

Pit Slope Optimization Based on Hydrogeologic Inputs

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ABSTRACT With the variability of commodity prices and the constant increase of mining costs, it has become increasingly important to optimize pit slopes of mines, taking into consideration the complexity and the uncertainties presented by ground conditions. The variables in slope stability, geology, rock mass strength, structural defects, inherent and induced stresses, rock weathering, alterations, and groundwater, are well known, as are their impacts on slope performance. Most variables cannot be changed to optimize slopes. However, groundwater is one variable that can be managed during pit excavation, to reduce the effect of pore pressure on slope stability.

Hydrogeologists and rock mechanics engineers combine their efforts in order to quantify, simulate, and control the effect of groundwater pressures on pit slope performance. Based on comprehensive field hydrogeological data collection and interactive numerical groundwater and geotechnical modeling, it is possible to evaluate the water pore pressure effect on the pit slope, to provide an efficient depressurization strategy to meet the geotechnical engineering targets, and thus to develop cost-effective mine plans.

This paper discusses how proper management of groundwater conditions can contribute to mine planning and operations, through pit slope optimization. We show a complete approach from collection of hydrogeological data in the early stages of a project to design of an appropriate depressurization plan, taking into account the rock mass conditions, the mining plan, and the time to achieve an optimal pit slope.

1 INTRODUCTION

Groundwater water in open pit mines affects normal operations in many ways. Excessive water inflow into the pit can significantly impact the mine operations by reducing equipment performance and increasing loading and haulage time. Water in the pit could result in incremental increases in mining cost, reduction of mining performance, the need for special blasting products, increases in drilling time, and mechanical damage of mine equipment, etc.

A poor knowledge of the hydraulic parameters could also have a negative impact on the slope design and stability performance of the pit, which could result in an over or underestimation of the mine design; directly impacting, negatively, the net present value (NPV) of the business.

It is clear that a good understanding of groundwater conditions and their effects on the mine operation and mine design can help mining companies optimize their business.

Several authors have developed methods of data collection, interpretation and modeling of groundwater conditions to provide recommendations for pore pressure reduction and mine dewatering (Read & Stacey, 2009; Beale & Read, 2013; and others). This paper does not intend to review and comment about the current data collection and modelling technics, the objective of this paper is to discuss how the integration of the hydrogeology and geotechnical disciplines can optimize the mine operations. The paper intends to demonstrate the importance of good data collection, interpretation, and groundwater numerical modeling on slope stability as an optimization tool.

2 EFFECT OF GROUNDWATER ON SLOPE STABILITY

The literature lists different ways in which groundwater can affect open pit mine excavations, including (a) changes of effective stresses and/or (b) saturation, both contributing factors of slope stability.

2.1 Changes of Effective Stresses

In its simplest definition, the water pore pressure is the pressure of groundwater held within a soil or rock in gaps between particles (pores). Pore water pressure is used in calculating the stress state in the ground soil mechanics using Terzaghi's expression for the effective stress of a soil (below).

Soil or rock can be pictured as a frame of soil particles enclosing continuous voids containing fluids (water, air, gas etc.) as shown in Figure 1. In fully saturated soil, water is considered to be incompressible, so that a reduction in volume is possible only if some of the water can escape from the voids. In dry or partially saturated soil a reduction in volume is always possible due to the compression of air in the voids which allows the opportunity for the rearrangement of particles within the soil. In 1923, Terzaghi presented the principle of effective stress. The principle applies only to fully saturated soils and relates the following three stresses: (a) total normal stress σ_N , (b) pore water pressure (u) and effective normal stress (σ'), which represents the stress transmitted through the soil skeleton only. The Terzaghi principle is expressed by the following equation (Eq.1).

$$\sigma_N = \sigma' + u \quad (\text{Eq.1})$$

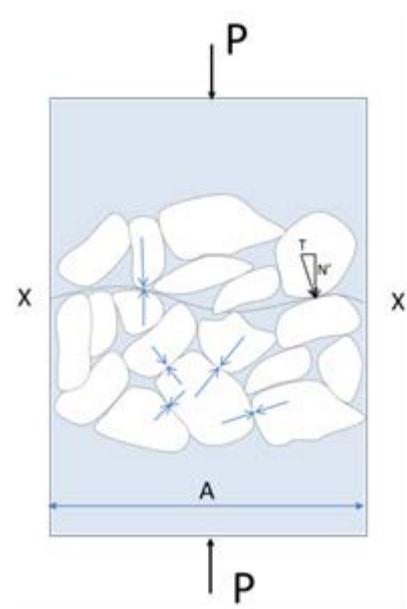


Figure 1. Interpretation of effective stresses.

