Modelling fractured rock heterogeneity in an open pit mine: groundwater model calibration using pilot points

Claudia Martínez, Tomás Opazo[1], Cristian Pereira[2], Rodrigo Cañete[3]

[1]*SRK Consulting Chile, cmartinez@srk.cl, topazo@srk.cl, Santiago, Chile*

[2]*SRK Consulting (U.S.), cpereira@srk.com, Denver, CO, USA*

[3]*AngloAmerican Chile, rodrigo.canete@angloamerican.com, Santiago, Chile*

ABSTRACT

Water content in rock units present in open pit mines has significant effects on pore pressure and in slope stability. For this reason, pore pressure distribution throughout the pit represents one of the most important factors in slope stability analysis, obtainable through groundwater numerical modelling. Generally, the hydrogeological units are defined using discrete geological-geotechnical domains related to its hydraulics parameters. However, once implemented in the numerical model, this approach may lead to an oversimplified zonation of piecewise parameter uniformity. As a result, the model has a limited capacity to express hydraulic property complexity, leading to diminished potential for using site data and evaluating predictive uncertainties. This paper describes the application of "pilot points" methodology as a means of spatial hydraulic property characterization in an open pit mine. It uses MODFLOW-USG with Quadtree Refinement and PEST. A multilayer model was divided into zones based on a geological model, and pilot points were used to evaluate intrazonal hydraulic property variations. The calibrated transmissivity fields show substantial heterogeneity with regions of high hydraulic conductivity, which correlates well with the location of main faults. Null Space Monte-Carlo uncertainty analysis shows important predictive error for groundwater inflows to the pit as well as for pore pressure distributions. These results are valuable for identifying data needs and optimizing future hydrogeological works.

INTRODUCTION

Understanding groundwater flow in fractured rock is a complex task. In most geological settings where open pits are located in Chile, involve very competent and impervious rocks wherein groundwater flow occurs through narrow and discrete fractured zones, often hard to be spatially followed. In several cases, field data are insufficient to develop a comprehensive conceptual model that includes features that are important to groundwater flow, especially because of the heterogeneity of hydraulic parameters. However, despite all the uncertainties and complexities recognized during the data analysis process, consultants are forced to delineate at least macro-hydrogeological units to feed the geometry of the numerical model that would finally provide predictive outcomes. As a result, the constructed numerical model usually does not include complexity derived from identified discrete flow zones. This can be quite unsatisfying when predicting pore pressures as an input for slope stability analysis, where their spatial variability is highly dependent on heterogeneity.

When modeling groundwater flow in fractured rock using the equivalent porous media approach (EPM), the "pilot points" methodology can be used as a means of representing the spatial property variability that cannot be imposed by working with zones of piecewise uniformity (Doherty, 2003). By honoring both hydraulic property data and piezometric head measurements, a spatial distribution of hydraulic conductivity and/or storage can be found by the use of inverse modeling. The obtained distribution can then be compared with identified features such as principal faults in order to improve the understanding of groundwater flow in fractured rock.

This paper presents a case study where the "pilot points" methodology was used at an open pit mine. Los Bronces mine is located in Central Chile, where groundwater became an operational and geotechnical issue at least since 2005. The geology is dominated by mineralized breccias and intrusive rocks, with secondary and primary mineralization, belonging to the Rio Blanco-Los Bronces ore deposit (Warnaars *et al*., 1985). Several subvertical faults have been identified (Carrizo *et al*., 2013), but their contribution to the groundwater flow system is currently unknown. A numerical model was built to gain insights regarding the dynamic between groundwater and main faults, to predict and evaluate pore pressure distributions as input for slope stability analysis, and to predict groundwater inflows to the pit. Additionally, the model served as a tool for exploring parameter and predictive uncertainty.

GROUNDWATER FLOW MODEL CONSTRUCTION

A 3D groundwater model was built using Leapfrog Hydro® for 3D geometry generation, Groundwater Vistas v6 (Rumbaugh and Rumbaugh, 2007) for numerical model setup, and simulated using MODFLOW-USG code (Panday et al., 2013). The model domain (Figure 1) is an extension of the watershed where the pit is located, and covers an area of 24 km^2. Lateral boundary conditions were simulated using General Head Boundaries (GHB – 3rd kind BC) and Constant Head Boundaries (CHB – 1st kind BC). The model grid presents a Quadtree refinement, with variable spacing ranging from 30 m at the area of the final pit to 240 m outside the pit, and is vertically divided into 19 layers (the upper 8 layers representing rocks with secondary mineralization, and lower 9-19 layers representing primary rocks), resulting in a total of 206644 active cells. Recharge was piece-wised distributed according to the location of recognized recharge zones such as glaciers and alluvium, and simulated with a seasonal signal according to the observed hydraulic head temporal variability, with an average recharge rate of 102 mm/yr equivalent to 20% of the average precipitation measured at the site.

