Reflooding of an Underground Mine During Closure – Analytical vs Numerical Model Estimation

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Abstract

Estimating mine inflows and reflooding rates is crucial for closure planning of underground mines, as it helps predict the mine's impact on the groundwater system and inform long-term management strategies. Both analytical and numerical methods can provide adequate estimations, with the choice depending on the complexity of the system, available information, and level of the study. This paper presents examples of high-level Excel-based analytical calculations compared to a numerical solution using FEFLOW to estimate the reflooding time of an underground mine.

Keywords: Mine, underground, reflooding, closure, modelling, analytical, numerical, FEFLOW

Introduction

To support mine closure strategies and planning, modelling is often conducted to estimate future environmental effects associated with closure. An important consideration in underground mining is the rate of reflooding of the mine and total reflooding time. Both analytical and numerical modelling methods can provide appropriate results, with the most suitable approach depending on factors such as the complexity of the system, available information, and level of the study. Understanding the rate of mine reflooding is key for defining optimal water management strategies, appropriate monitoring programmes, and potential effects on the groundwater system and nearby receptors.

As part of a closure study developed by WSP, numerical modelling was used to provide an alternative solution to an Excel-based analytical model developed by the client for estimating the reflooding time of an underground mine. The mine, primarily used to extract energy metals, reaches a maximum dewatering depth of approximately 400 meters. Longhole Open Stoping is the main mining method used, with the client estimating a total void volume of 2,150,000 m^3.

The analytical model estimated the reflooding time by dividing the total underground void volume by the estimated groundwater inflow. While a valid approximation, the analytical model assumed a constant inflow rate throughout the reflooding process equal to the current dewatering rate (5,900 m^3/d), which is expected to decline during reflooding due to a general reduction of hydraulic gradient from the rock towards the mine as mine water level rise. A total reflooding time of 1 year was estimated using the analytical model.

Numerical modelling using FEFLOW was conducted to provide a more detailed solution factoring in the complexities of the local geology, the intricate mine developments and workings, and the dynamic nearby hydraulic levels and gradients, including the time required to re-saturate the surrounding rock. An average groundwater inflow of 1,300 m3/d was obtained during the reflooding process, leading to a reflooding time of 4.5 years, considerably higher than the 1 year estimated by the analytical model. The updated results were subsequently taken into consideration for the mine closure planning.

Modelling Approach

The study was conducted through a multi-step process involving the use of Leapfrog, Excel, Python, FEFLOW and the FEFLOW Python Application Programming Interface (API). Presented below is the used modelling workflow:

1. **Representation of the underground mine in existing FEFLOW model** using the 3D mine wireframes provided by the client. The model was originally calibrated to piezometric data and dewatering rates.
2. **Creation of Volume-Elevation curves** using Leapfrog and Excel, based on the 3D mine wireframes provided by the client.
3. **Development of Python script for reflooding process and application using existing FEFLOW model**, considering the Volume-Elevation curves from Leapfrog.

Step 1: Representation of Underground Mine in Existing FEFLOW Model

A groundwater numerical model of the mine site was developed and calibrated by WSP as part of a previous stage of the study. For this purpose, WSP chose the use of the groundwater modelling software FEFLOW (Diersch, 2013), an industry standard finite element modelling code widely used in mining projects (Barnett *et al.*, 2012). Mine wireframes provided by the client were incorporated into the existing FEFLOW model, with three identified mine zones (Fig. 1). The underground mine was represented using seepage nodes for dry areas and constant head nodes for flooded areas, assuming hydrostatic conditions. As noted in Fig. 1, the three zones are connected at known depths, which is expected to affect the reflooding process. Recharge values, hydraulic conductivities and storage parameters were applied according to the conceptual model, and refined by calibrating the model to piezometric data and groundwater inflows. Recharge rates were reduced following one year of mine closure in mine facilities where covers are expected.

Step 2: Creation of Volume-Elevation Curves

Volume-Elevation curves of the underground mine were required as a key input for the modelling workflow, to determine how water ingress reflects on water level increase within the mine. For this purpose, mine wireframes in 3D CAD format were imported into Leapfrog to estimate volume versus elevation curves for the three zones independently from each other and as a whole. The obtained curves are presented in Fig. 2. It is acknowledged that the calculated void volume is an approximation derived from mine wireframes, and does not account for voids from other sources, such as fractures surrounding the mined area or the porosity of the rock mass within the depression cone. It should also be noted that a correction factor was also applied to the volumes extracted from Leapfrog to align with the total mine volume provided by the client.

