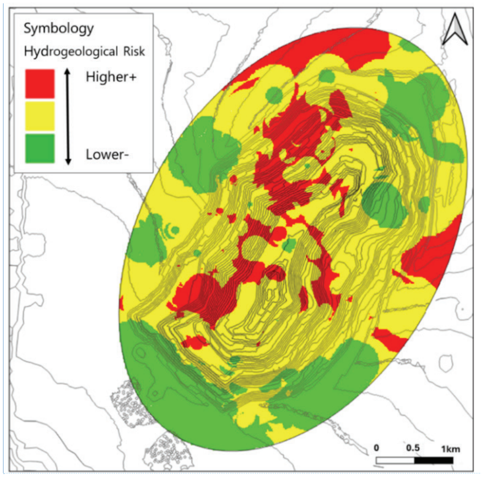

Figure 4 *Hydrogeological risk map associated with slope stability in the open pit.*

process, such as geological, geotechnical, structural and hydrogeological.

At the same time, the map provides relevant information to communicate hydrogeological needs (exploration and depressurization campaigns) to stakeholders in a simple and quick manner.

Discussion

This methodology successfully achieves its objective of quantifying the hydrogeological risk of an open pit mine, producing visual results that can assist stakeholders in their interpretations and analysis of the pore pressures effect on slope stability in the different sectors of the operation.

The proposed risk index was conceptualized as a simple combination of equal weighted factors, following risk definition for natural disasters outlined by UNDRO (1980) and Cordona (1993), which considers total risk as a product of hazard and vulnerability. Furthermore, considering the IPCC (2020) statement that adds the concept of incomplete knowledge or uncertainty as a key element in the definition of risk.

In these definitions, hazard refers to the possibility of an event, such as the natural phenomenon. On the other hand, vulnerability refers to the impact of the natural phenomenon, represented by physical factors like early warning systems. In this work, hazard is the probability of excessive pore pressure and its associated uncertainties, while vulnerability is reflected by the susceptibility of the slope stability and its potential reduction below the threshold due to variations in pore pressure.

Although, this index provides a simple way of conceptualizing risk, several factors can be considered (Ramli *et al.* 2020). One such factor is exposure, which refers to the infrastructure, ecosystem or population at risk. In this analysis, the entire pit is considered exposed; however, it is also possible to focus on specific areas, such as the slopes that will be excavated in the coming years.

Other factors could also be used, such as the uncertainty associated with the inputs of the numerical models, such as geological, geotechnical and structural information, which, in this case, are assumed to be implicitly incorporated in the results of the groundwater model's uncertainty analysis. Additionally, the uncertainty related to the FLAC3D model, which was not addressed in this study, as well as historical information on slope movements, could be important.

Moreover, if necessary, weights could be assigned to each factor based on their reliability or perceived importance. For instance, low confidence in numerical models, conceptualizations, target compliance measurements, or field data could reduce the weight of certain factors. Similarly, high compartmentalization or significant variation in geotechnical parameters might also affect the factor weighting.

On a different note, risk maps can be used dynamically to track the evolution of risk over time. This approach allows for the evaluation of past work by comparing 'before' and 'after' scenarios and helps assess future risks by analyzing the lack of information and the results of predictive simulations. This can guide data collection and slope depressurization campaigns aimed at reducing risk, as well as support the assessment of compliance with the operation's depressurization targets.

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