The simplified geologic model represented in the numerical model consists of andesites, igneous rocks, breccias, rhyolites, and a subsidence crater (Figure 1). Hydraulic conductivity values obtained from 200 packer tests and slug tests, range from 1.54E-09 m/s to 1.30E-05 m/s, providing evidence of highly heterogeneous rocks. Main faults were not explicitly represented in the model, but the use of pilot points was intended to explore intra-zonal hydraulic conductivity heterogeneity that may reflect the presence of faulting. Storage parameter zonation was simplified into secondary and primary rock with pilot points for intra-zonal variability.

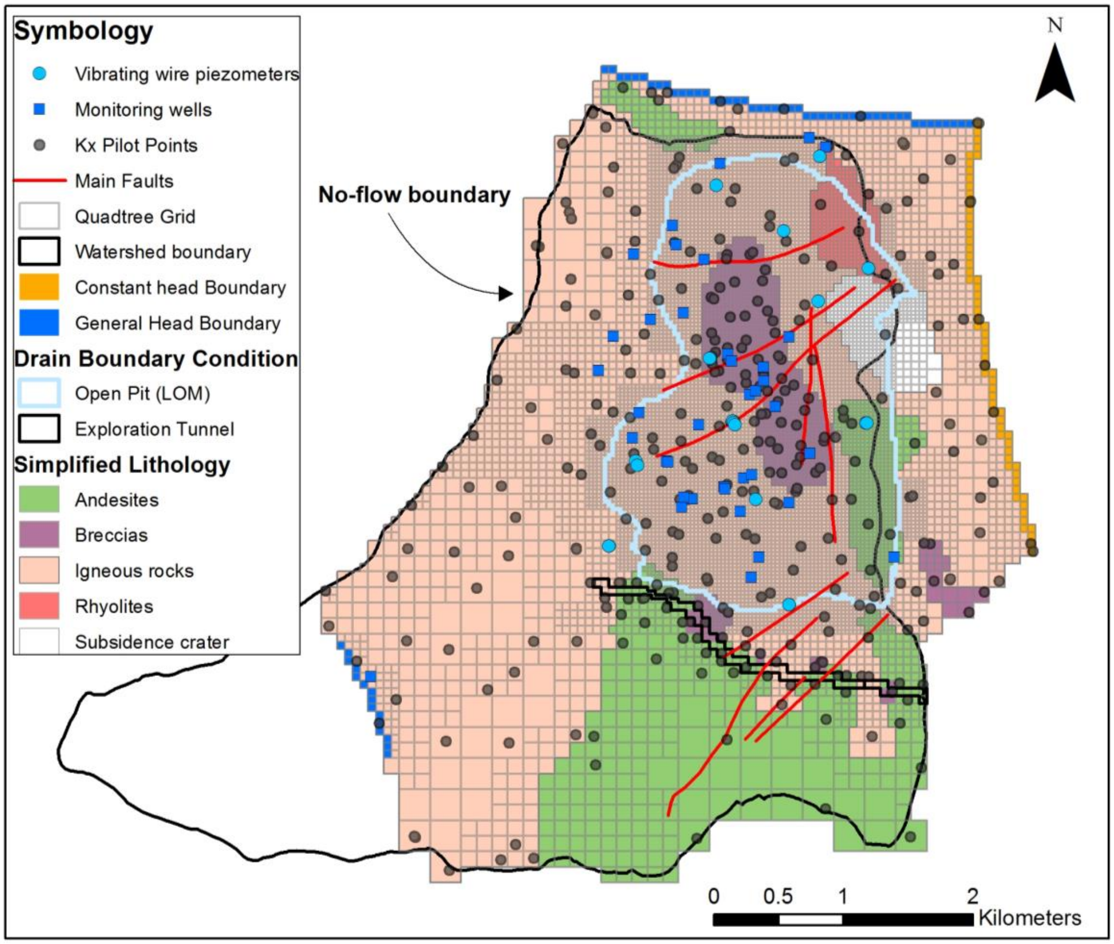

Figure 1 Groundwater numerical model main components in layer 3 (delineated drain boundary conditions represent the edges of the actual boundary)