Figure 1 shows a Normal force P applied on an area A, resisted by inter particle forces and the pressure located in the pore water. The physical model indicates that the forces at each point are in contact with the true plane XX, which can be split into two components; Normal Effective N' and tangential T forces, then the Effective Normal stress can be defined by the following equation (Eq. 2):

$$\sigma' = \Sigma N' / A \quad (\text{Eq. 2})$$

Given the fact that the Total Normal stress is:

$$\sigma = P / A \quad (\text{Eq. 3})$$

Then the points in contact between the particles should have a total pore pressure acting on the plane (entire area A), reaching the equilibrium in direction normal to XX plane given by:

$$P = \Sigma N' + u \times A \quad (\text{Eq. 4})$$

or

$$P/A = \Sigma N' / A + u \quad (\text{Eq. 5})$$

Therefore, $\sigma_N = \sigma' + u$ or $\sigma' = \sigma_N - u$

2.2 Shear Failure

In simple terms, failure occurs within the material when the shear stress becomes equal to the shear strength, expressed by Coulomb's principles (Das, Braja, 2011) in the lineal failure envelope, given in the following equation:

$$\tau = c + \sigma_N \times \tan \phi \quad (\text{Eq. 6})$$

where:

τ = shear stress;

c = material cohesion;

σ_N = normal stress; and

ϕ = internal friction angle of the material.

In other words, there are critical combinations between shear and normal stresses that produce failure. However, shearing resistance is developed by the inter-

particle forces; therefore, if the effective normal stresses are zero then the shearing resistance must be zero (at least there is cementation between the particles) and the value of effective cohesion (c') would be zero.

The physical model indicates that each point in contact on the true plane XX, the Normal Effective N' and tangential T forces, will be reduced and potentially reach a critical combination of normal and shear stresses over the failure envelop establishing the failure.

2.3 Water Pore Pressure in Slope Engineering

The pore pressure in slope engineering is one of the contributing factors in slope stability. The groundwater changes, effective stresses, and increased density of the materials cause changes in hydrostatic loading (Read & Stacey, 2009). There are several different techniques to simulate water pore pressure in slope analyses; computer simulations can provide a good approach to analyze the groundwater effect on slope performance.

For saturated or partially saturated slopes, rock engineering experience establishes that a reduction of pore water pressure will improve the results of the slope performance parameters creating the opportunity to optimize slope designs. In practice, the time required to achieve the reduction of pore pressure must be considered, as well as the flexibility in the mining plan to allow enough time for getting the depressurization targets established by the pit slope engineer.

3 MINE DEWATERING AND PIT SLOPE DEPRESSURIZATION

One of first steps in pit slope stability analyses is to understand the water pore pressures in the pit slopes as the result of mining and planned dewatering. As soon as the pit floor reaches levels below the water table, natural drainage of the wall will usually occur due to seepage and with response to mining which induces relaxation of the rock mass (Beale & Read, 2013). The natural drainage in conjunction with active dewatering (if implemented) will cause a reduction of pore pressures in the rock walls.

The second step is to evaluate an effect of additional pore pressure reduction on the pit slopes and the necessity of implementing a depressurization program. In some cases, the pore pressure dissipation achieved by passive and active dewatering is adequate for targeting the desired pore pressure goals. In other cases, to achieve the dewatering goals, a dedicated pit slope depressurization program is needed.

Pit dewatering is a necessary element of any mining that occurs below the water table. Pit slope depressurization is an optional method for additional reduction of pore pressure within pit walls if this is required for geotechnical reasons. Table 1 shows a comparison of general mine dewatering and pit slope depressurization. Table 1. Comparison of mine dewatering and pit slope depressurization

Parameter	Mine Dewatering	Slope Depressurization
Material/rock	High permeability	Low permeability
Target	Lower water table	Decrease effective stress of the slope materials
Volume of water	Often high	Normally low
Area of implementation	Normally pit-wide	Often local to a specific slope sector
Most common method	By in-pit sump and vertical wells	By horizontal drain holes or gravity flowing drains in conjunction with general mine dewatering

The ability to reduce pore pressure to achieve the desired target depends on hydraulic parameters, on timing, and on the effectiveness of dewatering and depressurization methods.

