Pile Scale Models for Acid Rock Drainage Prediction and Their Application

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**ABSTRACT:** In this paper, we developed pile scale models that include major mechanisms for acid rock drainage process, such as air flow, water flow, oxygen transport and consumption, geochemical production, and also heat transfer. Furthermore, the governing equations for these mechanisms are integrated in commercial software COMSOL with fully coupling features. This enables the proposed models to reasonably reflect the evolutions of oxygen concentration and temperature profile monitored inside the waste rock pile. We applied the proposed models to the main full-scale waste rock pile at the Equity Silver mine, Canada. The comparison between simulation results and monitoring data is provided; good agreement on the seasonal $O_2$ concentration fluctuation is observed. The changes of air convective pathway and oxygen supply due to the impact of a cover system are discussed; this helps us gain insights in the acid rock drainage processes.

1 INTRODUCTION

During the extracting process of hard rock mines, large amounts of waste rock are generated from open pits and underground operations. Most of the waste rock is placed in surface dumps, which are usually exposed to the open environment. In addition, significant amounts of waste rocks are also produced by major civil constructions such as highways, railways, airports and hydroelectric structures. When the waste rocks contain sulphide minerals, such as pyrite, pyrrhotite, sphalerite, galena, arsenopyrite, chalcopyrite, tetrahedrite, and molybdenite etc., they are identified to have strong acid generation potentials. As sulphide minerals interact with ambient oxygen and water, they gradually oxidize and release sulfate ions, proton and metal ions. Then those oxidation products are flushed by groundwater, releasing associated metals and metalloids into the surrounding environment. The acid rock drainage may under certain conditions have severe impacts on streams, rivers and aquatic life for decades or even hundreds years.

Currently acid rock drainage from sulphide bearing waste rock dumps is identified as one of the most serious environmental liabilities to the mine site owners or local governments. Most sulphide bearing waste rock dumps require perpetual treatment of seepage and runoff from the dumps. This requires substantial operating costs for labor, power, chemicals and maintenance. The cost of maintaining waste rock dumps is among the highest in the waste management facilities. Security bonds are often requested to provide assurance that these funds would be available over a long-term time. As a result, prediction of acid rock drainage production becomes important and essential for determining peak acid production rates, the duration of peak rates and the decline in acid production over time. Also a good prediction requires revision and calibration based on the historical data.
In order to predict acid rock drainage, extensive research has focused on studying integrated processes within waste rock and understanding the fundamental processes over the past several decades. For example, Davis and Ritchie (1986), Lefebvre, (1994), (2001) implemented mathematical modeling to compute the oxygen loss and heat production in the waste rock pile, which is based on reaction core model that considers pyrite oxidation as a function of temperature, oxygen concentration and pyrite mass fraction relative to the original pyrite concentration. In this paper, we proposed new pile scale models with fully coupled features to simulate the transport behaviors of reactant (oxygen) and product (proton) within the regime of waste rock piles. The purpose of this study is to evaluate the total acid rock reaction rate in the waste rock pile and investigate how the cover system impacts it.

2 PILE SCALE MODEL

Acid rock drainage is considered to originate from geochemical reactions on the waste rock surface contacting with water and air. The oxidation reactions of the pyrite can be summarized as

\[
\begin{align*}
2\text{FeS}_2 + 7\text{O}_2 + 2\text{H}_2\text{O} &\rightarrow 2\text{Fe}^{2+} + 4\text{SO}_4^{2-} + 4\text{H}^+ \quad (1) \\
4\text{Fe}^{2+} + \text{O}_2 + 4\text{H}^+ &\rightarrow 4\text{Fe}^{3+} + 2\text{H}_2\text{O} \quad (2) \\
14\text{Fe}^{3+} + \text{FeS}_2 + 8\text{H}_2\text{O} &\rightarrow 15\text{Fe}^{2+} + 2\text{SO}_4^{2-} + 16\text{H}^+ \quad (3)
\end{align*}
\]

Here the transport of reactants to and the removal of reaction products from among finer waste rocks are the keys to determine local geochemical reaction rate and also to estimate the total amount of acid generation in the entire waste rock pile, as those finer rocks have much larger effective surface area than coarse ones. Pile scale mass models are developed in this section to study the water flow, air flow, oxygen and proton transport, and also heat transfer in the finer portions of waste rock pile. The governing equations for these pile scale models are illustrated below. In addition, the coupling relationship between each model is illustrated in Figure 1. More details about the water film model mentioned here can be found in another author’s publication (Ma et al. 2018).