In order to simulate the advance of the pit the Drain package was used. According to the historic mine advance and to the LOM mine plan, a time-varying reference elevation representing the pit wall was assigned to each drain cell, honoring the geometry of the pit at all times. The advance of an exploration tunnel that registered groundwater inflows during its construction was represented by the drain package as well (FIGURE 1).

TRANSIENT CALIBRATION METHOD AND RESULTS

As recharge was unknown prior to the calibration process and due to the lack of pre-mining hydraulic head data, the calibration process only included a transient calibration that simulates the historic pit advance from 2006 to 2014, with monthly stress periods. For this purpose, transient groundwater levels from 42 monitoring wells and from 12 vibrating wire piezometers (with depth-discrete head measurements) were used as calibration targets ranging from layer 2 to layer 10, for a total of 1942 observations. Additionally, 299 observations of groundwater inflows to the exploration tunnel were also used as calibration targets, in order to better constrain the hydraulic parameters and recharge in that area. The calibration process was carried out using the "pilots point" methodology, singular value decomposition (SVD-assist) and regularization (Tonkin and Doherty, 2005), with PEST as the parameter estimation technique (Doherty, 2013). In simple words, pilot point is a xyz location within the domain where PEST has to estimate a specific parameter (kh, kv, Sy, Ss, or recharge) which value has to be in a specified range according with conceptual model. The pilot point does not necessarily correspond with a real well o test well or observation, but it can be located between or around observation wells because PEST needs observations to estimate value for each parameter o pilot point. Singular value decomposition is a technique to find numerical correlation between parameters (pilot points) in different zones of the model and based on that, estimates super parameters. Regularization is the way that modeler impose its conceptual model to PEST, assigning to each observations a weithg or importance on calibration process, and relationship between parameters based on conceptual model. A total of 401 horizontal and vertical hydraulic conductivity pilot points were used to account for hydraulic intrazonal heterogeneity, whereas a more simple approach was used for specific storage, specific yield, and recharge, with a total of 27, 17, and 7 pilot points, respectively. The krigged fields were generated by interpolating the pilot points values using the PLPROC package (Doherty, 2015), honoring the geologic boundaries, producing a continuously varying K field within each model zone. The hydraulic conductivity (Kx and Kz) and storage values (Sy and Ss) (TABLE 1) were estimated by PEST, respecting field measured and literature applied values, in order to get an acceptable fit between observed and simulated heads and groundwater inflows to the tunnel. Specific yield for the rock with primary mineralization (layers 9-19) was fixed to 0.1%. Given the high level of model parameterization, model runs were parallelized by the use of BEOPEST (Schreuder, 2009).

Table 1 Acceptable ranges for hydraulic conductivity, specific storage, and specific yield values. Bold numbers correspond to values assigned to rock with primary mineralization (layers 9-19).

Lithology	Hydraulic Conductivy (m/s)			Ss (1/m)			Sy (-)		
	Average	Min	Max	Average	Min	Max	Average	Min	Max
Andesite	2.8E-07	1.8E-08	6.2E-06	1.0E-05 **5.0E-07**	1.0E-07 **5.0E-08**	1.0E-03 **5.0E-06**	1.0E-03	5.0E-04	5.0E-02
Breccia	1.3E-07	1.8E-11	6.5E-06						
Igneous rock	1.0E-07	1.5E-09	1.3E-05						
Rhyolite	3.6E-08	5.3E-09	3.5E-07						

