Groundwater Flow Modelling Applications in Mining: Scopes and Limitations

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Abstract Water is a key component in the development of the mining industry; from potable water for human use to industrial water for mineral recovery. The rational and efficient use of water resources has became relevant in the evaluation and mine planning, since the exploration phase to closure, once operation is finalised.

In this context the use of numerical models as a tool for diagnosis, management and prediction of water behaviour in the ground, has been gaining considerable importance in the recent years. Although mathematical modelling has its advantages, it cannot be considered as the answer to all questions. It is a dynamic tool that must be constantly reviewed and updated in a continuous improvement process, in search of the representation of natural phenomena.

This paper presents a methodological approach for setting numerical models, addressing its capabilities and limitations, in case of different applications in the mining industry, such as open pit drainage and heap leach.

INTRODUCTION

Hydrogeological numerical models have become a frequently used tool for predictions related to water in mine operations. Applications of hydrogeological numerical models include groundwater flow model for mine dewatering predictions, environmental vulnerability study of aquifer, surface water related to acid mine drainage and also a flow model focused on the heap leach drainage.

Groundwater flow to an underground mine as to an open pit is generally three-dimensional (3-D) and should be simulated by a three-dimensional numerical model. Therefore, a three-dimensional conceptual hydrogeological model needs to be built.

On the other hand, heap leach irrigation process can be understood as a two-dimensional (2-D) vertical flow and can be simulated by a simple two-dimensional numerical model. Also, the drainage process of a heap leach pile includes the concept of unsaturated media. In this case a different set of parameters needs to be collected to simulate that process by a 2-D numerical model.

This document shows a brief explanation of modelling methodology, key parameters of different projects and two simple examples of application for open pit mine and heap leach pile.

GENERAL METHODOLOGY FOR MATHEMATICAL MODELLING

What is a mathematical model? A classic and formal answer could be the following: "a mathematical model is a representation of the essential aspects of an existing system (or a system to be constructed) which presents knowledge of that system in a usable form" **[1]**. For groundwater a numerical model represents the conceptual model of water flow. Numerical model is the second step of a series of activities.

A simple methodology to build a mathematical model can be explained in the following stages **(Figure 1)**:

1. *Definition of objective problem.* What are the needs or requirements that should be addressed? What will be the pit inflow? Will the mine dewatering activities impact the surface water bodies? What is the rate at which a heap leach needs to be irrigated? If we manage to define clearly and in enclosed form our request, it is also possible to evaluate whether it is relevant or not to build a numerical model as a solution.

2. *Conceptual model.* Conceptual model should be developed and matured before building the numerical model. It is essential to have field data characterisation to support our conceptual model and that allow as to calibrate the numerical model.

3. *Objectives of a numerical model.* Specific goals of the numerical simulations should be defined along with the conceptual model. The scale of numerical model should be in accordance with the simulations objectives. A regional numerical model of a basin with 500 km^2 for a pit dewatering estimate cannot accordingly reproduce the drawdown generated by pumping 1 L/s in a large diameter well.

4. *Construction of a numerical model.* A numerical code should be selected based on the previous stages to accurately reproduce the conceptual model and to achieve the proposed goals. At this point a second abstraction of the reality is done upon passing from conceptual model to the numerical model.

5. *Model calibration.* Field data measurements should be reproduced by the mod-

el within a range of precision. Calibration should be in accordance with the scale of the numerical model and the expected solution. For example, to calibrate a water level within a range of 1 cm is exaggerated if the objective is to verify drawdowns of more than 5 m in the water levels. Numerical model construction (geometry, boundary conditions, and hydraulics parameters) and conceptual model need to be evaluated during the calibration process to get a reasonable calibration.