![Figure 1. Couplings in Pile Scale Transport Models](image-url)

2.1 Water and air flow

To describe the pattern of water and air flow in the finer potions of waste rock pile, two phase Darcy’s law was applied to consider the capillary effects from both of air and water pressures. Here the saturation of each phase $S_\alpha$ is defined as the fraction of the pore space occupied by a given fluid:

\[
S_\alpha = \frac{\theta_\alpha}{\phi}
\]
where \( \theta_a \) is the volume content for phase \( \alpha \) and \( \phi \) is the porosity. It is obvious that the sum of the air and water saturations must be equal to one:

\[
S_a + S_w = 1
\]  

(5)

In addition, the definition of effective saturation for phase \( \alpha \) is also given as follow,

\[
S_{ea} = \frac{S_a - S_{a_{min}}}{S_{a_{max}} - S_{a_{min}}}
\]  

(6)

The capillary pressure in the pore is defined as the pressure difference between water and air. At the Darcy scale, the capillary pressure is commonly assumed to be a function of the water saturation:

\[
p_c = p_a - p_w = p_c \left[ S_{ea} \right]
\]  

(7)

The relationship between capillary pressure and water saturation is called the water retention equation, and van Genuchten (1980) introduced a very well-known form for this equation as follows:

\[
p_c \left[ S_{ew} \right] = p_g \left\{ \left( S_{ew} \right)^{1/n_g} - 1 \right\}^{m_g}
\]  

(8)

where \( p_g \) is defined as entry capillary pressure. The exponents \( m_g \) and \( n_g \) are related to the pore size distribution.

By applying the Darcy’s law, the velocities of air and water inside the pile can be determined:

\[
q_{\alpha} = -\frac{k_{\alpha} \left[ S_{\alpha} \right] \left\{ \nabla p_{\alpha} - \rho_{\alpha} g \right\}}{\mu_{\alpha}} = -K_{\alpha} \left[ S_{\alpha} \right] \nabla H_a
\]  

(9)

where \( k_{\alpha} \) and \( K_{\alpha} \) are permeability and conductivity tensors, which depend on the saturation of the phase \( \alpha \). \( H_a \) is the fluid potential.

The permeability for unsaturated condition \( k_{\alpha} \) in Eq.(18) is completely different from that for saturated condition \( k_{s\alpha} \) in the porous structure. If \( m_g = 1/n_g \), the relative permeability functions of water and air phases in the waste rock pile can also be deduced from the water saturation as below:

\[
k_{\alpha} \left[ S_{\alpha} \right] = k_{s\alpha} k_{s\alpha} \left[ S_{ew} \right] = k_{s\alpha} (1 - S_{ew})^{m_g} \left(1 - \left( S_{ew} \right)^{1/n_g} \right)^{2 m_g}
\]  

(10)

\[
k_{\alpha} \left[ S_{\alpha} \right] = k_{s\alpha} k_{s\alpha} \left[ S_{ew} \right] = k_{s\alpha} (S_{ew})^{m_g} \left(1 - \left( S_{ew} \right)^{1/n_g} \right)^{2 m_g}
\]  

(11)

In the waste rock pile, the water density \( \rho_w \) for Darcy’s equation is considered as constant and also the air density \( \rho_a \) can be estimated by:

\[
\rho_{w} \left[p,T \right] = \frac{p_{w}}{RT}
\]  

(12)

where \( R = 8.31447 \text{J/(mol} \cdot \text{K)} \) is the universal gas constant.

