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Prediction of Acid Rock Drainage in Waste Rock Piles

Part 2: Water Flow and Leaching Process

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Abstract

In waste rock piles, the leaching process involved in acid rock drainage is mainly controlled by water flow especially preferential flow. This paper (Part 2) investigates the effects of heterogeneities on the water flow by applying probability density functions to hydrogeological properties. A piecewise constant distribution is proposed to describe the permeability inside waste rock piles, which reflects the effect of both finer and coarser pores. Compared with uniform water flow obtained from traditional homogeneous modeling, various water flow patterns/pathways inside waste rock piles can be simulated by the proposed model. In addition, the leaching process is also investigated by coupling the calculated water flow with the geochemical reaction based on the water film model proposed in Part 1. For validation, these models are integrated and applied to the full-scale waste rock pile at Equity Silver mine in British Columbia, Canada. Because the iron loading is highly correlated to the acidity at this site, it is found that the fluctuation of annual lime consumption for neutralization at this site can be well predicted by the integrated model. In addition, the results indicate that waste rock piles with non-identical permeability distributions but with the same probability density function may have different water flow patterns and iron concentration distributions inside the pile. However, the total water flow discharge rate and iron loading profiles from the pile are almost the same in the temporal scale.

1 Introductions

Surface hard rock mines usually generate a huge amount of waste rocks during mining process. Over time, waste rocks are deposited into the storage facility such as waste rock piles. Some waste rock piles may create significant environmental footprints as they could contain over one hundred million tons and cover a few hundred hectares. When sulfide minerals enclosed in waste rocks are exposed to open environment and accessed by air and water, they oxidize gradually, generate protons and further dissolve metal ions into the water flowing through. This geochemical and transport process is called acid rock drainage and metal leaching (ARD-ML) (Parbhakar-Fox and Lottermoser, 2015; Dold, 2017). It is believed that ARD-ML is mainly controlled by two factors: the geochemical reaction and the water flowing through. Part 1 of this series paper has discussed the geochemical reaction by proposing a new water film model to consider the impact of water film thickness, oxygen concentration as well as geochemical kinetics on the total product generation at the particle level. This paper (Part 2) focuses on describing the water flow inside the waste rock piles, and how the water flow transports those generated geochemical products out of the piles.

In Part 1 paper (Ma et al., 2019), a pile-scale mass transport model including water and air flows, reactant/product transport and heat transfer coupled with the proposed water film model have been proposed and validated through a field scale case study. Similar to other modeling studies (da Silva et al., 2009; Lefebvre et al., 2001a; Lefebvre et al., 2001b; Mayer et al., 2002) , the mass transport models in Part 1 assumes that waste rock properties are distributed homogeneously within the whole pile so that all parameters related to the waste rock properties are set to constant in spatial scale. But in real field conditions, those properties especially hydrological properties for waste rocks are naturally heterogeneous as their particle size may vary from several micrometers to several meters. For example, Li (1999) found that the field waste rock piles are usually complex structures and the heterogeneity can result in layers with large ranges of particle sizes and/or physically distinct layers. These heterogeneous features of full-scale waste rock piles have been known and documented for many decades (Morin et al.,

1991). The heterogeneity may create local higher permeability pathway for water to flow through with higher speed. This phenomena is commonly called as preferential flow (Muniruzzaman and Pedretti, 2020) which has been widely observed in many waste rock piles (Trincherio et al., 2011; Eriksson et al., 1997). In terms of the volumetric percentage of the preferential flow in waste rock piles, Hendrickx and Flury (2001) identified that it is only a small fraction of the pore space. However, Ma et al. (2020) found that the total drainage water discharged from the piles are mainly from preferential flow. As a result, the heterogeneous hydrological properties inside waste rock piles and the resulted various water flow pattern especially preferential flow should be included in modeling for better prediction of ARD-ML.

For modeling various water flow patterns inside waste rock piles, Molson et al. (2005) and Fala et al. (2005) found that preferential flow channels can be reproduced from mesh grid orientation effects of the geometry model. In terms of physical mechanisms of water flow, it is believed that the heterogeneous distribution of permeability generates various flow patterns through waste rock piles. Pedretti et al. (2020; (2017) developed a conceptualized stochastic modeling framework based on assuming a bundle of stream tubes inside waste rock piles to assess the impact of heterogeneity of minerals and hydraulic conductivity. Lahmira et al. (2017) divided waste rock into four groups with different water retention properties based on different grain sizes (coarse, intermediate, fine and very Fine) and randomly distributed them in to the mesh grids of pile geometry to simulate preferential water flow pathways. However, the real permeability distribution should be continuous rather than discrete in nature, and may follow some specific distribution pattern. In addition, discrete permeability boundaries between different mesh grids could create significant computational hardness.

This paper adopts the concept of probability density function to describe distributed permeability on the 2-D cross-section of waste rock piles. To consider the impacts from both of finer pores and coarser pores, a piecewise constant distribution is proposed to describe the permeability in waste rock piles. Compared

with traditional homogeneous modeling, the distribution of permeability can be realistically defined and controlled, and the water flow pattern/pathways and the leaching processes are possible to be well simulated in the piles. The proposed water flow model is further coupled with the geochemical reaction calculated from the water film model proposed in Part 1, and applied to a full-scale waste rock pile to predict the annual lime consumption onsite.

