Risk assessment of acidic drainage from waste rock piles using stochastic multicomponent reactive transport modeling

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Abstract A recently developed risk-assessment framework based on stochastic reactive transport modeling allows evaluating the probability of acidic drainage from mineralogically heterogeneous waste-rock piles (WRPs) over 100s of years. The approach is based on multicomponent reactive transport solved through a computationally efficient streamtube-like formulation. Here, the framework is applied to evaluate the implication of mineral mixing (i.e. blending) and heterogeneity on the neutralizing potential ratio (NPR) within WRPs. The results cast doubt on the reliability of NPR =4 as a universal indicator to ensure that acidic drainage is not released from such piles. Blending can strongly mitigate the risk of acidic drainage.

Key words acid rock drainage, reactive transport, blending, uncertainty analysis

Introduction

Correct management of mine waste requires long-term predictions of environmental loadings from sulfide-rich by-products such as waste rocks. These materials can produce acidic drainage when exposed to weathering and in some cases waters with high acidity (pH < 3-4). Elevated concentrations of sulfate and other dissolved metals have also been observed in mine drainage. These aspects increase the water treatment requirements, in many cases for prolonged periods.

Assessing the environmental loadings from waste rock piles requires predicting if (and when) the piles will actually generate polluted drainage, and how much. This task is subject to substantial uncertainty. A main reason for poor predictive capabilities is the complexity in providing accurate quantitative estimates of the probability that infiltrating rainwater in contact with the host rocks will turn acidic over time.

Mineralogical heterogeneity plays a major role in this sense. The geochemical response of the pile depends on a large number of nonlinearly coupled factors occurring at a range of scales (e.g. Lorca et al. 2016; Pedretti et al. 2015). The amount and reactivity of minerals that can contribute to generate acidity (e.g. sulfides) and that of minerals that buffer the acidity, (e.g. carbonates) is necessary information, which is; however, impossible to characterize at each location within a WRP. Consequently, averaging the geochemical behavior of the pile is complicated and intrinsically uncertain.

Stochastic models provide a useful tool when making predictions under uncertainty for a variety of environmental applications (e.g. Pedretti et al. 2012), including mining contexts (e.g. Eriksson and Destouni, 1997; Malmström et al. 2008). However, stochastic reactive transport models of waste rock weathering are quite challenging, due to the computational intensity required to solve for nonlinearly coupled, large-scale simulations (e.g. Fala et al. 2013). A recently developed risk assessment framework based on streamtube-based modeling and multicomponent reactive transport has been proposed to circumvent some of these challenges and allows studying the likelihood (L) of acidic drainage from mineralogically heterogeneous waste rock piles.

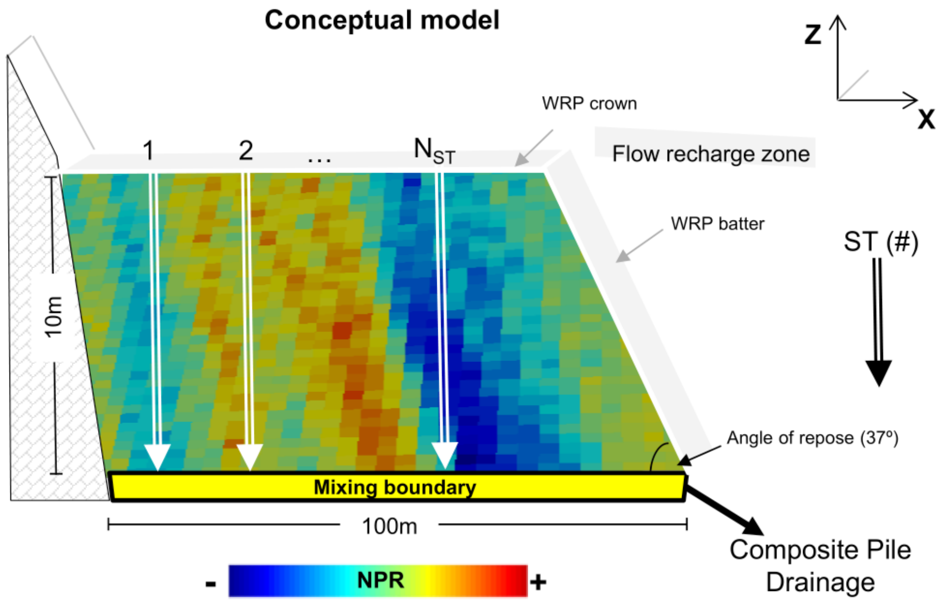

__Figure 1__ Conceptual model identifying the discretization of a mineralogically heterogeneous WRP into a sequence of streamtubes (STs) and the location of the mixing boundary (after Pedretti et al. 2017).