The obtained model fit has an absolute residual mean of 11.6 m (< 5% of differences between maximum and minimum head data) , root mean square error (RMS) of 16.3 m, and normalized root mean square error (NRMS) of 2.1%, acceptable according with SEA (2012). Figure 2 shows the calibrated K_x field for layers 1-4 (representing the upper portion of the model in secondary rock), and for layers 5-8 (representing the lower portion of the model also in secondary rock). The obtained K_x values range from 10^{-9} to 10^{-5} m/s, according to field measurements. One of the most important findings of the calibration process is how well the areas of high hydraulic conductivity can be correlated with the location of main faults. This is particularly evident at the center of the pit, where the two main NE-SW faults are related to high K values separating the breccia geologic unit (dashed zone in FIGURE 2) into two distinct hydrogeological domains, suggesting that these faults could be acting as preferential flow paths for groundwater. This configuration can be observed for layers 1-4 and layers 5-8, where depth-independent head data were used, suggesting that faults influence the hydraulic conductivity distribution for all the rock sequence with secondary mineralization. In the area of the exploration tunnel, another high K zone was obtained from the calibration process that is also well correlated with the location of NE-SW faults that intersect the trace of the tunnel. These faults would be responsible for most of the groundwater inflows identified at the tunnel during its construction.

The calibrated distribution of primary rock (layers 9-19) shows substantially less spatial variability, so this part of the model is not part of the discussion presented in this work.

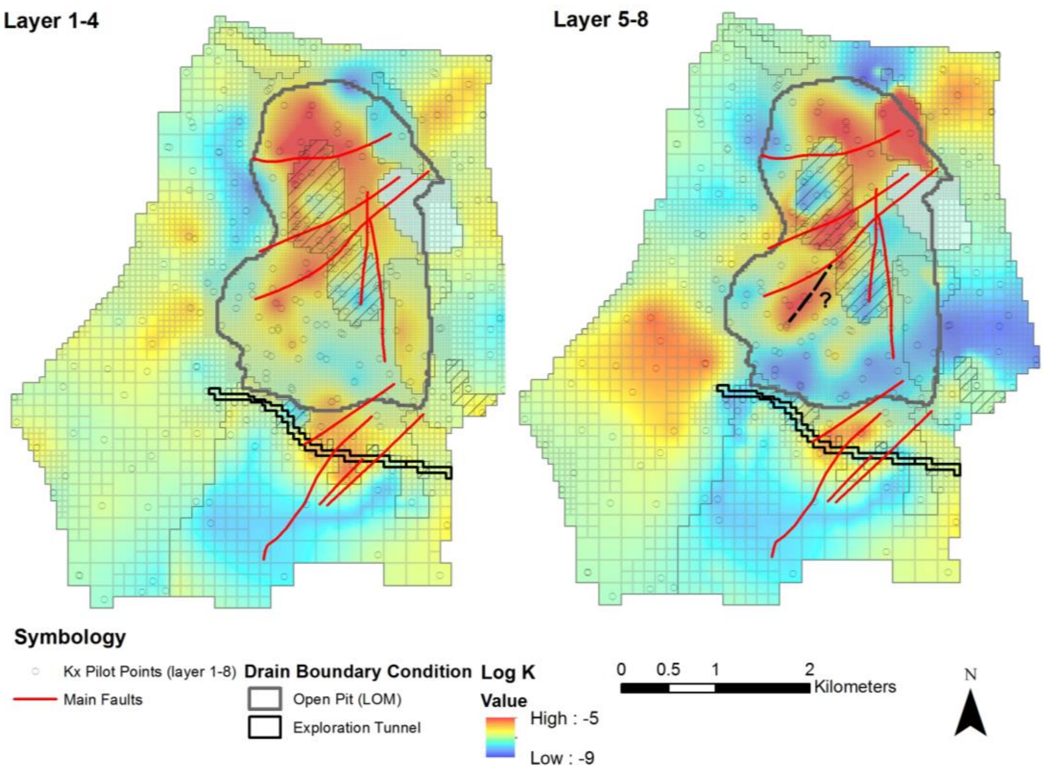

Figure 2 Comparison between calibrated Kx fields from layers 1-4 and layers 5-9, and main subvertical faults.

PREDICTIVE UNCERTAINTY ANALYSIS

Null Space Monte-Carlo approach (Tonkin and Doherty, 2009) was applied to explore predictive error variance of future groundwater inflows to the pit and of the predicted piezometric surface. A total of 100 random realizations were generated with the RANDPAR utility and projected into null space using the PNULPAR utility (Doherty, 2011), to obtain calibration-constrained random parameter sets. Each of the parameter realizations was calibrated with PEST and SVD-assist, rejecting the ones that resulted in a RMS greater than 20 m, or NRMS greater than 2.6%. Due to time constrains, only 40 parameter realizations were accepted. The accepted parameter fields were used in the predictive model where the pit development was simulated for 5 years, obtaining a range of predictive head distributions and groundwater water inflows to the pit.