2 Conceptual models

2.1 Water and air flows

As waste rock piles are built with rock particles, it is naturally porous and the saturation of air phase or water phase inside waste rock piles is denoted by S_α , which is defined as the fraction of the pore space occupied by that phase:

$$S_\alpha = \frac{\theta_\alpha}{\phi} \quad (1)$$

where θ_α is the volume content [-] for phase α , and ϕ is the porosity [-]. Here the sum of the air (a) and water (w) saturations is equal to unity:

$$S_a + S_w = 1 \quad (2)$$

Furthermore, the effective saturation for phase α is defined as

$$S_{e\alpha} = \frac{S_\alpha - S_\alpha^{\min}}{S_\alpha^{\max} - S_\alpha^{\min}} \quad (3)$$

where S_α^{\min} and S_α^{\max} are minimum and maximum saturations for phase α , respectively.

At the Darcy scale, the capillary pressure p_c in the pore is defined as the pressure [M/L/T²] difference between water and air:

$$p_c = p_a - p_w \quad (4)$$

van Genuchten (1980) introduced an equation to estimate the relationship between capillary pressure and the effective water saturation as

$$p_c = p_g \left((S_{ew})^{-1/m_g} - 1 \right)^{1/n_g} \quad (5)$$

where p_g is defined as the capillary entry pressure. The exponents m_g and n_g are the coefficients [-] related to the pore size distribution.

The permeability [L²] under unsaturated conditions k_α is generally far less than saturated conditions $k_{s\alpha}$ in the porous waste rocks. If m_g in Eq.(5) is assumed to be equal to $1 - 1/n_g$, the unsaturated permeability can be calculated by the form proposed by Mualem (1976):

$$k_a = k_{sa} (1 - S_{ew})^\kappa \left(1 - (S_{ew})^{1/m_g} \right)^{2m_g} \quad (6)$$

$$k_w = k_{sw} (S_{ew})^\kappa \left(1 - \left(1 - (S_{ew})^{1/m_g} \right)^{m_g} \right)^2 \quad (7)$$

where the connectivity factor κ can be treated as a fitting parameter [-] of the model.

By applying Darcy's law, \mathbf{q}_α are the velocities [L/T] of air and water inside the pile and they can be determined by using:

$$\mathbf{q}_\alpha = -\frac{k_\alpha}{\mu_\alpha} (\nabla p_\alpha - \rho_\alpha \mathbf{g}) \quad (8)$$

where k_{α} is the unsaturated permeability for phase α . μ_{α} is the viscosity [M/LT] for phase α , \mathbf{g} is the gravity vector [L/T²], ρ_{α} is the density [M/L³] for phase α .

Additional mass conservation laws for both of air and water phases are applied to ensure that the Darcy's equations are closed.

$$\frac{\partial}{\partial t}(\rho_{\alpha} S_{\alpha}) + \nabla \cdot (\rho_{\alpha} \mathbf{q}_{\alpha}) = 0 \quad (9)$$

2.2 Finer pores and coarser pores

As the pore size in the waste rock piles is randomly distributed, it is generally believed that the permeability inside waste rock piles should have certain kinds of distribution pattern. This means that the porosity ϕ and all parameters related to water retention in Eqs.(6, 7) should not be considered as constants like many traditional modeling studies have done.

In real situations, the porosity and water retention properties should all be expressed as probability density functions (PDFs) in the 3-D domain of waste rock piles to reflect these hydrogeological heterogeneities. As a preliminary study, this paper only treats the saturated permeability k_s on the 2-D cross-section of waste rock piles as a PDF and leave all other parameters as constants for simplification.

Although the size for waste rocks more likely follows Weibull distribution (Sanchidrián et al., 2014), translating the particle size distribution to pore size distribution and even permeability distribution is not easy and straightforward. For simplicity of calculation, this paper proposes that the saturated permeability k_s inside waste rock piles follows a piecewise constant distribution to consider the effect of both finer pores and coarser pores. Thus, the corresponding PDF for k_s is calculated as follows

$$f(x) = \begin{cases} \frac{e}{(b-a)} & a \leq x \leq b \\ \frac{1-e}{(c-b)} & b < x \leq c \\ 0 & x < a \text{ \& } x > c \end{cases} \quad (10)$$

where a is the lower boundary of saturated permeability for finer pore portion, b is the transition boundary of saturated permeability between finer pore portion and coarser pore portion (no permeability gap), and c is the higher boundary of saturated permeability for coarser pore portion. In addition, e is the fraction for finer pore portion, and $1 - e$ is the fraction for coarser pore portion in the waste rock piles.

In Eq.(10), the accurate values of a , b and c inside waste rock piles could be difficult to define or directly measure. However, the ratio between mean permeability from finer pores and coarser pores can be roughly estimated. As the distribution is uniform for each pore portion, the mean saturated permeability for finer pores is calculated as $(b - a)/2$, and that for coarser pores is $(c - b)/2$. By controlling the ratio between $(b - a)/2$ and $(c - b)/2$, and also the ratio between e and $1 - e$ (volume ratio between finer pores and coarser pores), a stochastic distribution of saturated permeability distribution k_s that considers both of finer pores and coarser pores can be well mathematically defined to simulate the heterogeneity of water flows inside waste rock piles.

The purpose of this study is to test and validate the proposed PDF concept for simulating the heterogeneity of water flow inside waste rock piles. The real hydrogeological conditions in the field are much more complicated than the proposed mathematical simplification on the permeability. In the future, the proposed method may be further refined by extending PDFs from saturated permeability to other parameters related to hydrogeology as long as the corresponding characterizations are available.

