Assessing Groundwater Conditions in Preparation for Post Closure Reflood of the Giant Mine, Canada Using a 3-D Numerical Model: Idealized vs. Reality

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Abstract.

Modeling future groundwater flow conditions following closure and reflood of underground mines represents a difficult task for hydrogeologists. The Giant Mine, located on the edge of Great Slave Lake in Yellowknife, NT, produced over 7 million ounces of gold and approximately 237,000 tonnes of arsenic trioxide dust as a waste product from the ore roasting process. The arsenic dust was stored in a series of 13 underground chambers with the expectation that, upon mine closure, initial permafrost conditions would return, effectively freezing the dust underground and preventing contact with natural groundwater after the mine is allowed to flood. Although the mine is currently owned and operated by Miramar Giant Mines Limited, Indian and Northern Affairs Canada is developing the final closure plan for the mine and the assumption of the return of natural permafrost is unlikely. In order to assess groundwater interactions with the frozen block, a numerical model has been constructed to simulate a calibrated model for current conditions and a preliminary conceptual model for reflooded conditions. Reflooded scenarios simulated include discharge to Great Slave Lake from existing mine openings, controlled outflow using “engineered spill points”, and engineered water levels using long term pumping. Comparison of two models incorporating different degrees of mine complexity indicates that the simpler approach is more robust. Results from both must be analyzed with caution during calibration due to intrinsic effects of the simplification. Comparison of reflood scenarios using an equivalent porous media approach vs. a discrete element approach for the tunnel system indicates significantly better results using discrete elements. While not capable of contaminant transport, the simple model can be an effective tool for aiding in preparation of a management plan.

1 Introduction and Purpose

1.1 Model Objectives and Past Efforts

The Giant Mine in Yellowknife, Canada has operated for over 50 years, producing over 7 million ounces of gold and approximately 265,000 tonnes of arsenic trioxide dust as waste from the ore refining process. Indian and Northern Affairs Canada is developing the final closure plan for the mine. Groundwater modelling was carried out for the Giant Mine, as part of a technical review of closure options to illustrate current groundwater interaction with the dewatered mine and possible reflooded conditions. These models were used to test a series of final flood conceptual models for closure planning. The modelling was used to assess “what if”, or extreme case scenarios, to see if uncertainty in hydrogeological characterization at the mine site scale could lead to unexpected problems with hydraulic control after mine closure.

1.2 Previous and Current Modelling

Previous modelling using a very simplified MODFLOW model could not take into account either seepage face drainage into the dewatered tunnels or flooded open tunnel flow, resulting in the need for further modeling.

Following closure and reflood, open tunnel flow is expected to dominate the system, even after accounting for partial tunnel collapse. Because of this, the tunnel system is expected to form an equilibrated lattice characterized by very small gradients capable of controlling water flow in the system. Integration of this concept was essential in creating a reasonable approximation of the flow system.

1.3 Site Conditions and Model Design Requirements

The mine workings consist of 11 levels extending from 100m to 600m below ground surface, comprising approximately 85 km of connected tunnels. The surface elevation of Great Slave Lake, located approximately one kilometre from the central mine area, is about 10 meters above the uppermost mine level.

Field data shows that groundwater interacting with certain faults is affected by drainage to the mine workings. Additionally, discretization required for “small scale” flow around workings was not feasible due to the scale of the mine (3km in length). Therefore, a tunnel system incorporated into a regional scale model was required.

FEFLOW® was chosen for the program to provide mesh discretization flexibility. Initial models included tunnels as high K finite elements. After encountering difficulties with reflood simulations, namely, unrealistic head loss, the model was re-designed using 1D lines for tunnels and seepage boundary assignment, and discrete elements in the reflood scenario.

This paper discusses the comparison between the equivalent porous medium approach, and the use of discrete elements in a large scale groundwater model to achieve a more realistic replication of the flow system. While still only a simplified version of the large scale flow regime, the method appears to be an improvement on more conventional modelling approaches to complex mine groundwater investigations.

2.0 Conceptual Model and Model Construction

2.1 Modelling Objectives

Considering the fractured rock nature of the system and level of uncertainty in characterizing the system at that scale, the primary objectives were simply to simulate the current flow system, and to illustrate various possible reflood scenarios including possible fault conduits, discharge from known spill points (open pits, adits, etc.) and control of mine flood levels using engineered spill points. Prediction of contaminant transfer was not considered feasible considering the nature of the system and presence of over 25,000 drillholes in the mine area.

