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In mine rock storage facility design, advective oxygen transport is king, but diffusion is queen

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Abstract

The concept is that through an established mine rock storage facility (MRSF) design and construction method a reduction in advective oxygen transport is achieved. This limits sulfide oxidation and the generation of stored acidity with a desired advantage of a reduced reliance on the final cover system and / or duration over which water collection and treatment may be required. In general, bottom-up MRSF construction is favoured over top-down construction due to the reduced overall airflow capacity and oxygen supply.

Mechanisms of oxygen ingress include diffusion, advection (in air and water), and barometric pumping. It has been generally accepted that advective air transport provides at least an order of magnitude greater oxygen supply than the other noted transport pathways. Advective airflow occurs when the air within the mine rock pores warms up, becoming less dense compared to the surrounding atmosphere. As a result, it starts to rise, drawing in cooler air at the toe of the facility.

While the aforementioned is certainly true, this paper provides a more comprehensive assessment of advective and diffusive oxygen transport in a Top-Down and Bottom-Up MRSF. Two-dimensional numerical simulations (oxygen consumption, water, air, and heat transport) were completed using a generalized MRSF and boundary conditions based on an information and literature review and supported by a blind study. In the Top-Down construction advective oxygen transport through the MRSF slope face was approximately five time greater than diffusion. Elevated mine rock pore-oxygen concentrations in the slope face supressed the concentration gradient that drives diffusion. However, across the plateau diffusive oxygen transport exceeded advection. Diffusive oxygen on the plateau accounted for approximately 30% of the total oxygen ingress, driven by a steeper pore-oxygen concentration gradient. Bottom-Up construction reduced the overall oxygen ingress by approximately 40% compared to the Top-Down MRSF. While advective oxygen ingress in the Bottom-Up construction was lower than the Top-Down analysis, this gain was offset by an increase in diffusive oxygen.

Results of this analysis highlight that coupled diffusive and advective oxygen transport should be considered in assessment of MRSF construction methods and the ratio of the MRSF slope to the plateau area will have a marked influence on simulated performance. In addition, there is a need to disseminate two-dimensional analysis to a three-dimensional outcome. This is due to bottom-up construction providing an initial overall larger footprint/surface area exposing a greater amount of mine rock over longer time frames to diffusive oxygen, which may moderate the benefit of bottom-up construction.

Keywords: *Mine rock storage facility, construction methods, bottom-up and top-down, advection, diffusion, oxygen consumption, sulfide oxidation, mine closure, progressive reclamation*

1 Introduction

There is a marked interest in the mining industry in the use of source control strategies in the design, construction, and closure of mine rock storage facilities (MRSFs). A key aspect driving this interest is MRSFs carry a high proportion of a sites metal leaching and acid rock drainage (ML/ARD) risk, which is noted to be in the range of 60% to 80% (O'Kane, 2017). There is also a greater emphasis on Social License To Operate in assessing current or future operations where closure risks are managed during operations and not deferred to closure. Over the past two decades there has been a substantial advancement using vadose zone hydrology in the design of cover systems for closure of mine rock and tailings facilities, and now there is a similar push towards the use of vadose zone hydrology in source control for MRSF construction methods. To support this effort guidance documents have been updated, such as the INAP (2020) mine rock placement strategy document. MRSFs have been instrumented with field performance monitoring systems to better understand airflow in the base case and alternate construction methods (Meiers, 2020 and Pearce and Barteaux, 2014). There has been a push to advance the concept of Best Available Technology in progressive reclamation to include MRSF design (Meiers and O'Kane, 2018). Additionally, a key aspect of advancing MRSF source control strategies is demonstrating performance through numerical simulation tools to enable informed operational and closure decisions. Numerical simulation models have been improved to better incorporate the hydraulic, airflow, heat, and geochemistry aspects of MRSF assessment (Meiers et. al., 2022).

Mechanisms of oxygen ingress include diffusion, advection (in air and water), and barometric pumping. It has been generally accepted that advective air transport provides at least an order of magnitude greater oxygen supply than the other noted transport pathways (Fala et. al., 2003 and Wilson, 2008). Advective airflow occurs when mine rock pore-air warms and becomes less dense compared to the surrounding atmosphere and starts to rise drawing in cooler air at the toe of the facility. The exfiltration of pore-air from the toe of MRSFs has also been noted to occur in the warmer summer months (Hockley et. al., 2009).