Step 3: Development of Python Script for Reflooding Process and Application Using Existing FEFLOW Model

A Python script was developed to simulate the reflooding process within the numerical groundwater model using the powerful

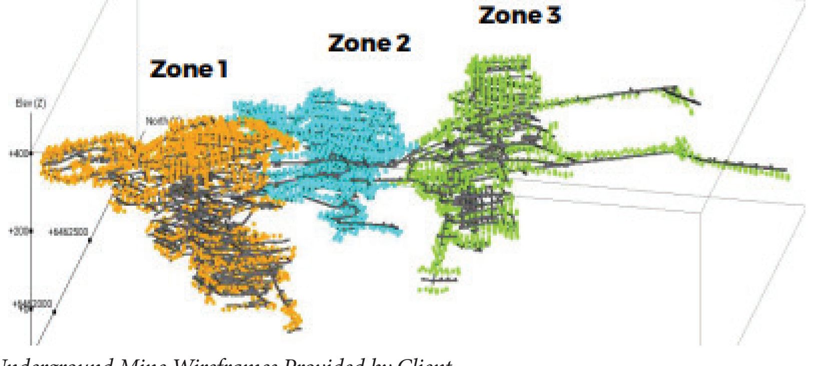

Figure 1 *Underground Mine Wireframes Provided by Client.*

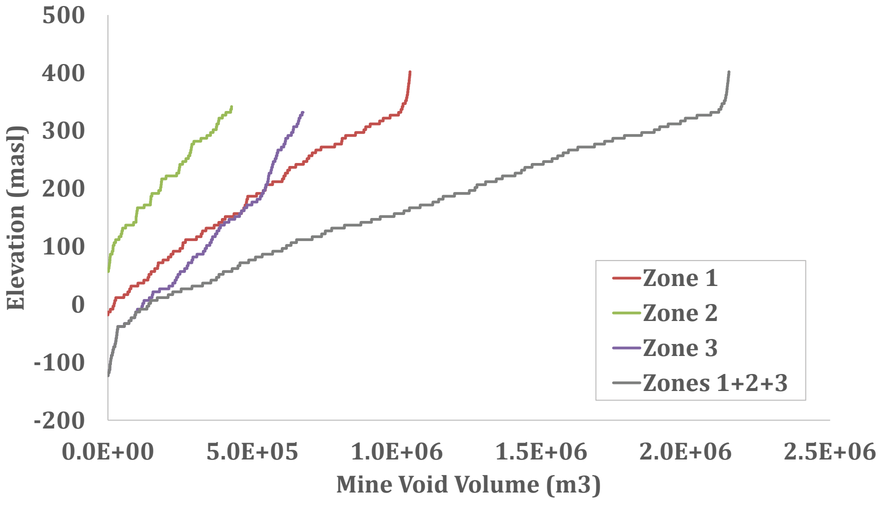

Figure 2 Volume-Elevation Curves of Underground Mine Zones.

FEFLOW Python API. Increases in flooded volume were calculated by FEFLOW and the Python script transiently by multiplying the mine inflows (L3/T) simulated by the model at a given timestep by the timestep length (T). The obtained volume increase was converted into an increase of flooded level using the previously determined Volume-Elevation curves. The new flooded level was used by Python to determine the new flooded areas and the necessary boundary condition conversion from seepage nodes into constant head nodes equal to the flooded level (i.e. hydrostatic assumption within the underground mine). Seepage nodes above the new flooded elevation remain unchanged to continue simulating seepage into dry (atmospheric) conditions. Flooding in each mine zone was considered to evolve independently by the script until interconnection at the identified elevations was reached, at which point water from different compartments start filling adjacent compartments with lower flooded level. When all zones reach an equilibrium, the system behaves as one unit. The model was run long enough to allow the mine time to flood completely.

3D Numerical Model Results

The simulated inflows and flooded elevations versus time were exported from the FEFLOW Python script and plotted over time (Fig. 3 and Fig. 4). Mine Zones 1 to 3 flood independently until an elevation of approximately 150 masl is reached at which point each zone becomes interconnected, flooding until an elevation of approximately 400 masl. At the beginning of the simulation inflow is equal to 5,900 m^3/d, decaying exponentially until the inflow rate reaches 0 m3/d. The numerical-based workflow estimates a total flooding time of around 4.5-years for the hydraulic parameters considered.

Alternative Analytical Approaches

It is acknowledged that the analytical approach selected by the client can be refined. Assuming a linear interpolation, an alternative method would involve using the constant average inflow rate of 2,950 m^3/day, rather than the maximum dewatering rate of 5,900 m^3/day throughout the reflooding period. This adjustment would result in an estimated reflooding time of approximately 2 years, thereby slightly improving the accuracy of the estimate.

Additionally, analytical solutions available in literature based on Darcy's Law (Darcy, 1856) can account for the reduction of hydraulic gradient from the rock into the mine over time. The Dupuit equation is a simplification of Darcy's Law (Equation 1), where Q is the discharge rate, K is hydraulic conductivity of the aquifer, dh is the head gradient, dx is the horizontal distance and A is the cross-sectional area through which groundwater

