Finely Discretized Numerical Flow Model of Complex Multiple Open Pit Mine For Reliable Inflow and Pore Pressure Simulations – An African Perspective

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Abstract Flow modelling has become one of the best prediction tools to quantify groundwater inflows and pore pressure distribution in open pit mines. Accurate discretization of the geological features, multiple hydrogeostratigraphic zones and detailed open pit geometries into numerical models are essential when assessing these aspects.
This paper presents a case study of Moatize Mine where multiple open pits are operated simultaneously in a complex hydrogeological environment. Fine model discretization allowed for a realistic distribution of input transmissivity and specific storage throughout the model domain. Simulated pore pressures and groundwater inflows were used to guide slope and mine water infrastructure design.

Key words fine discretization, groundwater inflow, numerical flow model, open pit

Introduction

The Vale SA Moatize Mine is located near the town of Moatize, approximately 16km north-east of the Provincial capital Tete, in north-western Mozambique. There are at least eleven potentially economic coal deposits in the Vale project area, of which six will be mined. Mining operations started in 2010 and will reach an annual production of 18 million tons in 2017.

Given the potential depth of the open pits (maximum depth of 290m below surface) groundwater was required to be managed as part of the mining process. Vale SA thus identified the need for a numerical flow model that could be used as management tool across the Vale mining area to quantify groundwater inflows and pore pressure distribution within the open pits.

Methodology

A comprehensive hydrogeological investigation was completed during the Bankable Feasibility Study (BFS) of the mine in 2006. This study entailed the siting and drilling of 131 hydrogeological test boreholes used for aquifer testing. A combination of hydrogeological drilling, aquifer testing as well as geological models was used to conceptualise the numerical model domain. The data was pre-processed for incorporation and translation into the numerical model.

The main purpose of model was to construct a calibrated steady state and transient model capable of simulating predictive scenario for groundwater influx and pore pressure estimation. Groundwater Modeling System (Aquaveo LLC 2017) a pre- and post-processing package for MODFLOW and MODFLOW-NWT (Niswonger et al. 2011) was used for the process. The modelling process involved the following steps:

- Construction and setup of the model;
- Conceptual model translation into the numerical discretization;
- Model calibration/verification; and
- Scenario Modelling.

Conceptual Hydrogeological Model

The project area is located in the Moatize-Minjova coal basin that has an asymmetrical synclinal structure, bordered by faults, with several inclined blocks (as can be seen in Figure 1). Coal formations in the basin, occur in a graben structure. Karoo Supergroup sediments were deposited unconformably onto the Proterozoic crystalline basement in subsiding grabens or half graben. Basement gabbro and anorthosite form the high lying ridges and hills surrounding the various mining sections. Post Karoo (early Jurassic) dolerite intrusion took place in both the Karoo sediment and the basement rock.

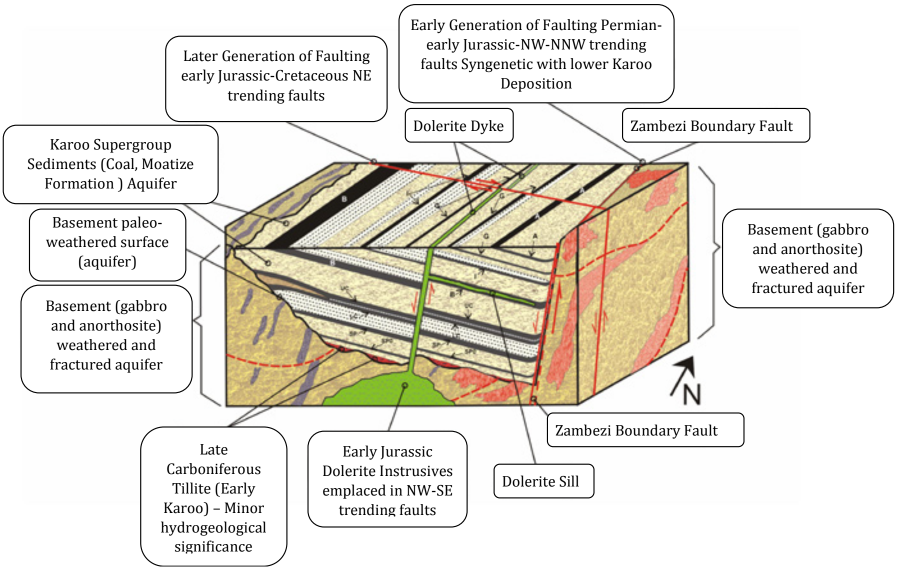

Figure 1: *Schematic block diagram of Karoo sediments deposited in a half graben structure (after Rio Doce Mozambique 2006)*