MRSFs source control focusses on restricting advective oxygen supply and sulfide oxidation over the construction period. The idea is that through reduction of oxygen ingress (i.e., stored load of oxidation products) ML/ARD can be optimized. This reduces ML/ARD risk at closure, increasing the likelihood of meeting closure objects for geochemical stability, reduces reliance on the final cover system, and duration/requirement for collection and treatment. As previously noted, the current conceptual model for advective oxygen supply is that the rate of advective oxygen is one order of magnitude greater than diffusive supply.

When considering MRSF source control it is important to note that the majority of MRSFs will not have an infinite source of finer textured materials. As such the construction of design elements focuses on materials that will impede airflow but not likely maintain a high enough degree of saturation to manage diffusive oxygen. This paper summarizes the simulated advective and diffusive oxygen transport using a Top-Down and Bottom-Up construction strategy. The simulated results highlight that diffusive oxygen should be included in assessing the performance of alternative construction methods for MRSF source control. An additional step of scaling up two-dimensional simulated results to three-dimensional mine rock placement is not included in this paper, where it is noted that Bottom-Up placement may expose a larger proportion of mine rock to diffusive oxygen.

2 Numerical simulation model

Numerical simulations were carried out using SOILVISION Edition V10 (Bentley Inc. 2020). SOILVISION is a numerical finite element model that can be used to solve one-, two-, and three-dimensional boundary-value seepage (SVFLUX), heat (SVHEAT), airflow (SVAIR), and mass transport (SVCHEM) problems. The software solves the partial differential equations for steady state and transient saturated-unsaturated seepage, heat, airflow, mass transport through a porous medium. SOILVISION software utilizes FlexPDE solver that is highly automated with adaptive mesh refinement to solve highly non-linear, partial differential equations, such as those encountered when solving unsaturated flow, heat, airflow, and mass transport coupling.

Unsaturated seepage analysis was conducted to simulate the degree of water and air saturation of the placed mine rock and engineered layers. This was used as an input to the airflow and heat coupling (SVAIR and SVHEAT) simulation. The resulting airflow was subsequently used as an input to simulate the oxygen mass transport and consumption (SVCHEM).

The numerical simulation of airflow generated by air pressure and temperature gradients is implemented via SVAIR and SVHEAT coupling. Heat production related to sulfide oxidation, which increases the temperature and leads to thermal air convection, is implemented based on the oxidation consumption rate.

2.1 MTSF geometry

Top-Down and Bottom-Up placement methods were compared to demonstrate how airflow, thus oxygen ingress, can be reduced during operations. The assessment included diffusive and advective oxygen transport. The overall mesh geometry of the Top-Down and Bottom-Up MRSFs are shown in Figure 1 and Figure 2, respectively. The MRSF has a height of approximately 210 m with a basal length of approximately 1,100 m. The Top-Down construction includes a 15 m thick rubble zone at the base of the facility, extending over approximately 50% of the basal length. Each lift in the Bottom-Up construction is 28 m with a 2.0 m engineered layer on the top of each lift.