2.3 Reactant/product transport and heat transfer

To investigate the transport of all geochemical species in the water phase related to ARD-ML processes inside a waste rock pile, a general species transport equation is adopted as:

$$\frac{\partial}{\partial t}(\theta_w C_i) - \nabla \cdot (\theta_w D_i \nabla C_i) + \nabla \cdot (\mathbf{q}_w C_i) = Q_i \quad (11)$$

where C_i and D_i are the concentration and diffusion coefficient for species i , \mathbf{q}_w is the Darcy's velocity for water phase calculated from Eq.(8), and Q_i (sink or source term) is the generation or consumption rate.

Similarly, the supply of oxygen with air flow (concentration C_{O_2}) for geochemical reactions can be calculated as:

$$\frac{\partial}{\partial t}(\theta_a C_{O_2}) - \nabla \cdot (D_{O_2} \nabla C_{O_2}) + \nabla \cdot (\mathbf{q}_a C_{O_2}) = Q_{O_2} \quad (12)$$

where D_{O_2} is the effective oxygen diffusivity [L^2/T], and Q_{O_2} (sink term) is the oxygen consumption rate [$M/L^3/T$].

To evaluate the effect of reaction heat and its impact on air flow/oxygen supply for ARD-ML reaction, the equation for heat transfer in the waste rock pile is also included,

$$c_p \rho \frac{\partial T}{\partial t} + c_w \rho_w \nabla T \cdot \mathbf{q}_w - \nabla \cdot (k \nabla T) = Q_h \quad (13)$$

where c_p is the specific heat capacity. Q_h denotes the heat generation rate from geochemical reactions.

The effective mass density ρ and the effective thermal conductivity k are defined as

$$c_p \rho = \phi \rho_w S_w c_w + (1 - \phi) \rho_s c_s \quad (14)$$

$$k = k_{dry} + \sqrt{S_w} (k_{wet} - k_{dry}) \quad (15)$$

where C_w and C_s are heat capacities for water and solid (waste rock particles), k_{dry} and k_{wet} are the thermal conductivities for waste rocks in dry and wet conditions, respectively. The ideal gas law is then applied to link the calculated temperature T to air pressure p_a and air density ρ_a to adjust the air flow calculation in Eq.(12).

As source/sink term for Eqs.(11-13), Q_i , Q_{O_2} and Q_h can be calculated from the water film model proposed in Part 1 or any other particle level geochemical models.

3 Case study

To validate above methodology, the conceptual models proposed in this paper combined with the particle level water film model proposed in Part 1 are further applied to the main waste rock dump at the Equity Silver Mine for a full-scale case study. The Equity Silver mine is located in the central interior of British Columbia, Canada. The waste rock piles of this mine totally have about 80 million tonnes of waste rocks, which have been producing ARD since the 1980s. Extensive research has been conducted at the Equity Silver since the 1990s, which focused on hydrogeological characterization, cover system modeling, modeling of infiltration, geochemical reaction, seepage flow and drainage chemistry, etc.

The case study focuses on the main waste rock dump at the Equity Silver. For simplification, a 2-D model is built and applied. A typical 2-D cross section from the main waste rock dump is simulated in this case study. The elevation contour of the main dump and the location of the 2-D cross section can be found in Figure 1.

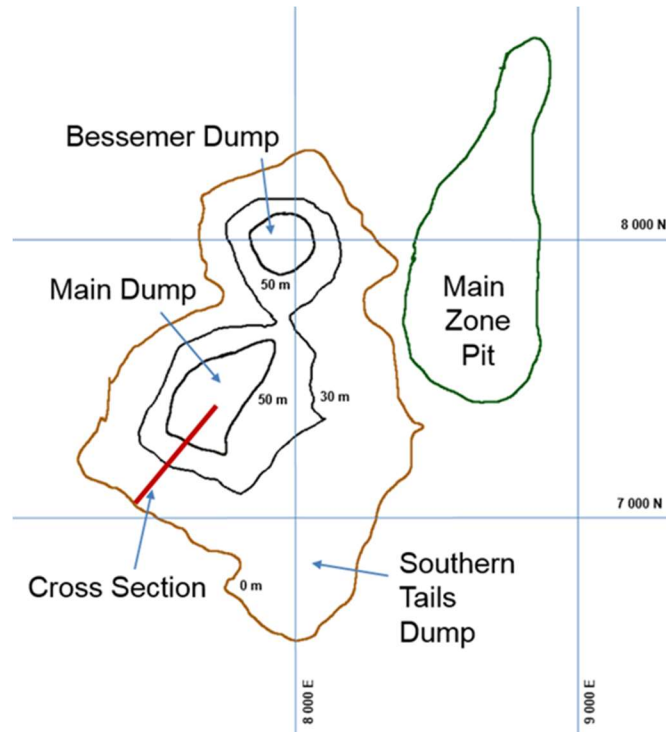


Figure 1. Topography of the waste rock piles at Equity Silver Mine

3.1 Environmental input

The top layer of the waste rock pile (cross section) receives the precipitation from the environment. The net infiltration amount is adjusted by the net infiltration rate that is from pre-estimation as by Ma et al. (2020). In addition, the environmental temperature is also applied on the top layer. Both precipitation and temperature data are collected from the weather station at the Equity Silver, which are extracted from Environmental Canada website. The pH of precipitation is set constantly to 5.5 during the whole simulation, which is consistent to the yearly average value measured at this site. The air pressure distribution adjusted by elevation (gravity effect) is applied on the top and slope surfaces of the pile, so the air advection can be well simulated. In addition, open boundary conditions are also set on the top and slope surfaces for calculating oxygen transport, which means oxygen diffusion is only considered when air ingresses. The water table was assumed to lie below the base of the pile, and a free drainage condition

was applied at the bottom of the cross section. This boundary condition reproduces the effect of a coarse and well drained layer, which is often observed at the base of a waste rock pile (Fala et al., 2005).