3.1 Depressurization Parameters

Major depressurization parameters and pore pressure reduction can be illustrated by a simple 1-D Flow (or Diffusivity) Equation:

$$\Delta h(x, t) = \Delta h_0 \operatorname{erfc} \left(\frac{4Kt}{S_s x^2} \right)^{-1/2} \quad (\text{Eq. 7})$$

where:

Δh = change in hydraulic head;

Δh_0 = initial hydraulic head;

K = hydraulic conductivity;

S_s = specific storage;

t = time;

x = distance; and

$\operatorname{erfc}(\alpha)$ – function which increases when α decreases and decreases when α increases.

This simple relationship (Eq. 7) indicates that slope depressurization depends on hydraulic parameters, time of dewatering, and distance from the dewatering (or depressurization) system. The hydraulic parameters need to be known. Time and distance are the only two variables which allow control of the pit slope depressurization.

Figure 2 indicates that for the given hydraulic parameters (K and S_s) the degree of depressurization increases with time and decreases with distance from the dewatering system. Figure 3 shows that more successful depressurization is potential for more permeable rock and shorter distances from the dewatering system. Equation (7) illustrates the mechanism for pore pressure reduction but it should be noted that it is based on various assumptions (linear flow, homogeneity, isotropy) that are unlikely to be met in practice, given the complex hydrogeological conditions surrounding many mine sites.

A key factor for designing a slope depressurization program in poorly-permeable materials is the time required to achieve the target pore pressure profile for the critical sector of the pit. Slopes excavated in higher-permeable rocks typically require less time for the depressurization to be effective.

In poorly-permeable weak rock environments, such as an operation with deep weathered zones or thick zones of argillic (clay) altered rock, it can take months to years to depressurize the slopes to desired targets (Beale & Read, 2013). Depending on the time available, it may be necessary to advance a general dewatering program to lower the water table and to provide additional time for drainage of less permeable pit sectors.

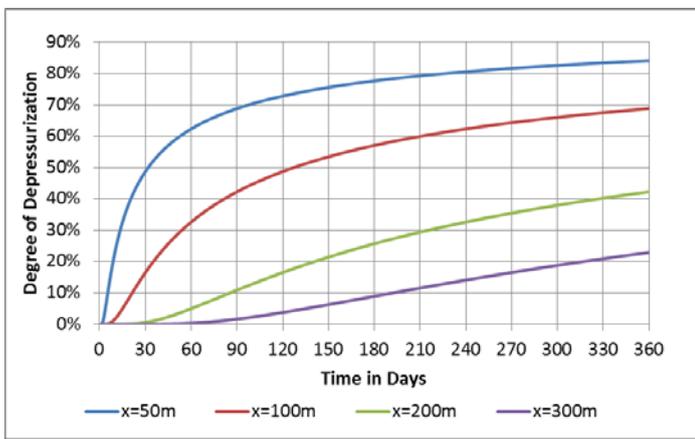


Figure 2. Pore pressure reduction vs. time and distance from dewatering ($K=10^{-8}$ m/s, $S_s=10^{-5}$ 1/m)

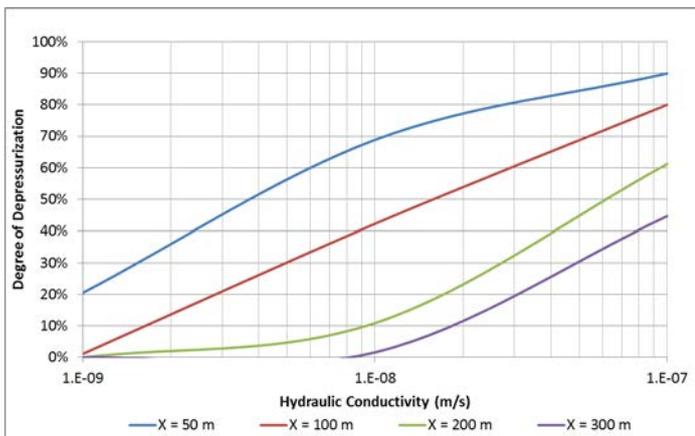


Figure 3. Pore pressure reduction as function of hydraulic conductivity and distance for 90 days of dewatering