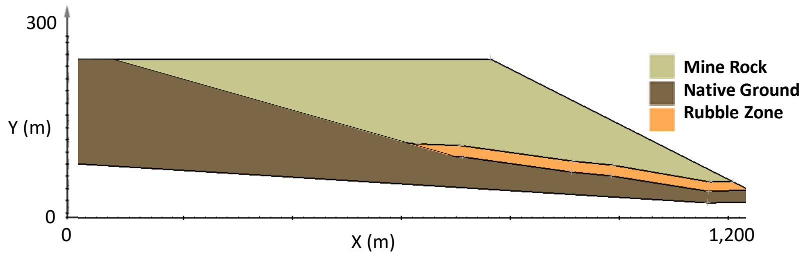

Figure 1 MRSF top-down section geometry

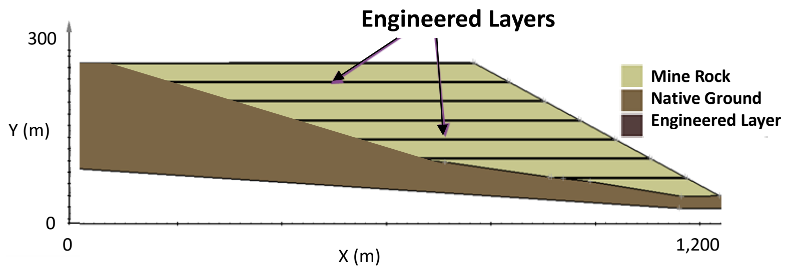

Figure 2 MRSF bottom-up section geometry

The transient numerical simulations were completed in four stages with an estimated mine rock placement rate of 9,000 m^3/yr in a two-dimensional cross-section with a width of 1 m. Due to the geometry of the slope or native ground in the 2D assessment, the two MRSFs provided a similar surface area over the construction period.

2.2 Material properties

The particle size distribution (PSD) was used to establish hydraulic and pneumatic properties. In general, mine rock representing the bulk of the MRSF volume is defined as having less than 10% silt and clay sized particles (referred to as fines, <0.076 mm), 5% to 35% sand-sized particles and 60% to 95% gravel, cobbles and boulders based on the Unified Soil Classification System. The material for constructing engineered layers in the Bottom-Up construction had a fines content of 20%.

Regarding the primary hydraulic properties, the following were considered: saturated hydraulic conductivity (Ksat), water retention curve (WRC), and hydraulic conductivity function (k-function). WRCs were determined using geotechnical index properties (void ratio, specific gravity, and density) along with comparison of the SoilVision Systems Inc. database of measured particle size distributions and WRCs (Fredlund et al. 2002). The WRC used in the numerical simulations were further updated with laboratory tests and field measurements.

The k-functions were developed according to the method described by Fredlund et al. (1994) using SVSoil (Bentley Inc. 2020). The method uses the Ksat and WRC estimated through the continuous mathematical function developed by Fredlund and Xing (1994). The Fredlund and Xing (1994) equation encompasses typical mine rock and can fit the entire range of suctions (Fredlund et al., 2002).

Air permeability functions (air-function) were developed using the SVSoils (SOILVISION, 2018) database and are shown in Figure 3. The air conductivity (ka) was estimated using hydraulic conductivity with the following expression.

$$k_a = \frac{k_{sat}\rho_a\mu_w k_r}{\rho_w\mu_a} \tag{1}$$

where:

ksat = saturated hydraulic conductivity, m/s,

ρa = air density, kg/m^3

µw = water dynamic viscosity, kg/m-s

µa = air dynamic viscosity at the given temperature, kg/m-s,

ρw = water density, 1,000 kg/m^3

The effect of water saturation on the air conductivity is evaluated using a coefficient of air relative permeability (kr) that is calculated using van Genuchten (1980) and Mualem (1976) approach:

$$k_r = (1 - S_e)^{1/2}\left(1 - {S_e}^{1/M}\right)^{2M} \tag{2}$$

where:

Se = effective degree of water saturation based on the result of seepage analysis

M = fitting parameter with van Genuchten WRC method, 0.9.