Pedretti et al. (2017) applied this method, focusing particularly on the impact of mineralogical heterogeneity on the effective neutralizing capacity of the piles. The mineralogical variability was idealized by a spatial variability of abundance of calcite and pyrite, described through geostatistical tools.

Experimental methods based on field and laboratory observations have been suggested to predict the risk for ARD release. For instance, indicators such as the Neutralizing Potential Ratio (NPR) have been proposed to estimate how likely the waste rock drainage will be buffered. When using this method, it is widely accepted that a waste rock with NPR =4 or higher would likely generate neutral pH drainage (e.g. Price, 2009). Approaches such as layering and blending of waste rock have been proposed in the past (e.g. Miller et al. 2003); however, their actual effectiveness to reduce the occurrence of acidic drainage has been questioned. Reactive transport models have been used to calculate the geochemical response of the piles to weathering using a process-based approach. (e.g. Mayer et al. 2002).

The purpose of this work is using the stochastic framework and to extend it to the analysis of scenarios that account for different geostatistics describing the mineralogical variability of waste rock piles. We formulate additional scenarios and by explicitly solving for random realizations within multiple Monte-Carlo simulations. Through this approach, we provide new insights about the impact of heterogeneity on the assessment of environmental risk from waste rock piles. In particular, we focus on the use of geostatistics to evaluate the impact of mineralogical mixing or blending as an effective solution to increase the effective pH-buffering capacity of a WRP.

Methodology

The stochastic framework is formulated according to the approach described in detail in Pedretti et al. (2017). Briefly, the approach describes a multidimensional (2D or 3D) system of any geometry, which is discretized into a number of streamtubes (STs). A ST can be seen as an individual 1D flow path, which is recharged by infiltrating rainfall at one boundary and releases drainage at the other boundary. The collection or bundle of STs forms the entire flow field within the pile. A conceptualization of this approach is depicted in Figure 1.

Each ST is in turn discretized into a number blocks, each of which is hydraulically and geochemically parameterized. Hydraulic properties and geochemical properties such as concentration of geochemical components and solids are defined for each block. A key property relevant for this discussion is the volumetric fraction of a mineral (φ). A heterogeneous distribution of physical and geochemical properties can be assigned by varying these properties in the blocks.

In the context of stochastic modeling, a heterogeneous distribution of these properties can be derived from a multidimensional geostastistical model. For instance, a stochastic distribution can be used to represent a random variability of mineral content (φ) initially present during the construction stage of the waste pile. A useful model to generate stochastic modeling is a Sequential Indicator Simulation (SIS), in which categories of simulated properties are varied according to spatial correlation functions, or equivalently a variogram model. A well-known model is for instance the directional exponential covariance function

$$C(\theta)=\sigma^2 \exp\left(\frac{d}{r_\theta}\right)$$

where r is the distance between two points, θ is the angle of the anisotropic covariance ellipsoid, a is the range of the correlation along that direction, and σ^2 is the variance of the studied property. The ratio between r_θ and the dimension of the domain along θ provides a measure of the continuity of the mineralogical content along θ .

Each ST forming the WRPs is parameterized according to the corresponding map of properties obtained from the geostatistical model. Each ST is then solved individually as a 1D reactive transport model, which describes unsaturated flow and concentration of components within the domain, according to a set of boundary conditions and the specific reaction network.

The solution of each ST provides the concentration of components and discharge rates at the base of each ST. Discharge from streamtubes tend to mix in areas of converging flow. This could occur for instance a stream or at the base of a WRP. Risk assessment of drainage quality from WRPs is not as important for discharge from individual streamtubes within the pile, but is more relevant to assess the overall composition of mixed drainage resulting from merging multiple STs. To facilitate this assessment, mixing of drainage from individual streamtubes must be included in the analysis.