A summary of the hydrogeological coneptualisation is discused below:

- Average depth of weathering in the Karoo Supergroup aquifer ranges between 15 and 20 m. Water strikes are associated with minor fracturing, most likely bed-

ding planes fractures on the contact with the major coal seams. Transmissivity values of Karoo sediments vary between 0.05 and 1.5 m2/d. and storativity, mostly between 0.001 and 0.00001.
- Groundwater occurrence may be enhanced along faults and dyke contact zones within the Karoo strata and/or within the underlying Basement rocks. Higher yielding boreholes are generally associated with NE-SW trending structures.
- NW-SE trending Zambezi Boundary Fault and dolerite dykes are potential flow barriers
- Groundwater levels are typical between 5 and 15 metres deep (range between artesian and 50 m below surface).
- Borehole yields were generally lower 1 l/s in areas where smaller weathered pockets and minor fracturing occur. An enhancement of groundwater occurs along faulting, with recorded yields from 3 to 15 l/s. A large number of these higher yielding structures have a NE – SW trend. The basement rock aquifer also have a low transmissivity in the order of 0.5 m^2/d, however faulting is associated with transmissivities up to 3 orders higher. Basement aquifer seems to be less developed with depth. Preferred basement aquifer zone is 25 to 60 m deep.
- Parts of the paleo-weathered surface offers better aquifer properties compared to areas investigated where the basement is exposed to surface with shallow weathering. Some of the highest borehole blowout yields identified during the BFS study were recorded where faulting occurs in the basement below the Karoo Supergroup units.
- Based on Chloride (Cl) Method calculations and previous studies, an average recharge value of 2.6 mm/annum was used (0.4% of mean annual precipitation) over the model domain.

Model discretization

Modelling focussed on the six mining sections in the current long term mine plan. The model area was discretized by a 689 x 1000 grid in the x and y direction and consisted of 33 layers (8m layer thickness). A total of 4782747 active cells were found in the model grid. Grid refinement of 25 m x 25 m x 8 m cells around the mining areas was applied with coarser grid cell sizes of 200 m x 200 m x 8 m away from the mining areas.

River boundary conditions were applied to the Revubue and Zambezi rivers at the northwestern and southwestern boundaries of the model domain. No-flow boundary conditions were applied to topographical catchment boundaries along parts of the north-western and eastern ends of the model domain.

For the area outside the concession coal resources only the four upper model layers were activated as the hydraulic conductivity in these areas decrease rapidly with depth in the presence of the basement rocks. For the mining areas the basement paleo-weathered aquifer was chosen as the bottom hydrostratigraphic unit of the model.

The hydrostratigraphic units were then translated into the 3D discretisation using a grid overlay function, whereby each cell of the model is assigned a hydrogeological parameters based on the intersecting hydrostratigraphic unit (as seen in Figure 2). The Moatize Formation solid was created by using the depth to weathering as the top and the Souza Pinto coal seam as the bottom. For the three major coal seams the top of seam and bottom of seam was used and included all the partings associated with each seam. Cells that should not contribute to groundwater flow (deep unfractured rock) were made inactive by assigning an 'inactive' hydrostratigraphic unit.