2.2 Proton and \( \text{O}_2 \) transport

To investigate the transport of proton related to acid rock drainage processes inside waste rock pile, a general species transport equation is adopted as below:

\[
\frac{\partial}{\partial t} \left[ \theta_{\alpha} C_{\alpha} \right] - \nabla \cdot \left( \theta_{\alpha} D_c \nabla C_{\alpha} \right) + \nabla \cdot \left( Q_{\alpha} \right) = Q_{\alpha}.
\]  

(13)

where \( C_{\alpha} \) and \( D_{c\alpha} \) are the concentration and diffusion coefficient for proton, \( Q_{\alpha} \) is the vector of matrix flow, and \( Q_{\alpha} \) (sink or source term) means generation or consumption rate. Similarly, the supply of oxygen, concentration \( C_{\alpha \text{O}_2} \) to geochemical reactions can be calculated as below:

\[
\frac{\partial}{\partial t} \left[ \theta_{\alpha} C_{\alpha \text{O}_2} \right] - \nabla \cdot \left( \theta_{\alpha} D_{\alpha \text{O}_2} \nabla C_{\alpha \text{O}_2} \right) + \nabla \cdot \left( Q_{\alpha \text{O}_2} \right) = Q_{\text{O}_2}.
\]  

(14)
2.3 Heat transfer

To consider the effect of reactive heat and cycle of ambient temperature on acid rock drainage processes, the equation for heat transfer in the waste rock pile is also included:

$$c_p \rho \frac{\partial T}{\partial t} + c_w \rho_w \nabla \cdot \mathbf{q}_w - \nabla \cdot (k \nabla T) = Q_h$$  (15)

where $c_p$ is the specific heat capacity. $Q_h$ denotes the heat generation rate from geochemical reactions. The effective mass density $\rho$ and the effective thermal conductivity $k$ are defined as:

$$c_p \rho = \phi \rho_w S_w c_w + (1 - \phi) \rho_s c_s$$  (16)

$$k = k_{dy} + \sqrt{S_w \left( k_{wet} - k_{dy} \right)}$$  (17)

where $c_w$ and $c_s$ are heat capacities for water and solid (waste rock particles), and $k_{dy}$ and $k_{wet}$ are the heat conductivities for waste rocks in dry and wet conditions respectively.

3 MODEL VALIDATION

To validate the proposed pile scale transport models, the waste rock pile of Equity Silver mine from the central of British Columbia, Canada was simulated and the calculation results were compared with monitoring data to investigate the main controlling mechanisms in acid rock drainage.

There is approximately 80 million tons of waste rock at the Equity Silver mine, covering an area of approximately 1.4 km². The waste rock dumps have been producing acid rock drainage also with metal ions since the early 1980s (O’Kane et al, 1995; Aziz and Ferguson, 1997; Morin et al., 2010, 2012). To minimize acid rock drainage, a till/soil cover was constructed over the main dump during 1990-1994, with about 1m thickness for preventing the infiltration of ambient water and oxygen into the dump. Historical site records indicate the average annual precipitation is about 600 mm, with approximate 60% of the precipitation occurring as snow generally from November to April. Snow starts to melt in April. Rainy season starts from late April and ceases by the end of June. In the study, the data of precipitation and ambient temperature from 1991 to 2001 (total 10 years) obtained from Environment Canada are adopted as the boundary conditions for the simulation, as shown in Figure 2.

![Figure 2. Precipitation and Ambient Temperature](image)

For simplification, a 2-D cross section from the waste rock pile is simulated in this study. The schematic of the cross section is in Figure 3 with detail geometry information. An onsite monitoring probe is installed at 17m depth on the symmetric axis (the left side of the 2-D section), which is approximately considered as the center of the waste rock pile. According to historical reports, all of the waste rocks were piled up on a bedrock slope (water impermeable). The height of the pile is around 50 m and the width is about 1000 m.
Regarding the initial status for simulation, a transient simulation without the effect of cover system was performed from Jan 1991 to Jan 1994 to get the reactants and products fully distributed within the waste rock pile. Starting from Jan 1994, the effect of till/soil cover was included in the simulation, which is consistent to the completion time for the real cover installation; then the calculation continued until Jan 2001 to simulate seven years for the scenario of the waste rock dump with the till/soil cover. The parameters for the modeling are listed in Table 1.