2.2 Conceptual Model

The conceptual model was constructed using available water levels, inflow mapping in the mine workings, detailed geological data for the site, and available hydraulic test data from Giant and other similar sites.

Based on available data, the following conclusions were developed:

a. Available geologic data suggest an equivalent porous media approach is reasonable for the bulk bedrock. 2nd and 3rd order structures, including fractures, represent the majority of the data set and were shown to have widely dispersed orientations when viewed from the regional scale. Hydraulic conductivity data for bedrock indicates a geometric mean of 2.7×10^{-7} m/s, but all tests were conducted at depths of less than 200 meters. Comparison of conductivity data from 8 similar sites suggests that the values measured at Giant are representative, but that conductivity should decrease with depth. Lithology may have an impact on hydraulic conductivity but the limited bedrock hydraulic conductivity data available does not justify separation.

b. Many 1st order structures may act as barriers to flow.
c. Current groundwater flow in the area of the mine is directed towards the workings, forming a dewatered cone (figure 1b). Groundwater flows into mine workings along a complex seepage face, the elevation of which is generally unknown.

2.3 Model Construction

FEFLOW© was used based its the ability to incorporate the complex 3D geometries of tunnels and faults, and the option to use discrete elements. One steady-state model was planned, with modifications for current and reflood conditions. Mine workings were input as seepage face boundaries. Water entering the workings was assumed to be instantaneously removed from the system (ie: pumped from mine) to simulate ditch flow within the tunnels. Faults, which at Giant are fairly steep, and surface features included in the model were based on detailed surface mapping.

Mine workings were simplified for mesh generation. Narrow, linear tunnel systems were incorporated with realistic geometry In areas of dense workings, a "mine envelope" approach was used. Graphically, the area of dense workings was wrapped with a single line, to which the mesh was later matched. The original complexity internal to the line was removed. This method was based on the assumption that in the relatively narrow areas of dense workings, the wrapped line would be sufficient to drain water that would enter the area originally occupied by the dense workings Two model versions were constructed based on different levels of tunnel and fault simplification:

Model A. – 3D tunnel and discrete fault width

- 24 layers
- Tops and bottoms of primary mine levels delineate 11 layers
- Layers created above and below mine workings
- 3D seepage boundaries incorporated along mine geometry
- Primary faults incorporated as discrete 5 metre wide features and extended vertically through entire model thickness
- Finite element mesh consists of 692,500 elements and 363,175 nodes

Model B – 1D tunnel and no discrete fault width

- 14 layers total
- Model slices set to bottom elevations of primary mine levels
- Layers created above and below mine workings
- Tunnels input as single lines of seepage boundary nodes assigned approximately along the center line of tunnels or wrapped around areas of dense workings on mine level slices, equivalent to the bottom mine level slice in Model A
- Primary faults incorporated as single lines of nodes with hydraulic conductivity assigned to adjacent elements
- Finite element mesh consists of 587,000 elements and 318,300 nodes

Model A was designed to use high K elements within tunnel cross-sectional areas. Elements representing the tunnels were assigned conductivities higher than bedrock. Conductivity values two orders of magnitude greater than bedrock were utilized. Contrasts higher than this did not converge. Model B was designed to incorporate discrete elements. Discrete line elements were input at the exact positions used for seepage boundaries in the current conditions model. Discrete element conductivities 7 to 10 orders of magnitude greater than bedrock conductivity were used.

2.4 Mesh Comparison

Much of the success in modeling complex systems such as these can relate to the mesh complexity and distribution of elements with poor geometries (obtuse triangles) for numerical solutions.

Model A incorporated increased mesh complexity around tunnels and faults. Faults and tunnels have discrete thickness. Refining the mesh around areas of mine workings and faults created significant lateral variation in element shape and area.

Model B was designed with higher mesh density but a simpler geometry. A higher mesh density extended the entire area of model but the decreased mesh complexity around tunnels and faults decreased the number of improperly shaped elements around tunnels and faults. Overall, there was a significant decrease in the number of obtuse triangles in Model B. While obtuse triangles in Model A were typically near faults and tunnels, obtuse triangles were more dispersed in Model B. In Model A, the presence of obtuse triangles in areas where high conductivity contrast would be input suggested that numerical instability may result. Obtaining fewer obtuse triangles in Model A with the desired complex tunnel system and faults, would have required a significantly larger number of elements and effort to construct.