3.2 Depressurization Methods

There are different methods of pit slope depressurization, which include:

1. Seepage from face and pumping from sumps.
2. Horizontal drain holes.
3. Gravity-flowing vertical drains.
4. Pumping wells.
5. Drainage tunnels with sub-vertical drain holes.

The first method is very common and used for passive dewatering or as part of active dewatering to intercept residual passive groundwater inflow coming to the open pit. The other methods allow for the addition of the reduction of pore pressures in the pit slopes to achieve the desired depressurization target. The choice of the best depressurization option, or a combination thereof, depends on the site specific hydrogeological, geological, structural, and geotechnical conditions which define the depressurization targets.

The use of horizontal drains or sub-horizontal drain holes (second method) is the

most commonly applied method worldwide for locally reducing pore pressures behind open pit slopes. To install the drain holes, specific targets need to be identified. These targets may include:

- The water contained in low permeable material.
- Water trapped in permeable but compartmentalized fractures behind the pit slope.
- Water “dammed” behind geological structures.
- New geological units which will be encountered in pushbacks as the pit is expanded.

The effectiveness of the depressurization system from horizontal drain holes depends on the success of intersecting the defined targets and, in case of a low permeable pit slope, timing, distance between drain holes and their depth, hydraulic parameters, and the ability to discharge more water than recharged from precipitation and surface-water bodies.

3.3 Hydrogeological Characterization and Data Analysis

Hydrogeological parameters affecting pit slope stability include:

- Water levels;
- Distribution of hydraulic conductivity of rock within pit slope;
- Groundwater storage parameters; and
- Recharge from precipitation and surface-water bodies.

These parameters need to be determined during hydrogeological studies. Where it is possible, hydrogeological data should be collected during the early stages of the project and in conjunction with geotechnical studies. Table 2 summarizes content of hydrogeological studies for different stages of the project and targeted level of data confidence.

Table 2. Hydrogeological study and targeted level of data confidence

Project Stage	Hydrogeological Study	Targeted Level of Data Confidence
Conceptual	Regional groundwater survey; water level data collection in exploration holes; identification of hydrogeological units based on Geological Model	>20%

Pre-Feasibility	Mine scale airlift, pumping, packer testing and piezometer installation; initial hydrogeological parameters and groundwater flow understanding; initial hydrogeological database and conceptual model established; preliminary groundwater model and sensitivity analysis; initial assessment of dewatering and depressurization requirements	30-50%
Feasibility	Targeted pumping and airlift testing; piezometer installation; enhancement of hydrogeological database and 3D model; advancement of assessments of dewatering and depressurization requirements	40-65%
Design and Construction	Installation of dewatering wells and piezometers; refinement of hydrogeological database, 3D model, depressurization and dewatering requirements	65-75%
Operations	Ongoing management of piezometers and dewatering well network; continued refinement of hydrogeological database and 3D model	>75%

Note: Table modified by authors from Read and Stacey (2009)

4 GROUNDWATER MODELING AS A TOOL TO PREDICT PORE PRESSURES

Numerical groundwater modeling is widely used to simulate groundwater inflow to open pits for relatively complex hydrogeological conditions. The modeling process includes development of a conceptual hydrogeological model, grid discretization, assigning of hydraulic parameters and boundary conditions, model calibration, and prediction. Predictions very often include two scenarios:

- Passive inflow (or how much water will enter into the pit during its excavation without active dewatering/depressurization).
- Active dewatering to reduce residual passive inflow to the pit or active depressurization to reduce pore pressure for pit slope stability.