Table 1. Parameters for modeling

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective air permeability (waste rock)</td>
<td>m²</td>
<td>5.10e-12</td>
</tr>
<tr>
<td>Effective air permeability (cover)</td>
<td>m²</td>
<td>5.02e-9</td>
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<tr>
<td>Entry capillary pressure</td>
<td>Pa</td>
<td>653</td>
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<td>Van Genuchten m parameter (cover)</td>
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<tr>
<td>Van Genuchten m parameter (waste rock)</td>
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<tr>
<td>Van Genuchten n parameter (cover)</td>
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<tr>
<td>Van Genuchten n parameter (waste rock)</td>
<td></td>
<td>1.43</td>
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<td>Hydraulic conductivity of water phase</td>
<td>m/s</td>
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<tr>
<td>Thermal conductivity of dry rock</td>
<td>W/m °C</td>
<td>0.5</td>
</tr>
<tr>
<td>Thermal conductivity of wet rock</td>
<td>W/m °C</td>
<td>3</td>
</tr>
<tr>
<td>Oxygen diffusion coefficient</td>
<td>m²/s</td>
<td>1.76e-5</td>
</tr>
<tr>
<td>Proton diffusion coefficient</td>
<td>m²/s</td>
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</tr>
<tr>
<td>Heat capacity of water</td>
<td>J/Kg/K</td>
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</tr>
<tr>
<td>Heat capacity of rock</td>
<td>J/Kg/K</td>
<td>1139</td>
</tr>
</tbody>
</table>

As the competition of oxygen consumption and oxygen supply is directly related to acid generation rate, we tried to analyze the oxygen concentrations in the pile to understand the limiting factors in acid rock drainage. It is interesting that the historical monitoring data (oxygen concentration) from the probe has annual fluctuations. This “respiration” phenomenon is believed to be the results of annual cycle of ambient temperature, as temperature change has the same frequency. The change of ambient temperature significantly impacts the air density on the pile surfaces thus may influence the air flow pathway and also oxygen supply inside the full-scale waste rock pile.

Figure 4 shows the comparison of oxygen concentration at the probe between measurement and simulation. It should be addressed again that the effect of cover is applied to the model starting from Jan 1994 for the simulation, while the real full-scale cover onsite was installed during 1990 to 1994. The simulation before Jan 1994 was just the initialization stage to achieve relative stable stage of acid generation and storage in the pile. Starting from Jan 1994, the simulated oxygen concentration shows a similar fluctuation pattern to that observed from measurement: higher concentration in winter time and lower concentration in summer time.
Measurements are missing from winter 1996 to spring 1997, but we believe that the oxygen concentration rose during this period based on its historical trend. Another observation is that the simulated oxygen concentration on average decreased during the first several years after the installation of the cover, while the site monitoring also showed a similar downwards trend.

![Figure 4. Comparison of O$_2$ concentration between simulation and measurement](image)

The explanation for the lower O$_2$ concentration status after the installation of cover system is that the cover changed the air flow pathways in the waste rock pile. Figure 5 top shows the oxygen concentration and the air flow driven by convection in Dec 1993, right before the cover installation in the simulation. It indicates that the fresh air came into the waste rock pile through the right bottom toe and most eventually escaped from the top of the pile. Figure 5 bottom illustrates the air flow pathway in Dec 1996. The results indicate that the low permeability of the cover blocked the main air flow outlet on the top side and the air had to circulate within the waste rock pile and went out through the toe, which significantly increased the length of air pathway compared with uncovered status. Generally, longer air flow pathway indicates insufficient oxygen supply and lower oxygen concentration status. In addition, oxygen is not able to diffuse through the top surface in outflow conditions (uncovered), while the air circulation scenario (covered) makes it possible for oxygen diffusion through the top surface, especially for heavier air conditions in winter time. As a result, O$_2$ concentration in the pile starts to have annual cycle with seasonal temperature fluctuation.