An additional expected benefit to incorporating 3D tunnel geometry in Model A was the ability to incorporate transfer boundaries to control inflow to workings if desired. During model conceptualization and construction it was determined that using bedrock conductivity values for tunnel walls would be the most appropriate and justifiable approach. At the regional scale, the ability to incorporate exact tunnel dimensions and transfer boundaries may not be necessary to simulate seepage conditions. Figure 1 is a schematic depicting the use of simplified 1D seepage face boundaries vs. 3D seepage faces at larger scales.

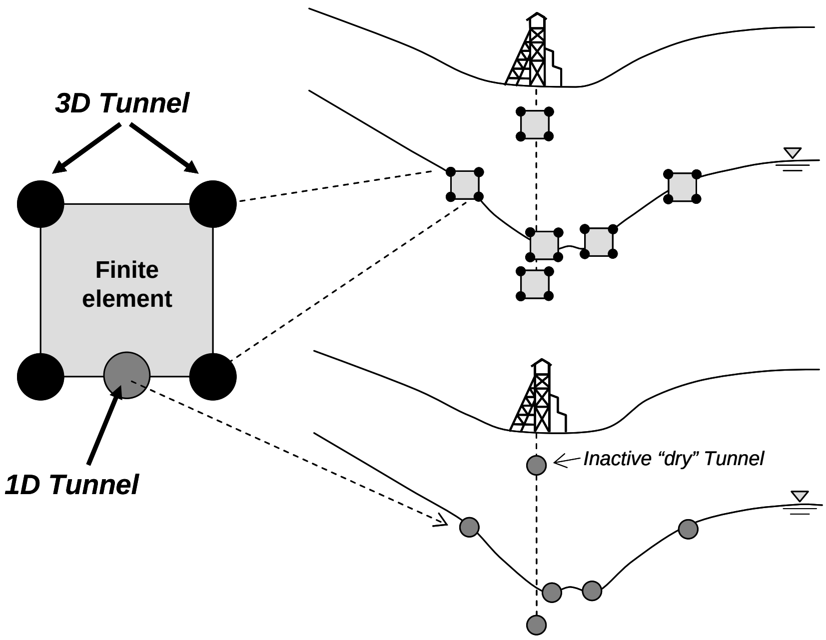

Fig. 1. Schematic of 3D and 1D seepage face boundary approach for regional models, showing concept that at large scales, 1D tunnels produce similar results to 3D-tunnels.

3 Reflood Scenarios

Project objectives required the final model had to be capable of simulating reflood conditions in addition to current conditions. The scenarios tested included

- reflood to a controlled level (10 m below lake level to maintain hydraulic capture zone
- full reflood to the level of the expected “spill point” (engineered or natural)

4 Results

4.1 Current Conditions

Both Model A and Model B converged under the current conditions scenario. Both models obtained a similar head solution. Head residuals were generally within calibration goals. Two open boreholes, for which water level data is available, indicated an area for potential future study. Both models depict a dewatered cone around mine workings and the influence of structural and surface features. The dewatered cone reaches to the edge of Great Slave Lake, from which a moderate amount of inflow is incurred. Two significant 1st order structures, each of which is instrumented on both sides, calibrated reasonably well and are shown to have an influence on the shape of the dewatered cone.

Total tunnel inflow results for each model were lower than observed values by approximately 5-15%, but show similar inflow trends with depth.

Sensitivity analysis indicated that inflow and head residual for current conditions were most sensitive to bedrock conductivity, but required a decrease in conductivity with depth. Variation in fault conductivity, recharge and surface infiltration had relatively lower influence on model results.

4.2 Reflood Conditions

4.2.1 Model A

Model A under reflood used high conductivity elements input within the 3-dimensional tunnels. Conductivity contrast greater than two orders of magnitude caused non-convergence Using a two order of magnitude contrast, observation points along tunnels indicated a head loss on the order of 25 meters along the length of the mine workings. This contrast value, in conjunction with the approximately 50 meter regional gradient, allowed groundwater to flow through, as well as along, the workings (figure 6a). Non-convergence when using higher conductivity contrasts was likely due, in part, to the high number of obtuse triangles in close proximity to the tunnels.

4.2.2 Model B

Model B, utilised discrete elements and conductivities contrasts of 7 to 10 orders of magnitude. Convergence was attained and the model produced a reasonable head distribution. Maximum head loss between 26 observation points, located throughout the mine, was 0.25 meters. All water entering the tunnels flows within the tunnel system and discharges at the spill point. Sensitivity runs using a conductivity contrast of only 4 orders of magnitude, resulted in approximately 25 meters of head loss. Pathline analysis indicated that, while flow along sections of tunnels would occur, water would often exit the tunnel system, re-entering the bedrock system and flowing to the regional low, Great Slave Lake. This was viewed as an incorrect solution based on the open tunnel flow conceptual model, and so illustrated the requirement for using discrete elements to obtain very high K contrast between "tunnels" and bedrock.