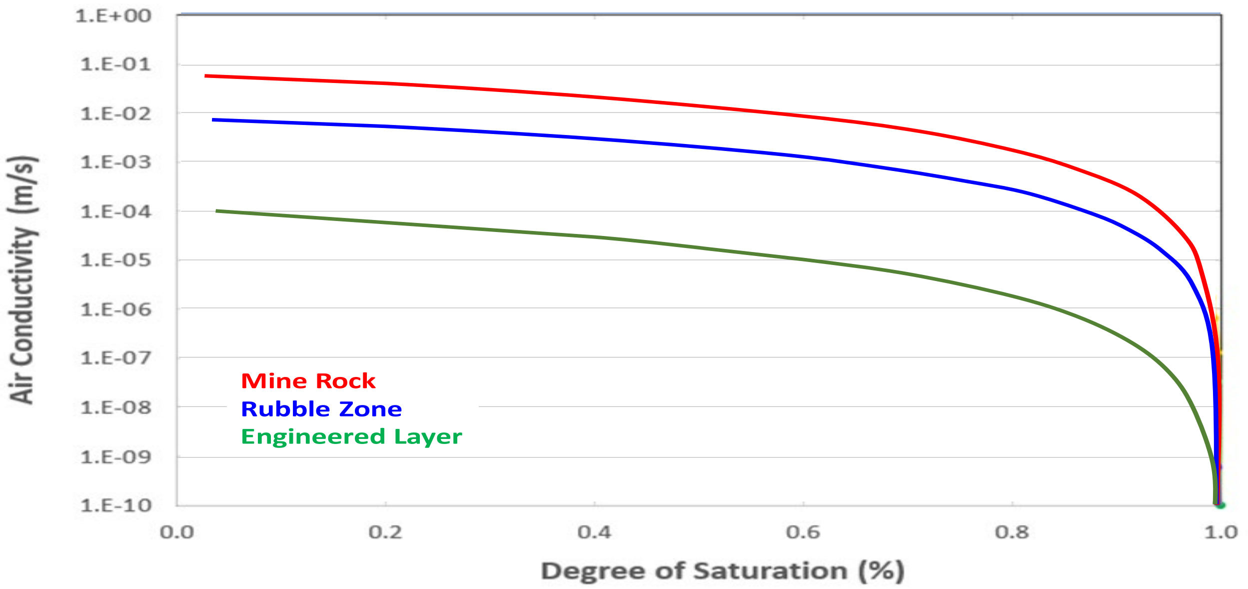

Figure 3 Air-functions used in the MRSF numerical simulations

The heat capacity was estimated according to the fraction and heat capacity of water, ice, and solid component following Jame (1977) and Newman (1995). Thermal conductivity was established using the method by Johansen (1975). A thermal conductivity of 150,00 J/day/m/°C and a heat capacity of 1,800,000 J/day/m/°C were used.

The conceptual model for MRS facilities is that heat is generated due to the oxidation of sulfides. The heat source results in a decrease in the pore-gas density, which influences airflow. The heat source generated in the chemical oxidation reaction is estimated according to the following:

Heat source (J/m^3/day) = exothermic generation rate (J/mol) / air molecular weight (kg/mol) × oxidation rate (kg/m^3/d)

The air molecular weight is taken as 0.0288 kg/mol, and the value of exothermic generation rate is 400 kJ per mole of oxygen consumed. A laboratory oxygen consumption rate of 3.5x10^{-8} kg/t/s was used, and a dry density of 1,863 kg/m^3 was applied to estimate tonnage per cubic meter, along with a Zero-Order Rate of 5 g/m^3/d. The dry density was estimated from reported void ratio and specific gravity values. The oxygen consumption rate used in the analysis was derived by assigning a scaling factor of 0.1 to the laboratory test Zero-Order Rate to account for grain size corrections and potential change in the oxidation rate over time and are as follows. The oxygen consumption rate used in the analysis was 0.5 g/m^3/d.

2.3 Boundary conditions

Meteorological conditions are used to establish temperature and pressure boundary conditions for the simulation model. A mean annual temperature of 1.0 °C was used. The upper boundary pressure conditions adopted a pore air pressure of 0 kPa at the base of the model and -2.65 kPa at the crest. The atmospheric oxygen concentration along the outer boundary is 280 g/m^3 (corresponding to 20.9 vol.% oxygen). A net infiltration rate of 500 mm/yr was distributed over 365 days and applied as a constant seepage flux condition along the outer boundary. The mine rock was assigned an initial temperature of 5°C.

3 Numerical simulations

Transient numerical simulations were carried out to evaluate the MRSF construction sequence on advective and diffusive oxygen ingress and load of potential stored oxidation products. The simulations were carried out over a 15-year construction period in four stages with an estimated mine rock placement rate of 9,000 m^3/yr. Each period in the Bottom-Up and Top-Down methods was arranged to maintain a progressive increase in the cross-section area, which reflects the mine rock placement rate. Given the alternate geometry the progressive increase in the cross-section area was similar but not exactly the same.