6. *Model validation*. Even if the model is calibrated, using field data, it should also be validated using the independent set of data, that differs from the one used in model building and calibrating.
7. *Model sensitivity*. The sensitivity should be analysed in the range of confidence of the parameter measurements used to feed the model. In some cases, even a very small change in the value of these parameters will result in very different model responses (model robustness can be discussed here).
8. *Predictive simulation*. Predictive simulation is the "last stage" of the modelling process. This activity should be developed when it has got a reasonable calibration. The first predictive simulation is not necessarily the last stage of a modelling project, since the results of this simulation can be unreasonable and it would be necessary to check the previous stages (calibration, numerical model construction and even the conceptual model).

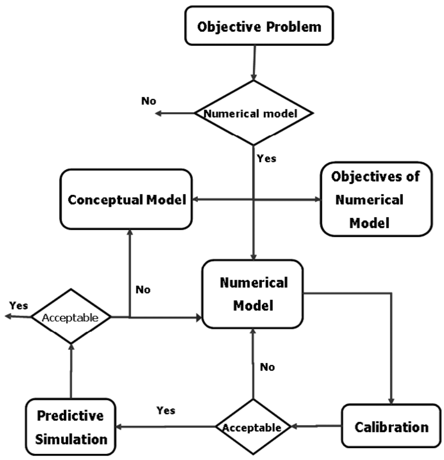

Figure 1 Flow diagram of mathematical modelling.

Numerical modelling should be understood as an iterative process in which the reasonableness of results in each step should be checked before proceeding to the next step. If predictive simulation results are unreasonable, it is necessary to go back through calibrations to check assigned parameters and models extension, or even to change the conceptual model. This iterative process is necessary in order to keep predictions within an acceptable range of error according to the level of study, and not to receive disproportionate over- or underestimated values.

On the other hand, time used on each stage of the modelling process should be consistent with the stage requirements **(Figure 2)**. Conceptual model, for example, can use between 30% and 40% of the efforts, and predictive simulation should use no more than 25% **[2]**. In general, objective definitions and conceptual model should not take less than 25%, and the numerical model construction and calibration between 35% and 50%.

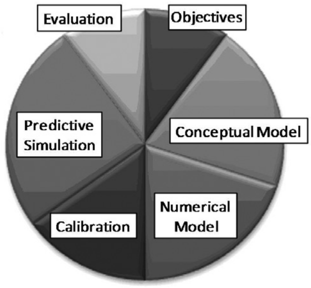

Figure 2 Example of an acceptable time of work by modelling activity.

LIMITATIONS

Even though the previously shown methodology is widely known to modellers, in most of the mining projects data is limited. In general, the availability of data for building, calibrating and validating a model is reduced or nonexistent. This would represent the bigger and the most common limitation to the modelling process and could lead to an idea of impossibility of building the model. However, in these cases a preliminary model could be a good tool for setting field work priorities in order to improve hydrogeological knowledge and to reduce the uncertainties of predictions.

On the other hand, the model represents the hydrogeological media always as a porous media. In this sense fractured rock in mining should be represented as porous media with average parameters.

Geometry of different units in general has limited representation. To get a better representation a very refined grid should be built and in that case files of model can become very heavy and take a long time to run. A regional model to analyse the effect of an open pit on groundwater levels often requires a lot more discretisation to analyse slope stability in the same pit.

Working with the average parameters for hydrogeological units can make it difficult to get a good calibration and many modellers are tempted to make specific changes in few cells to obtain a better calibration. A good calibration should be obtained by using average parameters and getting a good representation of the different trends in water levels, drawdown, inflows and outflows, rather than by matching levels in each well and making specific changes.

MINE DEWATERING MODELLING: KEY FACTS AND PARAMETERS

Mine dewatering requirements, active dewatering options (if required), potential environmental impacts on groundwater levels and surface water bodies and post-mining conditions (pit lake formation or flooding of the underground mine) can be predicted and evaluated by using a 3-D numerical model. Numerical modelling can also be used for sensitivity analysis and field work planning.

A 3-D hydrogeological numerical model should be based on a 3-D hydrogeological conceptual model, which, in turn, should be based on a 3-D characterisation of groundwater data. Hydrogeological data necessary for a 3-D characterisation should primarily be collected in the area adjacent to the ore body and at a depth of at least 50 m below the proposed ultimate bottom of the open pit or underground mine **[3]**. This depth should be confirmed based on the particular hydrogeology of each project.