The active dewatering scenario is used when the rock within the pit slope is permeable and the amount of passive inflow cannot be managed safely during the mine operation. The active depressurization scenario is used when the rock within the pit slopes has low permeability, and high seepage face and pore pressures that are causing slope stability problems. The numerical groundwater models used for dewatering predictions are typically 3-D and developed at the regional scale with additional discretization around the pit both laterally and vertically. The discretization of regional dewatering models very often is not sufficient to precisely

predict pore pressure distributions within the pit slopes. Therefore, 2-D cross sectional or 3-D (strip or asymmetrical) and more detailed pore pressure models are used along critical pit sections as “windows” within the regional groundwater model. These models use the hydraulic heads from the regional model to incorporate boundary conditions

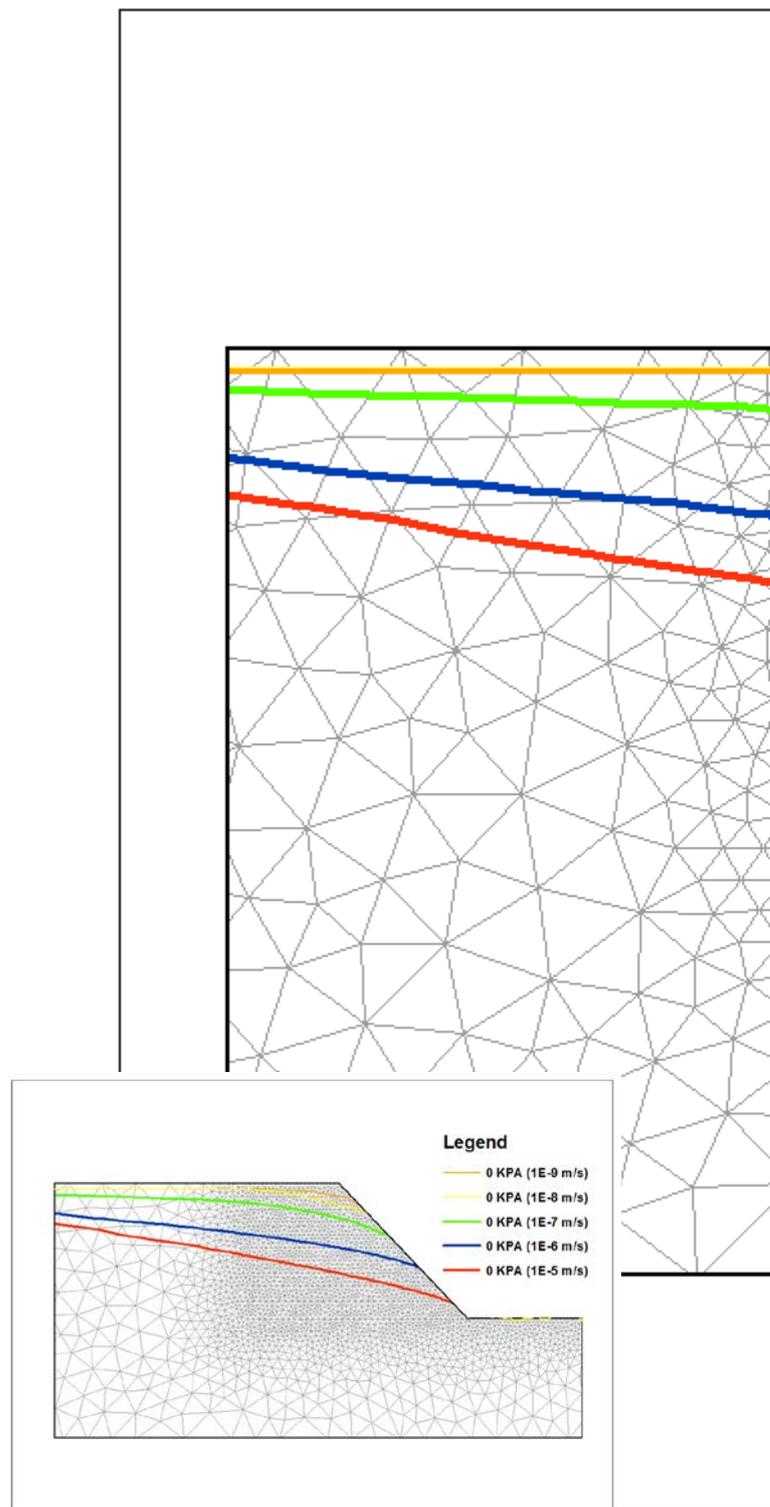


Figure 4. Predicted water table (P=0 kPa) at end of open pit excavation used for slope stability analysis

The numerical simulation provides the pore pressure distribution in the slope, which easily can be used for the slope stability analysis, as showed in Figure 5.