3.1 Diffusive and advective results

Results of the Top-Down transient analyses for the plateau and slope are summarized in Figure 4. The simulated pore-oxygen concentrations and internal temperature of the Top-Down facility was calibrated to monitored internal MRSF conditions. The advective flux of oxygen through the slope is approximately five times greater than diffusion. The cumulative advection and diffusion flux into the slope is 109,040 kg and 18,700 kg, respectively. The rate of advective oxygen supply increases after year five in response to an increase in vertical temperature and pressure gradients.

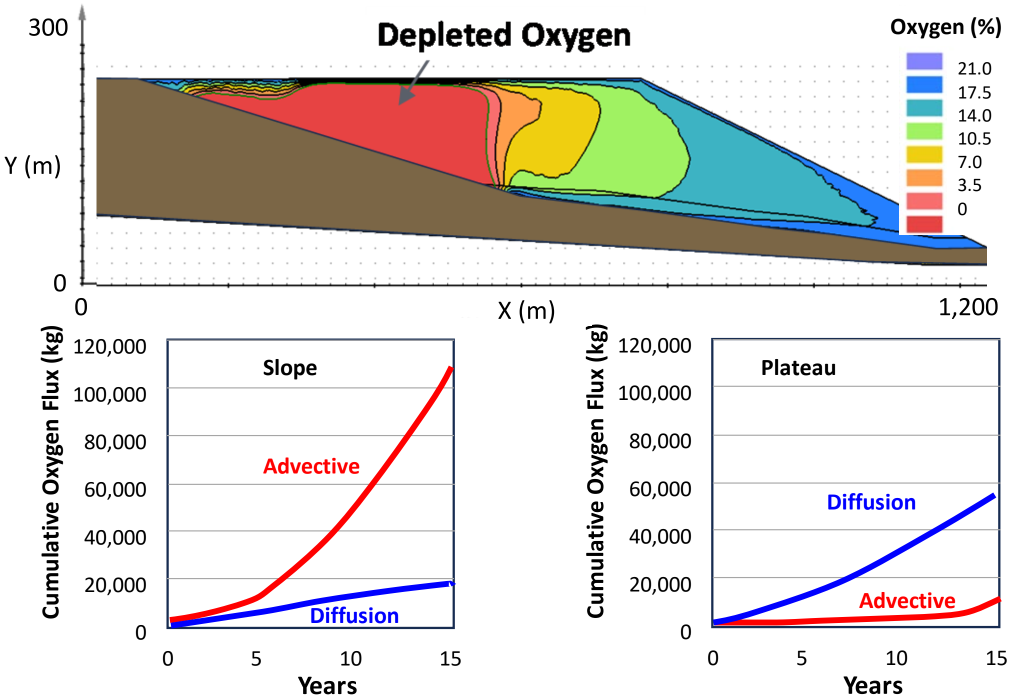

Figure 4 Top-down transient simulation showing simulated pore-oxygen concentration and advection and diffusion for the plateau and slope

The cumulative advection and diffusion flux into the plateau are 8,300 kg and 61,200 kg, respectively. This lower rate of advection is in part due to the exfiltration (i.e., negative airflow) of air on the plateau and larger concentration gradients driving diffusion. The diffusive flux at the plateau is 87 kg/m^2 (61,200 kg) approximately 40% of the advective flux for the slope, which is 218 kg/m^2 (109,040 kg).

An additional key aspect related to the simulated performance is the advective flux at the plateau. It is observed that the rate of advective oxygen on the plateau starts to increase in year 13. At this preliminary stage it is uncertain if the increase is related to an increase in temperature and differential pressure or the fact that there is a greater proportion of mine rock further back from the toe / rubble zone of the MRSF (longer basal length). This similar trend was observed in the blind study for which the aforementioned simulation is based. It was noted in the blind study that the advective airflow rate on the plateau increased to nearly 50% of that observed on the slope. This highlights that there is value in extending the simulation beyond the construction period to gain insight into long term airflow dynamics. It also highlights that with larger MRSFs that have a longer basal length or where airflow is restricted at the toe, advection across the plateau may increase to satisfy the internal low-pressure condition.