Utilizing the higher conductivity contrast, the concept of spill point control was shown to be valid. The spill point is defined as the lowest surface elevation to which water would rise flowing through the workings. In the case of Giant, the spill point is the rim of an open pit to which an open portal is connected. The rim of this pit is approximately five meters above the elevation of Great Slave Lake.

4.3 Summary of Modeling Approach

Comparison of Model A and B indicates that the simpler, more robust, Model B is capable of achieving both of the project objectives. Head distribution and tunnel inflow are within acceptable ranges.

Distribution of seepage face elevation is reasonable. The greatest depression of the water table occurs in the area of densest mine workings. Seepage face elevation rises away from the central core towards peripheral sections, which tend to be higher in elevation and generally not defined by high density workings.

5 Idealized vs. Reality

Ideally, models simulating mine systems should incorporate as much inherent complexity as possible. In reality, numerical models are constructed based on project objectives and budget, often requiring significant simplification of the system.

An overriding assumption for this model was the use of an equivalent porous medium (EPM). Using this approach, tunnel inflow is distributed along the entire length of tunnels. In these models, the seepage face is depicted as relatively smooth, and may exist along the entire length of a tunnel. In reality, due to the fractured system, this is likely not true. The seepage face is likely not smooth. Reconnaissance of accessible workings suggests discrete inflow, but with available data, EPM is the only viable approach. Structural analysis indicates that fracture distribution is heterogeneous, both in density and orientation. Whether specific structures have the ability to convey significant flow will only be known during reflood. The results of the study do indicate orientations are widely dispersed and an EPM is reasonable at large enough scales. The results presented suggest that results of an EPM approach require careful analysis.

5.1 Simplification of Tunnel System

The tunnel system used in this modeling is complex, but remains an approximation of the true distribution. Inclusion of all workings would result in an extremely complex mesh. In the case of Giant, a complete model of workings will never be available; a representation must suffice.

Figure 2 is a plot comparing cumulative 1D tunnel length by mine level to inflow. The relationship visible from this data indicates that inclusion of tunnel detail may be important, and calibration to tunnel inflow by adjusting only bedrock conductivity is inappropriate for a simplified system.

5.2 Utilisation of the Simplified Model

While numerical modeling at Giant cannot attempt contaminant transport, it can be used for “proof of concept” scenarios. The idea of spill point control can be shown and “*What-If*” scenarios, such as fault structures becoming transmissive upon reflood, can be designed and results prioritized to identify areas for local monitoring during reflood.

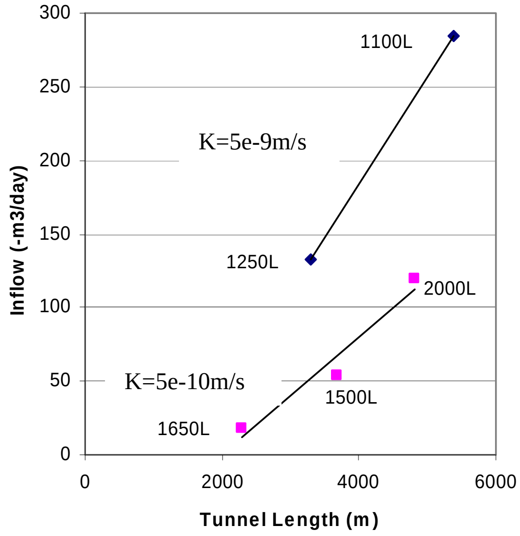

Fig. 2. Graph showing relationship between cumulative 1D tunnel length and inflow for two bedrock conductivity zones

5.3 Model Scaling

Small scale models were developed using multiple software packages as a check on validity and probable accuracy of the modelling. The necessity for testing components of a large scale model at a small scale for proper scaling up to final model scale cannot be underemphasised. This was shown to be essential when the original porous media model was successfully used to simulate dewatered conditions, but failed for the reflooded state due to significant hydraulic losses in the "tunnels". While improved use of verification models would have decreased the project timeline, final results emphasised the attention required for simplified EPM models.

6 Conclusions

The models presented here illustrate the concept that a simplified approach can be used to identify zones or features for further investigation or monitored during reflood. While not capable of contaminant transport, the simple model allows for the creation of a realistic management plan. Uncertainty will inevitably remain large at Giant until reflood is monitored, but the numerical models will allow for testing of hypothesis and the prioritization of potentially high risk zones.