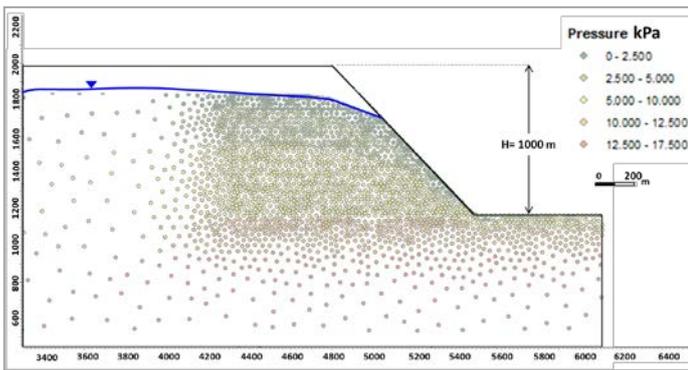


Figure 5. Pore pressure distribution at year 10 of pit excavation, $K=10^{-8}$ m/s

Based on these models, the FoS of each pore pressure distribution was determined in order to demonstrate the effect of the hydraulic conductivity on pit slope stability. For this exercise, the simplified stability models considered the single rock mass medium to be continuous, isotropic, and lineally elastic, and assumed the lineal Mohr & Coulomb failure criteria to be valid and a good estimation of the rock mass strength.

Even though the described rock mass conditions are rarely found in the real world, this condition will be assumed valid for the purpose of this exercise.

Changes of hydraulic conductivity have a strong effect on the FoS. Figure 6 shows the FoS for 300m, 600m, and 1,000m pit slopes (excavated in 3, 6, and 10 yrs., respectively) as function of hydraulic conductivity. The geometry and the rock mass strength parameters were fixed for this example and a variable range of the hydraulic conductivity values were used to simulate the pore pressure field for each case.

This example does not intend to discuss the acceptability of the FoS given different pore pressure conditions; the chart, rather, shows the impact of the water pore pressure field, based on a large range of hydraulic conductivity, on the slope performance.

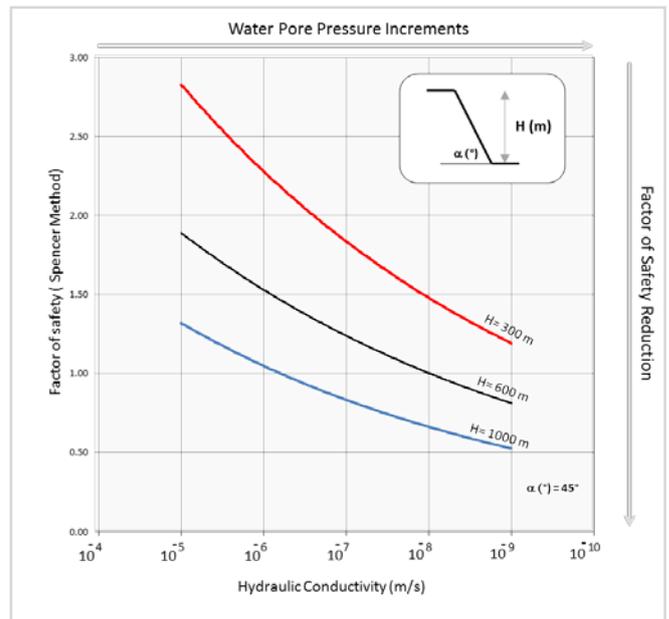


Figure 6. Relationship between FoS and hydraulic conductivity, obtained by using a test model.