Key parameters for a 3-D characterisation include: horizontal hydraulic conductivity values within different hydrogeological units; vertical hydraulic conductivity (Kv) for specific units; water levels in plan-view and at different depths (to estimate lateral and vertical groundwater gradients); hydraulic connection between groundwater system and surface water bodies; and water chemistry with depth.

Mine excavation can generate impact on the groundwater system up to 10 km from the ore body boundary or more, depending on the hydraulic parameters of the groundwater system. Then, a hydrogeological numerical model should have enough extension outside the ore body and below the bottom of the final mine configuration (with an adequate vertical discretisation) to get a good estimate of the mine inflow and impacts on both the groundwater levels and superficial water bodies.

MODELLING OF UNSATURATED FLOW

For unsaturated flow modelling it is necessary to know the unsaturated hydraulic properties of the materials that are involved in the model, such as Soil-Water Characteristic Curve (SWCC) and the unsaturated hydraulic conductivity (Kr (Ψ)).

SWCC can be estimated by laboratory testing, by using data bases or by the grain size distribution curve of the material. There are various methods to adjust the SWCC curve, among the most known are those developed by Brooks & Corey [4], Van Genuchten [5] and Fredlund et al. [6].

Fredlund's work stands out among these authors. Fredlund [6] has developed a methodology to estimate the SWCC based on the material grain size distribution and a database of laboratory testing for different types of soils.

Unsaturated hydraulic conductivity can be estimated by several equations but the one developed by Van Genuchten [5] is the most widely used. This equation connects the negative or matricial pore pressure with the unsaturated permeability, based on the saturated hydraulic conductivity. The latter parameter should be estimated by permeability testing (in situ or in laboratory). Moreover, since soil permeability is a function of its density, it is necessary to know the density ranges that will be used in the model and carry out testing on compacted samples in accordance with those density values.

It is recommended to characterise the material as follows:

- Estimate SWCC (soil water characteristic curve).
- Estimate specific gravity weight (Gs).
- Estimate grain size distribution and Atterberg limits.
- Estimate in situ densities.
- Estimate saturated hydraulic conductivity.
- Estimate the unsaturated hydraulic conductivity curve.

NUMERICAL MODELLING EXAMPLES

Case 1: Open pit drainage

Passive inflow and drawdown extension for a pre-feasibility level study were estimated for a two pit excavation by a 3-D numerical model.

Proposed pits will be excavated through 20 m to 25 m below the initial water table, in a very low hydraulic conductivity sedimentary sequence with groundwater at very shallow location. Recharge in the area is reduced due to the high evaporation rate, then the water source for the pit inflow is mainly the groundwater storage.

Excavation of pits was simulated as a one-time excavation at the first time step of the simulation. This condition will apply a very high stress on the system and predict a large volume of water inflow to the pits at the beginning of the simulation. However, inflow will be reduced and stabilised after a few days of running time steps. As many models at scoping and pre-feasibility levels, this exercise has very limited field data and is focused on obtaining an initial knowledge of the groundwater situation, the future pits and the possible inflow and drawdown using a 3-D numerical model instead of an analytical solution. This is considered an acceptable approach for a pre-feasibility level estimation.

Passive inflow to the pits was estimated to be about 5 m^3/hrs **(Figure 3)**. A very high inflow rate (more than 100,000 m^3/hrs) predicted at the beginning of pit excavation is the result of the one-time excavation of the pit simulated at the first time step of the model. It is expected that in future stages of the study the gradual excavation of the pit will reduce this high inflow, which should be divided between different steps of the pit excavation. Results of this kind of simulation allow having a first estimation of pumping requirements for mine dewatering.