3.2 Parameters for the study

The key parameters to control the heterogeneous distribution of water flow in waste rock piles are a , b , c and e which are defined in Eq(10). As these parameters are proposed and defined theoretically, and no clear boundary can be provide to distinguish finer pores from coarser pores at this stage, some estimation and simplification have to be applied in this case study. Nichol et al. (2005) and Webb et al. (2008) found that the wetting front velocities in coarse heterogeneous material travel several orders of magnitude faster than the mean water velocity in finer waste rocks, so the mean permeability for coarser pores $(c - b)/2$ is generally assumed here to be 1000 times higher than mean permeability for finer pores $(b - a)/2$ in this study. The mean permeability for finer pores is based on the study of Part 1 . In terms of volume fraction for finer pore portion e , it is even difficult to get rough estimation as no such characterization is available at this time. Based on previous studies on this site, a parametric study (e for 90% and 80%) is performed to evaluate how it impacts on the water flow pattern within the pile. In addition, an increasing number of studies indicate that the water flow through coarser pores may still be dominated by capillarity (Neuner et al., 2013; Appels et al., 2018), so water retention shown in Eqs(5-7) can also apply on them. For simplification, all parameters related to water retention are shared between finer pores and coarser pores in this study.

Other parameters of the waste rock and the cover related to water and air flow, and those parameters that determine oxygen transport, heat transfer and the leaching process are given in Table 1. Water film model proposed in Part 1 is adopted to calculate the particle level geochemical reaction, and related parameters are described in that paper.

Table 1. Other parameters used for the case study

Symbols	Units	Values
ϕ	-	0.4
S_w^{\min}	-	0.05 ^(A)
S_w^{\max}	-	0.38 ^(A)
m_g	-	0.6 ^(B)
n_g	-	2.5 ^(B)
K	-	0.5 ^(B)
p_g	Pa	653 ^(B)
K_w (waste rock)	m/s	1e-3 ^(C)
K_w (cover)	m/s	1e-5 ^(C)
$D_{Fe^{2+}}$	m ² /s	7.2e-10 ^(F)
D_{O_2}	m ² /s	1.76e-5 ^(F)
k_{dry}	W/m °C	0.5 ^(G)
k_{wet}	W/m °C	3 ^(G)
c_w	J/Kg/K	4181 ^(H)
c_s	J/Kg/K	1139 ^(H)

(A): Molson et al. (2005); (B): Noel and Ritchie (1999); (C): Lahmira et al. (2009);

(D): Gerke and van Genuchten (1993); (E): Ma et al. (2019); (F): Haynes (2014);

(G): Lefebvre et al. (2001a); (H) Eppelbaum et al. (2014)

In this study, the simulation time period is from 1981 to 2002 (22 years) totally. For the time period 1981-1990 (10 years), insufficient weather monitoring data are available, so yearly average precipitation and temperature are set in that time period. The simulation results for this initial time period are used to make geochemical reaction and mass transport balanced within the pile and to initialize the simulation for the subsequent time period 1991 to 2002 (12 years), during which measured precipitation and temperature data are applied. The overlying soil-till cover system is included in model starting from Jan 1994, which is based on the fact that the cover was installed between 1990 and 1994, and completed in 1994. This case study is based on monthly average precipitation and temperature, so hourly or daily response in seepage water and leaching geochemistry cannot be assessed at this stage.

As the permeability distribution are not only generated based on Eq. (10), but also dependent on the mesh grids, the effect of mesh shape and mesh size on simulation results are also investigated in this study. A parametric study on mesh grid is performed: 16337 triangle elements (dense mesh), 3954 triangle elements (coarse mesh), 8904 sweeping quadrilateral elements (oriented mesh). The oriented mesh scenario simulates the waste rock as piled layer by layer each with its own PDF, however, each layer shares the same permeability distribution in this case study.

3.3 Case study results

In summary, totally 5 scenarios are simulated for the 2-D cross section from the main waste rock dump of the Equity Silver mine: Higher finer pore portion ($e=90\%$) with coarser mesh, less finer pore portion ($e=80\%$) with coarser mesh, less finer pore portion with dense mesh, less finer pore portion with oriented mesh. In addition, the original model with homogeneous saturated permeability ($a=b$, $e=100\%$) are also simulated for comparison. The randomly generated distribution of saturated permeability for the first four heterogeneous scenarios are plotted in Figure 2.