The results of the test model indicate:

- Reduction of the hydraulic conductivity results in incremental increase of pore pressure within pit slopes. Therefore a reduction of the FoS is expected.
- Slopes less than 300m could be considered stable for rock with any hydraulic conductivity values, median pits (H is about 600m) requires additional depressurization for $K < 10^{-7}$ m/s, however for deep slope (1,000m) the FoS could be reduced to values below the limit of equilibrium (it should be noted that this statement is valid for only the test model used).
- In low permeable rock (K from 10^{-8} m/s to 10^{-9} m/s) increasing of FoS by additional pore pressure reduction could be not achievable due to required timing of depressurization and change of slope angle might be required, and should be reviewed in more detail.
- Figure 6 shows that the stability of the slope could depend upon the hydraulic conductivity at different heights. This example shows, for a medium size slope ($H > 600$ m), that a wrong assignment of the hydraulic conductivity can over or under estimates the slope angle, resulting in extra capital cost, NPV of the project and/or safety issues, mining difficulties, negative impact on the

mining plan and could jeopardize the mine reserves and the business.

5 HYDROGEOLOGICAL AND GEOTECHNICAL INTEGRATION

The success of an open pit mine design is based on quality, quantity and distribution of the geotechnical and hydrogeological data. Also, interpretation and modeling plays a “key” role in the final results. Today, mining companies have a clear understanding of the importance of data requirements, and extensive budgets are assigned to this task during different stages of the project. Unfortunately, there can be disconnection between the geotechnical and hydrogeological disciplines, affecting the final results. For example, hydrogeologists very often focus on dewatering and not on water pore-pressure modelling, placing more attention on high permeability units and not considering, in detail, the low permeable units, which might present problems for slope stability. Another example of this disconnect is reflected in the geotechnical design constraints; sometimes the geotechnical engineer’s design assumes certain hydrogeological conditions, which are not achievable in reasonable time.

The disconnect between disciplines normally results in extra cost for drilling, opportunities lost for data collection, misunderstanding of the geotechnical requirements, use of non-achievable assumptions, missuses of the hydrogeological models, over or under estimation of the slope designs or excessive costs for missed selection of appropriate slope depressurization systems.

To minimize the negative impacts, it is important to recognize the need for the integration of both disciplines during each stage of the project.

Figure 7 below shows an integrated chart of geotechnical and hydrogeology processes for slope stability analysis recommended by the authors.

6 CONCLUSIONS

Integration of geotechnical and hydrogeological studies during different stages of the mining project can provide required hydrogeological input for slope stability analysis and pit optimization. At early stages of the project the Geotechnical

Engineer needs to identify potential effects of pore pressure on slope stability, allowing the Hydrogeologist to characterize geotechnically important hydrogeological units. Data collected in the field need to be sufficient to develop reliable conceptual hydrogeological and numerical groundwater flow models to predict pore pressures in pit slopes during excavation and dewatering. At late stages of project development, these models should be sufficient to predict additional pit slope depressurization options (if they are necessary) and to define the required time for pore pressure reduction. These models, along with comprehensive sensitivity analysis of remaining uncertainties, should provide an input for cost-benefit analysis of implementation of pit slope depressurization. Numerical test modeling completed for this study indicates that for a medium- and high-permeable rock in a medium size slope (200 – 500 m height), there is significant impact of hydraulic conductivity on slope performance. This indicates that the accuracy of the hydrogeological inputs, and the interpretation and the modelling of the hydrogeological conditions are essential during the geotechnical investigation.

For saturated or partially saturated slopes, rock engineering experience establishes that a reduction of water pore pressure will improve the results of the slope performance parameters, creating the opportunity to optimize slope designs. Unfortunately, in some cases the slope depressurization requirements are not properly assessed due to lack of hydrogeological understanding, hydrogeological modelling objectives and, in some cases, due to miscommunication between the Hydrogeologist and rock mechanics Engineers. This disconnection between the hydrogeological and rock mechanics teams results in a potential of over or under estimation of slope designs. In order to avoid this, it is useful to consider the following questions:

- What will pore pressures be in the ultimate pit slope and how will they change in time during planned mining/dewatering?
- What would be the effect of pore pressure reduction on slope stability?
- How much time is required to reduce pore pressure?