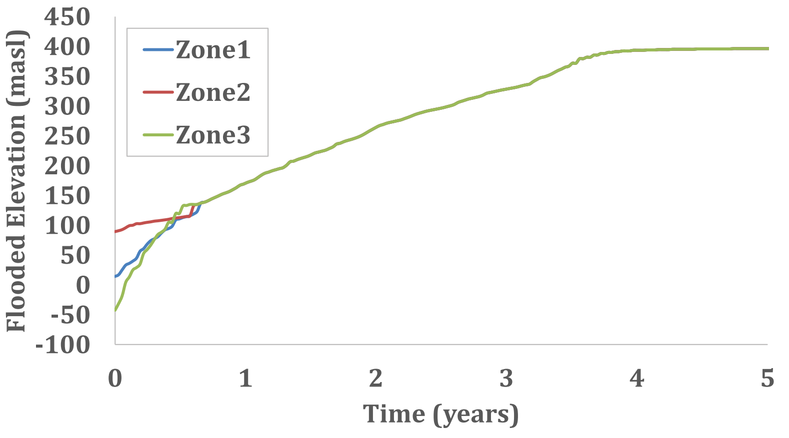

***Figure 3** Numerical Estimate of Flooded Level Throughout Time.*

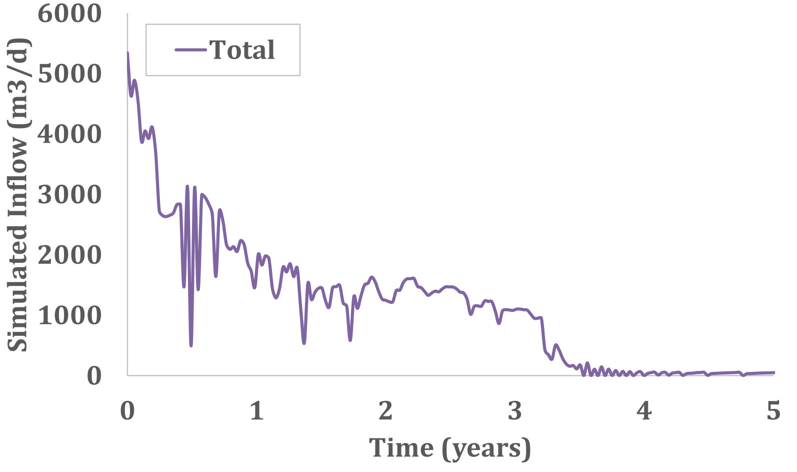

***Figure 4** Numerical Estimate of Groundwater Inflow Throughout Time.*

flows (Woessner *et al.*, 2020). Using the Dupuit (Dupuit, 1863) equation an average inflow rate of 2,020 m³/day was calculated, estimating a reflooding time of approximately 3 years.

$$Q = -K \frac{dh}{dx} A$$

***Equation 1** The Dupuit Equation (Woessner* et al., *2020).*

Comparison of 3D and 2D Results

The comparison of results from different methods for estimating reflooding time highlights variations (Table 1). The analytical method, using a constant inflow rate of 5,900 m³/day, estimates a reflooding time of 1 year. Refining this approach with an average inflow rate of 2,950 m³/day extends the estimate to 2 years. Literature-based solutions using the Dupuit equation (Dupuit, 1863), which account for the reduction of hydraulic gradient over time, predict a reflooding time of 3 years with an average inflow rate of 2,020 m³/day. In contrast, the numerical-based workflow, provides a more accurate estimate of 4.5 years, considering variable inflow rates and hydraulic parameters, with a mean inflow rate of approximately 1,300 m³/day.

Conclusion

The analytical model implemented by the client offered a simple and easy to use equation for estimating the total reflooding time, which under the right assumptions can guarantee the estimation of a minimum

Table 1 Comparison of the Analytical and Numerical Modelling Results for the Reflooding of the Underground Mine.

Model	Estimated Flooding Time year	Average Inflow Rate m^3/d
Analytical (Maximum Inflow)	1.0	5,900
Analytical (Average Inflow)	2.0	2,950
Analytical (Dupuit)	3.0	2,020
Numerical	4.5	1,300

possible time for total reflooding. However, at the level of the developed study the results provided by the analytical model were considered too approximate due to the assumption of a constant inflow rate equal to the current dewatering rate. This resulted in an overestimation of the predicted average inflow rate during the duration of reflooding, and an underestimation of the total flooding time. It is recognised that the analytical approach can be improved by altering certain assumptions or by using analytical solutions available in literature based on different forms of Darcy's Law, to account for the reduction of hydraulic gradient from the rock into the mine over time.

In contrast, the developed FEFLOW-Python coupled numerical approach can easily represent the complexity of the surrounding geology, the detail of the mine workings and developments, and the dynamics of the nearby groundwater system and flooded level over time. Transient modelling captured the progression of mine flooding according within each underground zone, the connection between zones at identified levels, and the behaviour after all levels were connected. The developed workflow can easily be extended to incorporate other terms of the water balance if they exist, such as external addition of water into the mine, or pumping from the mine. Furthermore, the developed script was already extended to be applied in open pit studies, to account for atmospheric interactions (rainfall, evaporation, and snowmelt), and other terms of the water balance. It should be noted that the most appropriate modelling approach is project and site dependent. The comparison of alternate methods indicates the importance of selecting the appropriate method based on the specific requirements of the project and available data, with the 3D numerical approach offering the most realistic estimates for this study.

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