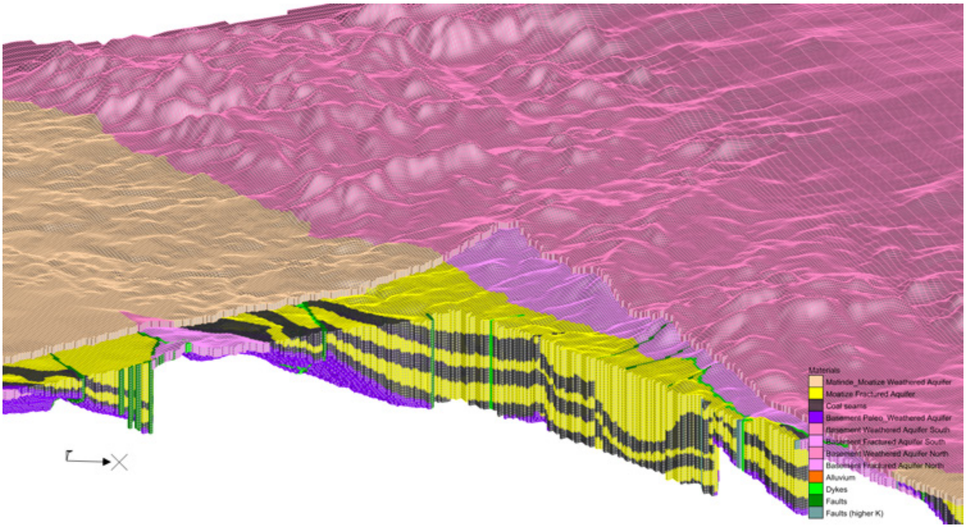

Figure 2*: 3D Oblique view of model illustrating the translation of the hydrostratigraphic units into the discretization*

Model Calibration and Sensitivity Analysis

Initial estimates of the hydraulic conductivity for the different geological units were obtained from the aquifer test data collected as part of the hydrogeological field program. These hydraulic conductivity values were assigned to the hydrostratigraphic units in the model area. Performance measurements were evaluated during the calibration of the model as:

- Model convergence: Model convergence was obtained during calibration and a maximum change in heads between iterations was set to 1.0 x 10^{-5} m.
- Water Balance: The mass balance for entire model achieved a water balance error of less than 0.0001%.
- Quantitative measures: The difference in measured compared to calculated head was less than 5 m for 124 observation boreholes. Steady-state calibration was regarded as sufficient at mean error (ME) = -0.33 m, mean absolute error (MAE) = 2.75 m, root mean square error (RMSE) = 3.41 m and normalised root mean square error (NRMSE) = 3.3%.

A sensitivity analysis of the model found recharge and hydraulic conductivity of the weathered aquifer to be sensitive to change. Groundwater inflows into one of the deeper operational pits was used to verify the model and the models ability to perform predictive scenarios. An estimate inflow of ~400 m^3/d was simulated for the beginning of 2016, this volume correlated to the inflow flux measured by the mine.

Fine discretization thus allowed for a more realistic representation of the geological model in the numerical model grid. A refined distribution of transmissivity and specific storage/ specific yield throughout the model domain was achieved.

This finely discretized numerical model with a large number of cells pushed the boundaries of the graphic user interface and computer processing abilities. Nevertheless the model run time was acceptable and the model was able to perform predictive simulations for the open pits based on the transient life of mine plans.

Simulated groundwater inflows

Scenario modelling using the calibrated transient model was conducted to assess the pit groundwater inflows and drawdown extents for existing and proposed open pit mining. Latest available pit shells and schedules were incorporated into the model. Annual pit shells with yearly intervals were provided for the period 2016 – 2026, after which the interval increased to 5 yearly. Simulated groundwater inflows volumes (Figure 3) were extracted for all six mining areas with the cumulative volume reaching ± 7000 m^3/day in 2040.