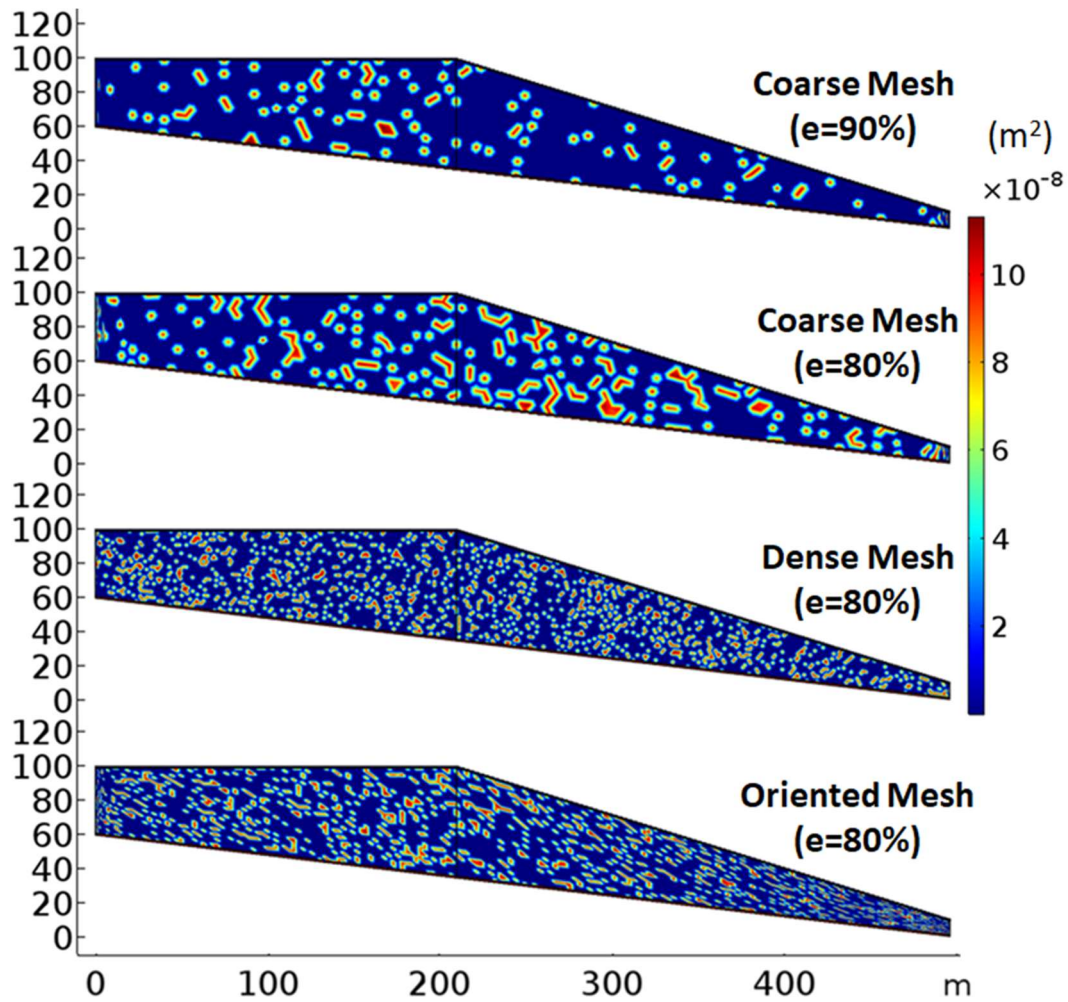


Figure 2. Saturated permeability distributions for 4 heterogeneous scenarios

Figure 3 indicates the streamline for water flow inside the waste rock pile for the simulated 5 scenarios. For the homogeneous scenario, the results show that the water flow infiltrates the top surface and go vertically through the piles in straight lines as the permeability is constant everywhere. For the coarse mesh (e=90%) scenario, it is observed that the streamlines combine together when they move deep into the piles and the streamline density is significantly reduced when they leave the pile from bottom. This observation of combined streamlines has been confirmed by test work (Li, 1999). The scenarios of coarse mesh (e=80%) and dense mesh (e=80%) appears to have similar streamline pattern, and the streamline density for these two scenarios is found to be higher than that obtained in the first scenario. The

streamline pattern in the oriented mesh (e=80%) scenario seems completely different, as the water flow in the slope region (right part of the cross-section) tends to move along the layer direction while going down to the bottom of piles.