![Figure 5 Simulated airflow pathway in the pile](image)

In addition, the total amount of acid generated rate from the geochemical reactions within the 2D cross section is illustrated in Figure 6, which indicates a similar downward trend like
oxygen concentration shown above. The decrease trend of total acid generation rate is also reflected by the real consumption of lime to neutralize the acidities in the water treatment facility.

![Graph showing lime consumption vs total acid generation rate](image)

Figure 6. Lime consumption vs total acid generation rate

Note that there are still a lot of unknowns at the site, such as waste rock pile construction history, rock size distribution, underground water flow pattern and rate, rain infiltration rate, water content distribution, and microbial activities inside the waste rock pile. The unknowns are either due to lack of characterization data or difficult to measure on site. Therefore it’s difficult to exactly match the models against the monitoring data. But matching with the trend of the monitoring data can still reveal the controlling mechanisms to the acid rock drainage generation processes.

4 CONCLUSIONS

To gain a comprehensive understanding of the physical and geochemical processes involved in acid rock drainage generation process, a set of mathematical models are coupled to simulate the transport of reactants and products in the waste rock piles. The full-scale waste rock pile from Equity Silver mine is used to validate the proposed model. The observations from the simulation results are generally consistent with the monitoring data, which reveals the air flow pathway in the waste rock pile. Through analyzing the simulation data, the function of the cover system for the waste rock pile was investigated and discussed in this paper. The proposed models are capable of capturing the main acid rock drainage geochemical and physical mechanisms. Therefore, these models can be an effective tool to optimize waste rock pile configurations and evaluate the design of cover systems to reduce acid rock drainage generation.

ACKNOWLEDGEMENTS

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REFERENCES


Pile Scale Models for ARD Prediction -
- Case Study on Equity Silver Mine

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Oct 1, 2018
The NRC Canada comprises:

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Environmental Advances in Mining program

- ARD / ML Prediction and Prevention
- Mine Effluent Treatment
- Environment Friendly Extraction Processes
- Mine Closure & Reclamation
- Sensing and Monitoring
**1 Objective: Fundamentals in ARD/ML**

**Step 1 Geochemical Reaction**

**Step 2 Leaching Process**

Step 1: Oxidation of sulphide minerals

\[ 2FeS_2 + 7O_2 + 2H_2O \rightarrow 2Fe^{2+} + 4SO_4^{2-} + 4H^+ \]

Oxygen?  Water?
Look into Monitoring Data:

Oxygen Concentration Profile

Moisture Content Profile*

*Saretzky, G.T., Hydrological Characterization of a sulphide waste rock dump, Master thesis of University of Saskatchewan, 1998
Step 2: Drainage Leaching - Water Flow Type

Rate-Control Quotient of Mineral Dissolution from Waste Rock Dumps – Simon Liu
B.C.’s 41st Annual Mine Reclamation Symposium
2 Modeling ARD Reaction

- Air Flow
- Reactive Heat
- Ions Transport
- Pore Water Flow
- Reactant (O2) Supply
- Geochemical Reaction
3 Case Study on Equity Silver Mine
Total Precipitation and Ambient Temperature
From Jan 91 to Jan 01
Measured and Simulated O2 concentration at 17 m depth of P-7 point
Oxygen Concentration and Air Flow Direction

Dec 1993 (Before Cover Installation)
Oxygen convection and diffusion fluxes at Top and Slope Surfaces:
Total Acid Generation Rate vs Lime Consumption (Step 2 involved):
4 Conclusions

- O2 controls the total geochemical reaction rate
- Channel flow controls the leaching of reaction products
- Cover system extends the air flow pathway in the pile
- Optimization of the pile/cover configuration by using modeling iterations leads to the reduction of total acid generation in the pile
The End

Questions?