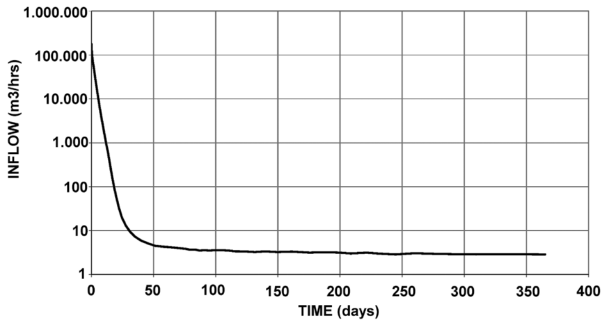

Figure 3 Predicted inflow to the pits.

Case 2: Heap leach

Behaviour of a heap leach under irrigation (both on top and on slopes) was evaluated to maximise the copper recovery.

Historical data was studied to define the material variability. Samples were taken from both leached and pre-leaching materials to characterise by hydraulic testing and estimate their SWCC by their grain size distribution curve **[6]**.

Saturation distribution within the pile on irrigation regime was estimated by a FEFLOW 2-D vertical transient numerical model **[7]**. This model allowed identifying the slope irrigation effect on the behaviour of water flow through the heap leach toe. The latter allowed an adequate estimate of the Security Factor to the slope slides.

This type of modelling allows to make a sensitivity analysis of the results using different materials and to evaluate which of those materials may generate a high phreatic level in the heap leach **(Figure 4)**. High phreatic levels in the heap leach have a negative effect on the leaching process. Particularly, in this case, the leaching solution was observed leaving the pile by above the drainage system.

The sensitivity analysis involved reducing the Van Genuchten parameter “a”, allowing the soil to retain more humidity. Observations of the real pile show a slightly increased phreatic level at the bottom of the pile compared to the phreatic level predicted by the model. This difference can be explained by changes in the retention properties of the material after leached process has started.

Calibration of this type of numerical models can be done against flow measurements of the drainage system, phreatic levels and moisture content measurements in the pile by piezometers and with depth (Diviner, GEM2).

The construction of the heap leach pad itself generates zones of heterogeneous materials and at this level of study it is not possible to analyse the interaction between these zones along the pile.

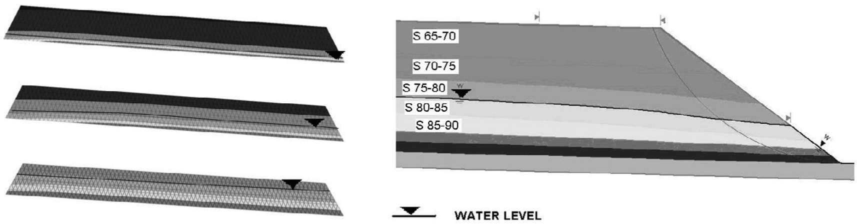

Figure 4 Heap leach model (a) variability of water level within the pile and (b) slope stability analysis.

CONCLUSION

Numerical groundwater flow modelling should be based on a conceptual model matured and validated by empirical data. In this sense, it is important to allocate at least 25% of the time to build the conceptual model and clearly define the objectives of this numerical model.

Numerical modelling should be understood as an iterative process in which the reasonableness of the results in each step should be checked before proceeding to the next step. If predictive simulation results are unreasonable, it is necessary to go back through calibrations to check assigned parameters, extension of models or even change the conceptual model.

Hydrogeological data necessary for a 3-D characterisation should primarily be collected in the area adjacent to the ore body and at a depth of at least 50 m below the proposed ultimate bottom of the open pit or underground mine **[3]**. A hydrogeological numerical model should have enough extension outside the ore body and below the bottom of final mine configuration in order to get a good estimate of the mine inflow and impacts on the groundwater levels and superficial water bodies.

Unsaturated flow theory is commonly used to estimate flow in heap leach, which allows determining different levels of saturation within the pile. For this type of modelling it is necessary to know the unsaturated hydraulic properties of materials (SWCC, Kr, and saturated permeability). Results of this kind of modelling can explain the behaviour of the heap leach and can also be compared to in situ measurements of water levels or moisture content.

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