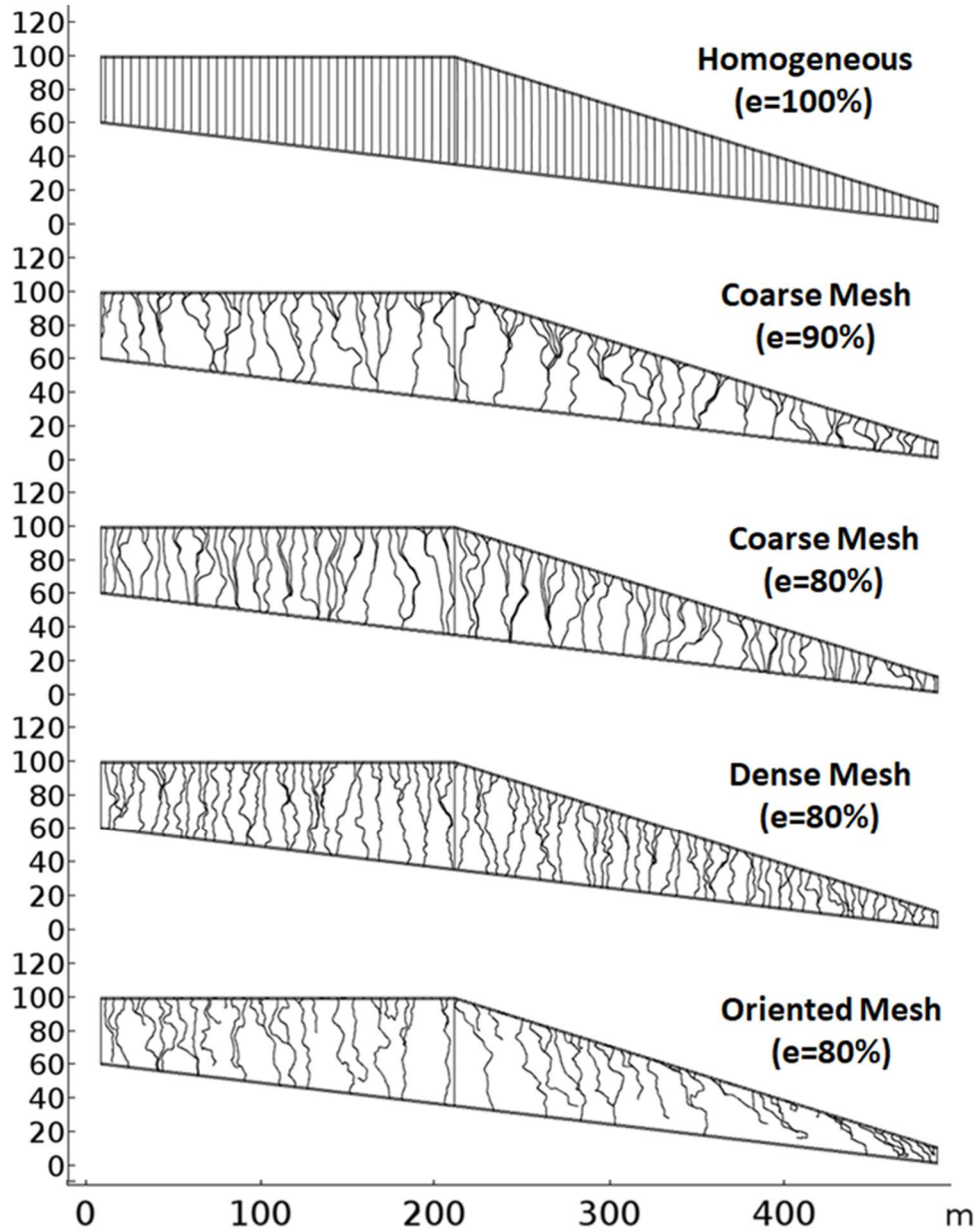


Figure 3. Calculated streamlines in waste rock piles

As the PDF only indicates the probability of distribution, even the same PDF does not guarantee identical permeability distribution in spatial scale. As a result, the water flow pattern may not be completely the same for two scenarios that share the same PDF of permeability. At this stage, the real water flow pattern inside waste rock piles is technically difficult to be directly characterized. Mine site engineers usually pay more attention to the total effect of these internal water flows, which is the integration of all water flows discharged at the bottom and received at the collecting ditch. Figure 4 provides the comparison of the total water flow rates leaving from the simulated cross-section for all 5 scenarios. It is shown that the total flow rate profile of homogenous scenario is different from those of heterogeneous scenarios. The scenarios of coarse mesh (e=80%) and dense mesh (e=80%) have almost same total flow rates profile. This means that even real permeability distributions and streamlines pattern are not identical for two scenarios with the same permeability PDF, but the total effects on (integration of) the water flow discharged at the pile bottom are almost same for them. In addition, Figure 4 suggests that lower e may bring higher fluctuations into the total water flow profile.

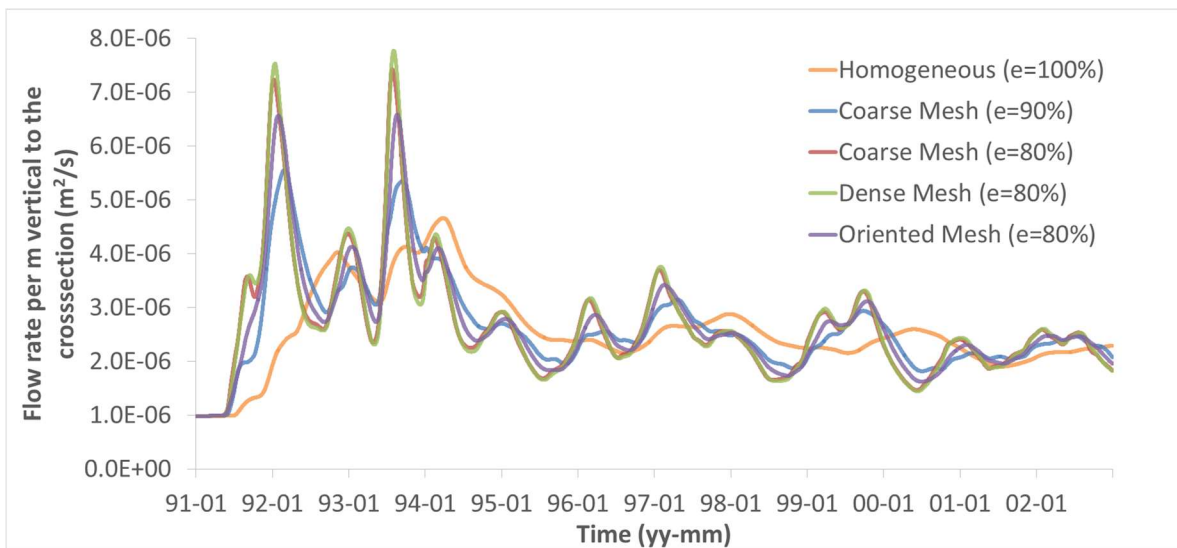


Figure 4. Comparison of total flow rates discharged from the bottom of the 2D cross-section

Figure 5 shows the calculated iron concentration distributions inside the waste rock pile at the end of simulation period for all scenarios. The homogenous scenario has the concentration distributed in layers.

Some disturbance can be observed at the left part, as the oxygen controlling the reaction is periodically depleted there. For all scenarios with heterogeneous saturated permeability, the iron concentration distributions are also heterogeneous. However, the maximum level of iron concentration is in the same scale and located close to the middle of the cross-section.