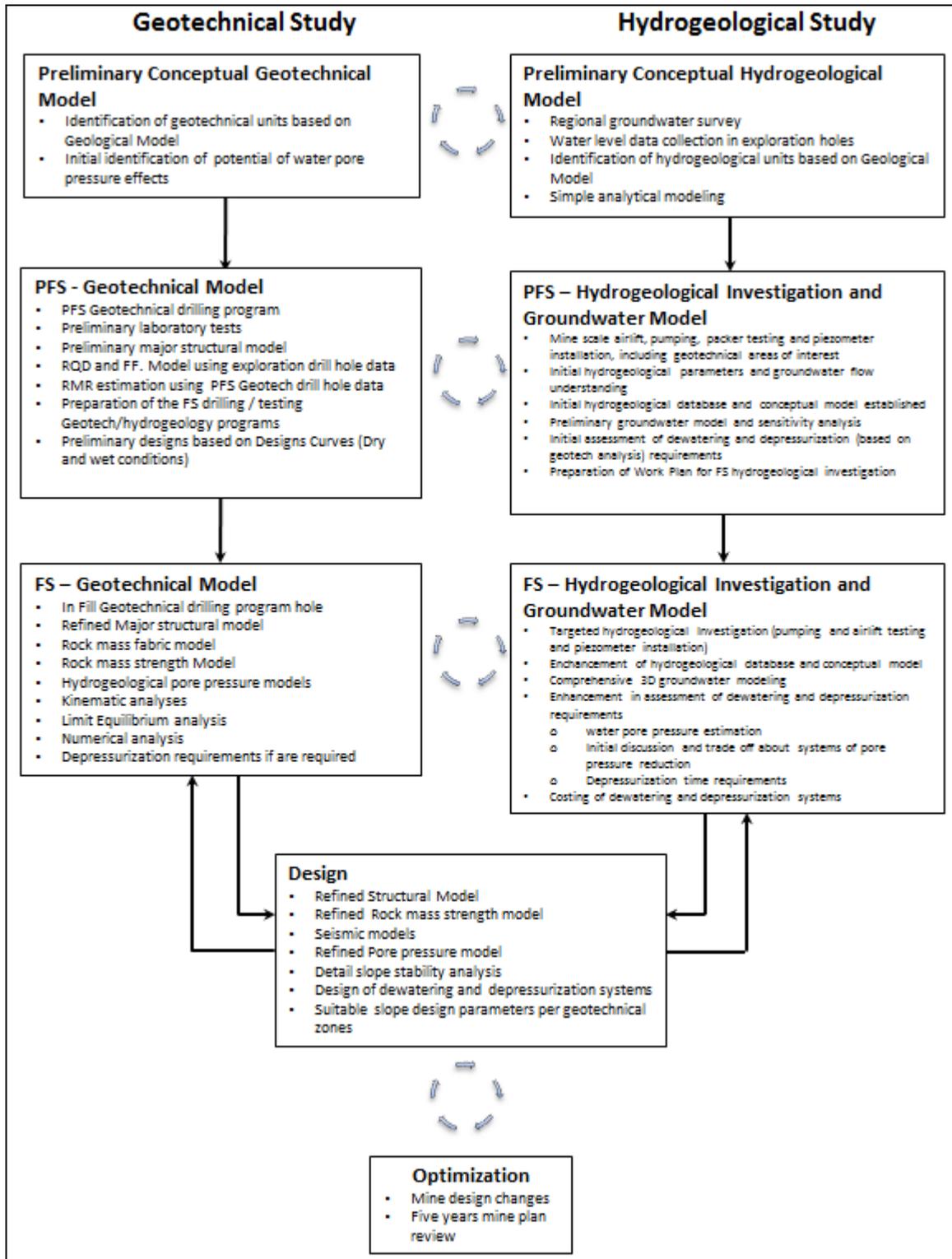


Figure 7. Integration of geotechnical and hydrogeological studies during different stages of the project (PFS: Prefeasibility Study, FS: Feasibility Study)

- Is the time required for depressurization in alignment with the mine plan and life of the mine?
- Is the knowledge regarding the hydraulic parameters sufficient for constructing a detail model to simulate the depressurization requirements?
- Does the mine plan have the flexibility to develop a proper depressurization plan?
- What depressurization method is the best for site specific hydrogeological conditions?
- What is the cost-benefit of implementation of pit slope depressurization?

These questions must be addressed in detail before moving forward to more detailed engineering.

Slope engineering is a common effort between different disciplines, and the understanding of each of the disciplines is critical in determining the final results. Also, the design process should be considered as an iterative process, where the integration between Geotech - Hydrogeology and Mine plan areas is a key in the mining cycle.

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