The simulated advective and diffusive oxygen ingress for the Top-Down and Bottom-Up assessments are summarized in Figure 5. Advective oxygen supply in the Bottom-Up facility is 15,100 kg or approximately 14% of that simulated for the Top-Down construction. The lower advective oxygen supply in the Bottom-Up facility is due to the lower air permeability of the engineered layers. Diffusion is greater for the Bottom-Up compared to the Top-Down construction primarily due to the larger concentration gradients that drive diffusion across the interface. Total oxygen ingress for the Bottom-Up construction is approximately 40% lower than the Top-Down construction; hence, it can be inferred that the store load of oxidation products for the Bottom-Up would be lower.

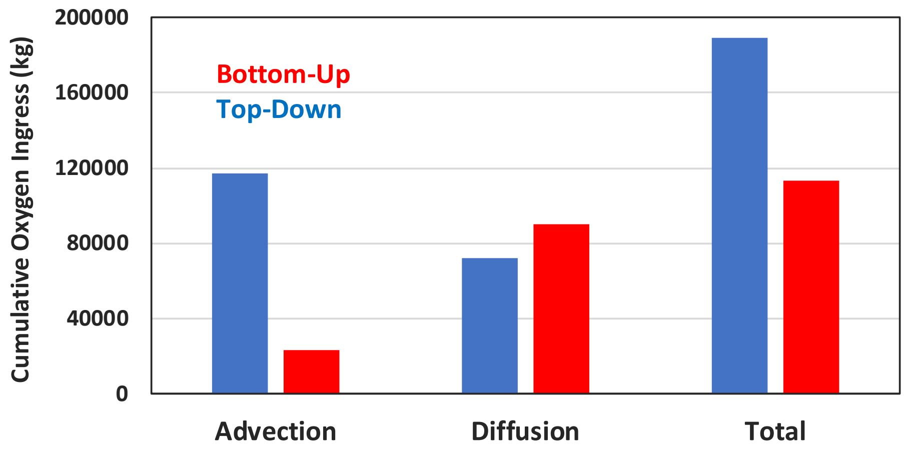

Figure 5 Advective and diffusive oxygen ingress over the 15-year construction period for the Bottom-Up and Top-Down scenarios

Oxygen ingress due to diffusion for the Bottom-Up facility was estimated at 135 mol/m^2/yr, which suggests that the engineered layers have limited effect on attenuating diffusive ingress (INAP, 2017). Advection on the slope for the Top-Down and Bottom-Up was estimated at 475 mol/m^2/yr and 65 mol/m^2/yr. This highlights that while the engineered layers are effective at reducing airflow, diffusive transport is virtually unrestricted. In order to manage diffusive oxygen finer textured materials would be required that retain higher degree of saturations.

4 Conclusion

The simulated performance of alternate MRSF construction methods highlights the benefits of source control in terms of reducing oxygen consumption and hence the ML/ARD risk at closure. The simulated results also highlight the importance of including diffusion in any assessment, given its overall potential contribution to sulfide oxidation. The diffusive assessment was coupled with the simulated advective pore-oxygen concentrations. As a result, there was a realized increase in the diffusive oxygen in response to a decrease in advective oxygen supply. This suggests that, in some situations, as advective airflow is reduced using alternate construction methods, there may be a slight compromise in the benefit gained.

While the primary advective airflow is inward through the basal rubble zone and slope, it is noted that the exfiltration of airflow at the plateau can, to some extent, reverse direction providing an additional point of inflow to a MRSF. This was observed to occur later in the construction period and anticipated to be associated with an increase in the basal length and internal temperature. This is an important aspect in that while there is generally a focus on reducing airflow into the rubble zone, larger MRSFs will likely have additional advective airflow entry points driven by the low internal pressure condition. This represents a slight variation to the current conceptual model of MRSF airflow.