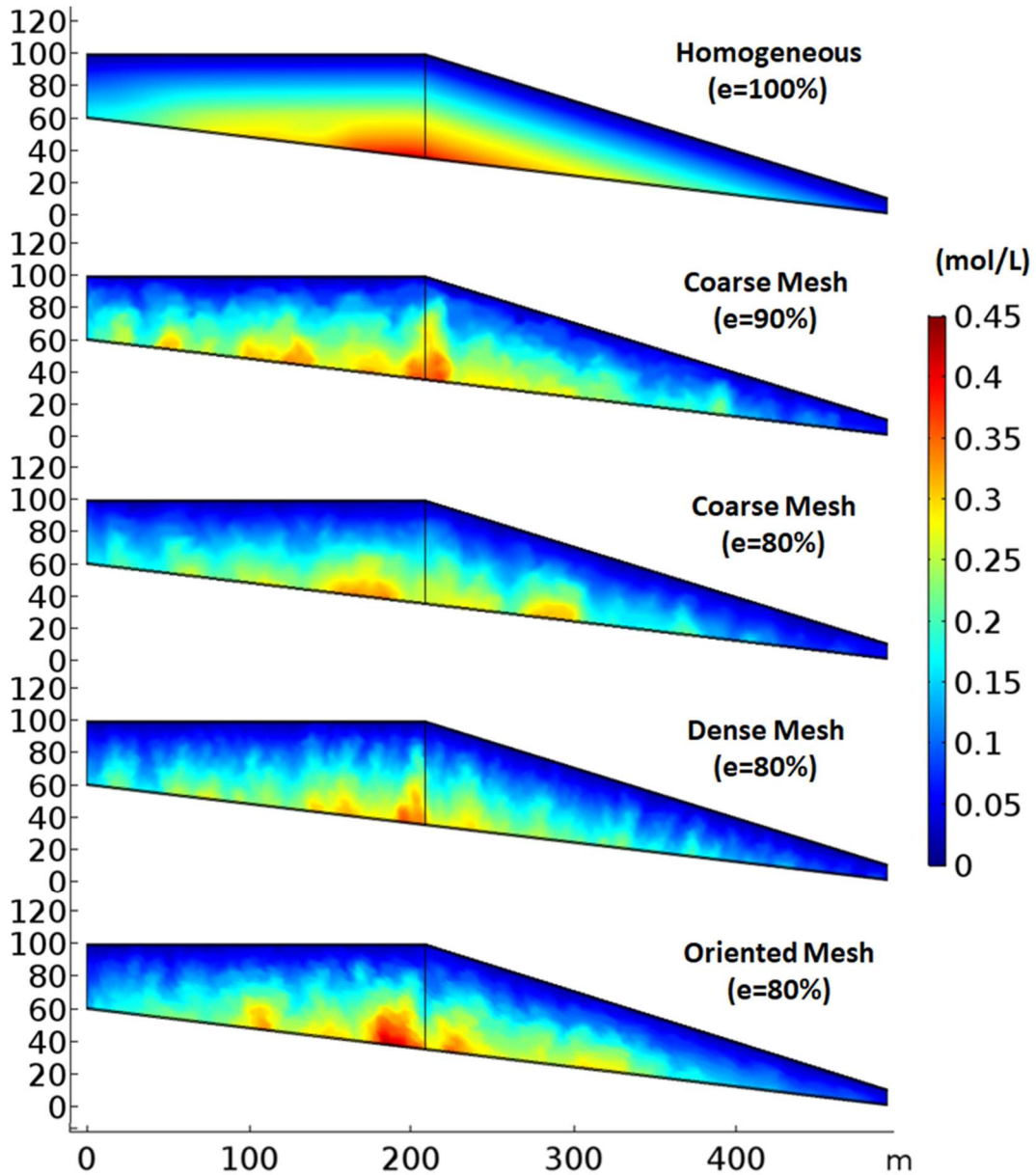


Figure 5. Calculated iron concentration distributions inside the waste rock pile

Then the total effect of the iron concentration distribution is also investigated, which is defined as the integration of iron discharge rate (iron loading) from the bottom of the pile. Figure 6 provides the comparison of the iron loading in temporal scale for all 5 scenarios. Similar to the comparison of water flow rate, the iron loading obtained from the homogeneous scenario has significant difference compared with those from remaining heterogeneous scenarios. Both of scenarios with coarse mesh ($e=80\%$) and dense mesh ($e=80\%$) have almost the same iron loading profile, which confirms that the integration of iron discharged at the bottom of the waste rock piles is only dependent on the PDF, not on specific permeability distribution. Two scenarios with the same saturated permeability PDF should have almost same iron loading profile.