FIGURE 3 shows a frequency histogram of average groundwater inflows to the pit for the 5 years of simulation, where the distribution is positively skewed with a mean inflow of 69 ± 25 l/s, suggesting that future groundwater inflows to the pit could reach maximum values of 100 l/s.

FIGURE 4 shows the predicted error variance for the piezometric surface at the end of the 5-year simulation. Although the error is in general less than 20 m for most of pit area, the east pit walls exhibits errors that exceed 100 m. This area can be defined as a priority zone for further hydrogeological investigations.

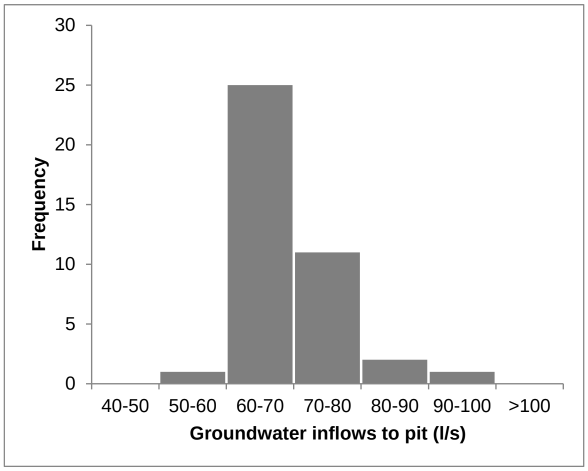

Figure 3 Frequency histogram of 5-year average groundwater inflows to the pit

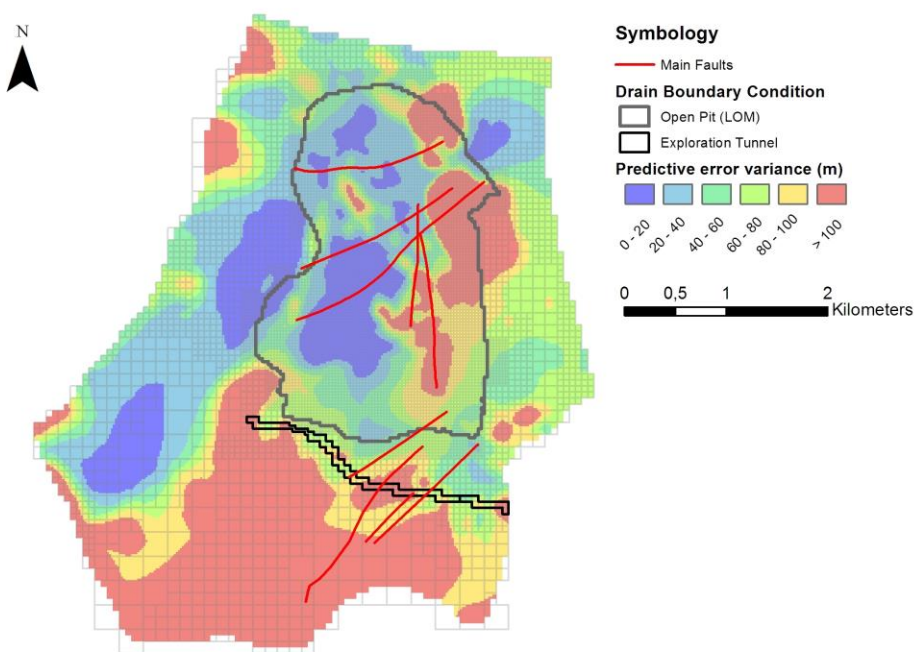

Figure 4 Piezometric surface predictive error variance (2σ) at the end of the 5 years of simulation

SUMMARY

The application of groundwater model calibration and uncertainty analysis using pilot point methodology at an open pit mine was presented. The calibrated hydraulic conductivity fields suggest that the main faults are a first order feature for preferential groundwater flow, which had not been identified during previous site characterization campaigns. This finding provides valuable insights about the role of faults in the groundwater dynamics and orientates future works.

Predictive uncertainty analysis using the NSMC approach showed a noticeable degree of variability of the predicted groundwater inflows to the pit, but especially of the piezometric water surface, with a maximum error variance of 100 m at the eastern pit wall. This finding provides guidance on planning future hydrogeological campaigns.

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