The simulated two-dimensional assessment, to some extent, does not fully capture differences in the three-dimensional surface area of the MRSFs built using the Top-Down and Bottom-Up placement methods. In general, Bottom-Up construction provides a larger initial surface area and would exposes more rock to oxidative conditions. Hence, the inclusion of phased construction with a three-dimensional MRSF in which two-dimensional cross section are based, would allow scaling of oxygen ingress rates to a landform surface area. This additional step would further advance the interpreted performance of the simulated MRSFs and could potentially attenuate the benefit of Bottom-Up construction. An expanded field program to monitor the in-situ conditions of MRSFs reflective of the Top-Down construction is also being proposed.

References

Bentley Systems Incorporated. 2020, SOILVISIONTM CONNECT Edition V10 (SES), Pennsylvania, United States, PA 19341

Fala, O, Aubertin, M, Molson, J, Bussière, B, Wilson, W, Chapuis, R, and Martin, V, 2003, Numerical Modelling of Unsaturated Flow in Uniform and Heterogeneous Mine Rock Piles. In “Proceedings of the Sixth International Conference on Acid Rock Drainage”, Cairns, Australia, 14-17 July (Eds. T Farrell and G Taylor), pp. 895-902. Australian Institute of Mining and Metallurgy, Carlton, Victoria.

Fredlund, M,D, Wilson, G,W, and Fredlund, D,G, 2002, Use of the grain-size distribution for estimation of the soil-water characteristic curve, Canadian Geotechnical Journal 39 (5):1103-1117.

Fredlund, D.G. Xing, A. & Huang, S. 1994, Predicting the permeability function for unsaturated soils using the soil-water characteristics curve. Canadian Geotechnical Journal 31(3):533-546.

International Network for Acid Prevention (INAP) 2020, Global cover system design technical guidance document, November

International Network for Acid Prevention (INAP) 2020, Rock placement strategies to enhance operational and closure performance of mine rock stockpiles, Report No. 1977.03.04, January

Hockley, D, Kuit, W, Phillip, M, 2009, Sullivan Mine Fatalities Incident: Key Conclusions and Implications for Other Sites. 8th International Conference for Acid Rock Drainage, June 22-26, 2009

Jame, Y,W, 1977, Heat and Mass Transfer in Freezing Soil. Ph.D Thesis. University of Saskatchewan

Meiers, G, Pernito, M, and Bianchin, 2022, An optimized approach to progressive reclamation that includes assessment of mine rock storage facility construction methods – Development of a simulation model, Tailings and Mine Waste Conference, Novembre

Meiers, G, 2020, A Case Study of the Influence of Shorter Tips in Mine Rock Storage on Internal Air Flow Capacity, Presentation given at BC-MEND December 1-3, 2022

Meiers, G, and O’Kane, M, 2018, Progressive Mine Reclamation is Considered Best Available Technology…Can We Enhance this Practice to Include Mine Rock Facility Design. 2nd International Conference on Planning for Closure of Mining Operations. Santiago Chile, November

Newman, P, 1995, Heat and Mass Transfer in Unsaturated Soils During Freezing. M.Sc Thesis, University of Saskatchewan

Mualem, Y, 1976, A new model predicting the hydraulic conductivity of unsaturated porous media. Water Resour. Res. 12:513–522.

O’Kane M, Weber P, McKeown M, Christensen D, Miller S, Bird B, 2017, Forecasting long term water quality after closure: Boliden Aitik Cu Mine. Bell LC, Edraki M, Gerbo C. (eds) Proceedings of the Ninth Australian Workshop on Acid and Metalliferous Drainage, 20-23 November 2017, Burnie, Tasmania, 197-205

PDE Solutions Inc. 2021, FlexPDE 7.19. Spokane Valley, WA 99206

Pearce, S, Barteaux, M, 2014, Instrumentation in waste rock dumps: Going deeper. Proceedings of the Eighth Australian Workshop on Acid and Metalliferous Drainage, April 24, 2014

van Genuchten, M, 1980, A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44:892–898.

Wilson, W. 2008, Why are we still battling ARD. In "Proceedings of the Sixth Australian Workshop on Acid and Metalliferous Drainage", Burnie, Tasmania. 15-18 April 2008. (Eds LC Bell, BMD Barrie, B Baddock, and RW MacLean) pp 101-112 (ACMER: Brisbane).