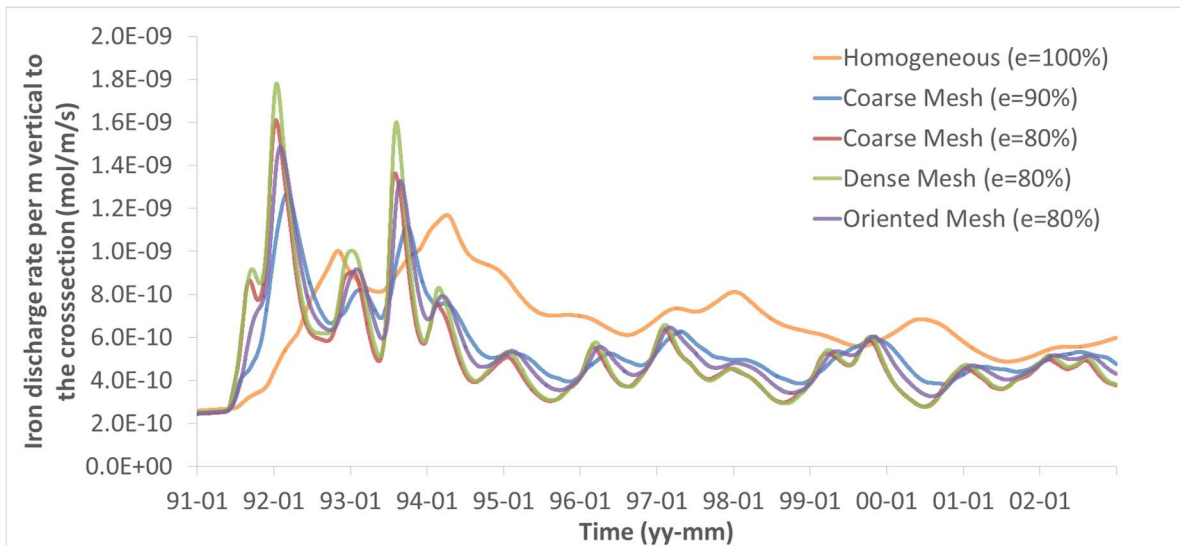


Figure 6. Comparison of the iron loadings from the 2D cross-section

The iron loading is highly correlated to the acidity (Kirby and Cravotta, 2005) at this site, and the acidity is generally proportional to the lime consumption used for neutralization and ARD treatment. Thus the iron loading is further integrated in time scale to get the annual iron loading, which is compared with the annual lime consumption at this site. As the iron loading and lime consumption are on different scales, the fluctuations compared with their 12 years mean are provided and compared in Figure 7. As the cover

is implemented in the model starting on Jan 1st 1994 while the real cover was installed between 1991 and 1994, the comparison before 1994 is not reliable. It can be observed that the homogeneous model generally fails to correlate the iron loading to the lime consumptions at this site. After the cover is built, the heterogeneous models (e=80% is better than e=90%) can match the fluctuation of lime computation in most of years except for 1997 and 2002 when the higher than normal lime consumptions are recorded due to unusually wet years.

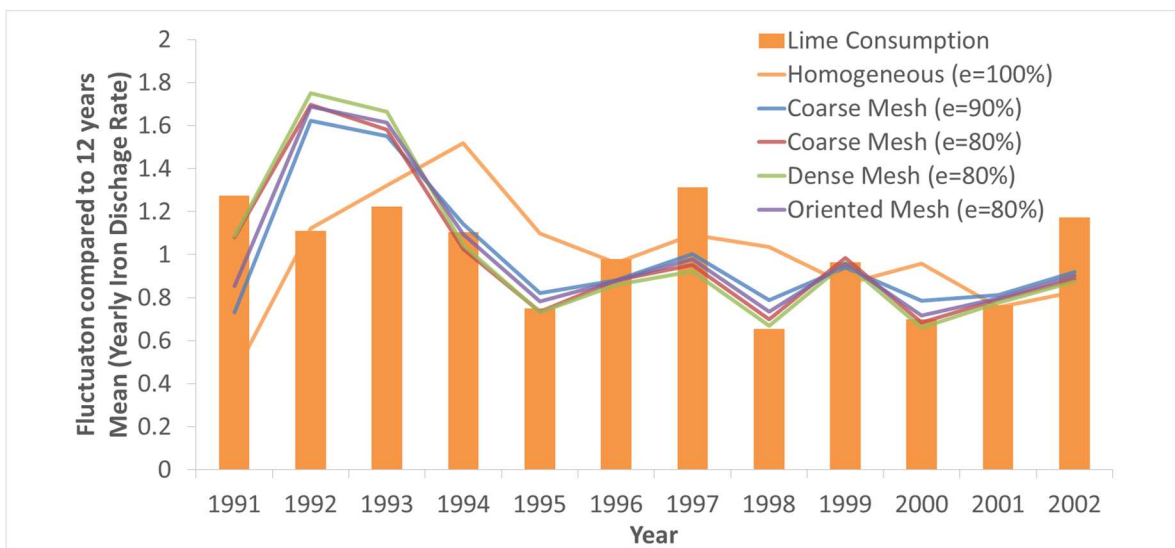


Figure 7. Fluctuations of lime consumption and calculated iron loading

4 Conclusions

Traditional ARD-ML investigations on waste rock piles are usually performed based on the simplification of homogeneous material properties. However, real material properties for waste rock piles are generally heterogeneous in field conditions. This paper (Part 2) adopts PDFs to describe the heterogeneity of the hydrogeological properties for modeling various water flow pattern in the full-scale waste rock piles. In addition, the various water flow patterns calculated from the proposed method is further integrated with geochemical reactions obtained from water film model proposed in Part 1, so that the leaching process of ARD-ML can be simulated in a realistic manner. The results of the full-scale case study show that

preferential flow pathway can be simulated by the proposed model. It is observed that waste rock piles with non-identical permeability distribution but sharing same PDF may have their own water flow patterns and iron concentration distributions inside the pile, respectively. However, the total water flow discharge rate and iron loading profiles of the whole waste rock pile are almost the same in temporal scale. It indicates that the distribution pattern (PDF) of hydrogeological properties impacts waste rock piles in a total manner, regardless of localized difference of water flow pattern. As this is a preliminary study, the PDF is only applied to the saturated permeability of waste rocks in the case study. Further investigation on the correlation between particle size distribution and the distribution of water retention properties in spatial scale is highly suggested for more realistic water flow and ARD-ML modeling of waste rock piles.

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