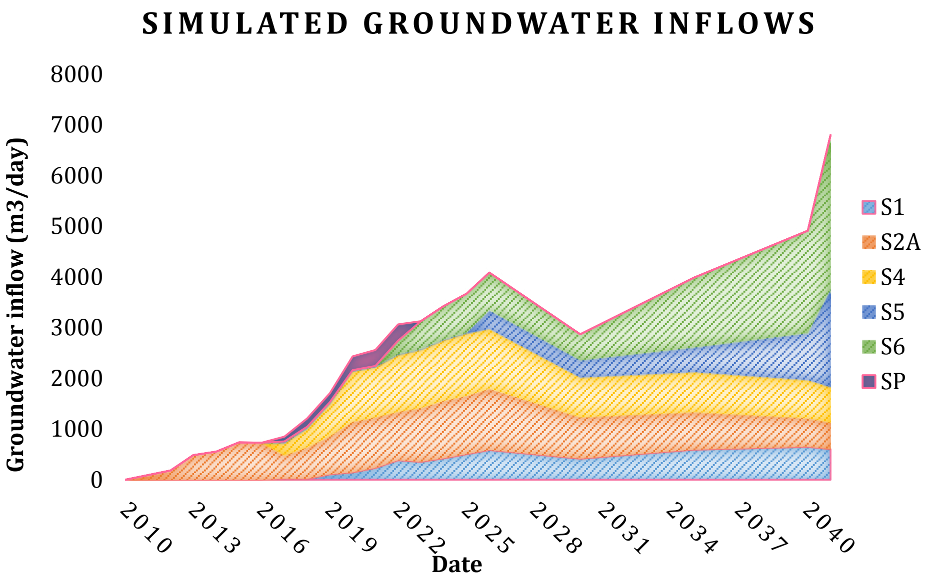

***Figure 3**: Simulated groundwater inflows of the six open pits which was used in the mine water balance to assist with long term water management and planning*

Mine water management

Moatize Mine has a water deficit and is located in an areas with unreliable rainfall (MAP: 642mm), where severe dry spells could occur. Evaporation generally exceeds the average rainfall. Groundwater inflows therefore played an important role in augmenting the water supply especially related to dust suppression and beneficiation plant demand. Simulated groundwater inflow volumes was also used to guide water infrastructure design and to assist in the planning of future water availability for the mine complex.

Mining occurs in a hydrogeological environment with generally a low to average permeability as a result simulated groundwater inflows into the pits was be regarded as manageable without the need for active dewatering systems such as abstraction boreholes (based on the present mine scheduling). Mine scheduling and design could thus allow for upfront planning, sizing and construction of dewatering sumps at least two benches below the mining level with the assistance of modelling results. Simulated groundwater inflow volumes was used to spec appropriately sized sump pumps and infrastructure required to abstract the passive groundwater inflow into each pit. This information was also required as input into external mining service provider contracts as they were often required to provide turnkey mining operations and thus operate the dewatering system.

A finely discretized flow model allowed the mine to assess the changes in drawdown around the open pits as the pit geometry changed, thus providing an early warning system for any potential impact on community supply boreholes.

Three dimensional pore water pressures was extracted from the model based on the transient pit shell schedules. These pore water pressures provided valuable input into the geomechanical models and was used in the slope design process (a cross section from the model can be seen in Figure 4). Flow modelling also allowed for the testing of different pit shells whereby the results could be fed back into the geomechanical investigation.

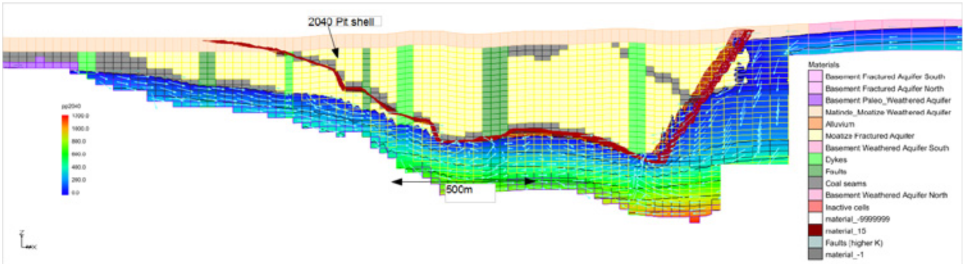

***Figure 4**: Model Cross Section depicting a 2040 open pit shell with associated simulated pore water pressures (kPa) and flow vectors. The deeper sections of the high wall appear to be saturated. These profiles were used by the geotechnical engineers during the slope design.*

Conclusions

A realistic aquifer depressurisation and flux for each mining step could be simulated as the open pit geometry could accurately be included in the finely discretized model. Simulation results were more realistic than previous simpler numerical models developed for the mine. The numerical model is thus used as an active groundwater management tool that is updated periodically with the latest pit shells and groundwater monitoring data to continuously assess the changes and potential impacts on the hydrogeological environment.

A finely discretized flow model provided inputs to various stakeholders and departments at the mine such mine planning, water utilities, geotechnical and environmental, by reliably estimating transient groundwater inflows and pore pressures for the different open pits.

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References

Aquaveo LLC (2017) Groundwater Modeling System (GMS), version 10.2.4.

Niswonger, R.G., Panday, S, and Ibaraki, M (2011) MODFLOW-NWT, A Newton formulation for MODFLOW-2005: U.S. Geological Survey Techniques and Methods 6–A37, 44 p

Rio Doce Moçambique, (2006). Moatize Coal Project – Feasibility Study Level: Geological Exploration Report. Final Version.