Application

We applied the stochastic framework to analyze the role of mineralogical heterogeneity on the effective neutralizing capacity of WRPs. The problem is defined as in Pedretti et al. (2017), who already addressed a similar problem. We focused on pyrite and calcite as the two primary minerals controlling the distribution of the neutralizing potential ratio (NPR) within the pile. The goal of the application is to evaluate if the mean NPR value calculated by simple averaging over the entire content of pyrite and calcite minerals within a pile is a sufficiently accurate metric to predict if the total pile drainage will become acidic or remain circumneutral.

Pedretti et al. (2017) concluded that a bulk NPR =4 (a value traditionally considered "safe" for practical applications at mining sites) can sometimes be insufficient to ensure that drainage does not become acidic. Pedretti et al. (2017) adopted a defined r_θ , which corresponded approximately to the vertical extension of the domain (L). In this sense, their simulations mimicked poorly mixed mineralogical conditions within the piles. We extend in this paper the work by Pedretti et al. (2017) by adding new scenarios, which simulate the effects of distribution of minerals with a shorter r_θ , representing conditions of increased mineralogical mixing within the pile.

In Figure 2 we report examples of resulting pyrite 100m $\times$ 10m 2D maps, discretized into cells of 1m² and resulting from the use of different r_θ . Similar fields can be derived for calcite. On average, the two distributions have the same mean amount (i.e. φ) of pyrite. On top, the ratio $r_\theta / L \approx 1$ results in continuity of the individual mineral property along the vertical direction. At the bottom, we adopted a ratio $r_\theta / L \approx 0.3$, which results in more mixed mineralogical conditions within the piles. Readers more familiar with terms more traditionally adopted in the mining industry can find an analogy between "non-blended" (case with $r_\theta / L \approx 1$) and more "blended" (case with $r_\theta / L \approx 0.3$) scenarios. We use these applied terms in the discussion below for clarity.

Following Pedretti et al. (2017), we assumed vertical flow, fully controlled by the recharge rates, and lateral hydraulic homogeneity. No effect of preferential flow is simulated, an aspect which is left open for future developments. Each column of the 2D mineralogical map shown in Figure 2 represents one ST. The resulting mixing of water from the various STs is calculated by taking the concentrations of components from all STs at the bottom of the pile, and mix them at sequential time intervals. High gas permeability is assumed in the simulations, leading to conditions in equilibrium with the atmosphere.

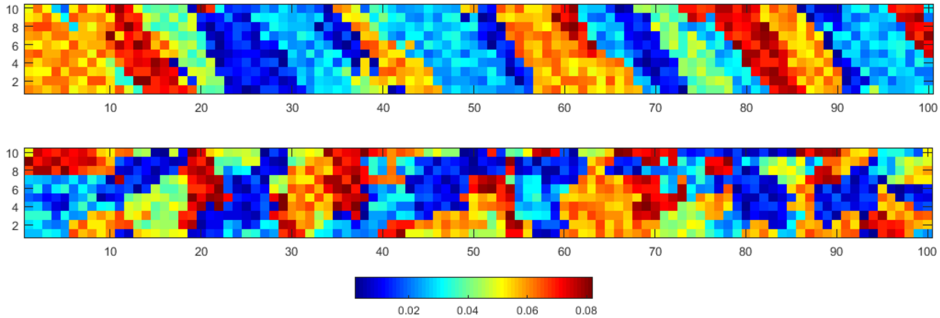

Figure 2 *Examples of individual realizations of geostatistical pyrite maps. The mineral distribution in the blended scenario is characterized by short correlation lengths of mineral maps, resulting in more mineralogical mixing than within the non-blended piles.*

To directly compare with Pedretti et al. (2017), and using the same r_θ/L ratios defined above, we studied the likelihood that a WRP will generate acidic conditions from piles characteristic by two different mean NPR values (NPR =2 and NPR =4). The results are reported in Figure 3, which shows the cumulative density functions obtained for each scenario from an ensemble of 100 equally probable stochastic simulations, all characterized by the same mean NPR and other statistics characterizing their mineralogical properties.

The results highlight the importance of mineralogical mixing on the expected behavior of a pile. In the case of poor mineralogical mixing (i.e. piles not blended) (Figure 3-left), the piles are expected to generate acidity. The likelihood that a pH<4 occurs 50 years after the pile construction, for instance, is approximately 90% for NPR =2 and above 75% for NPR =4. This issue, already highlighted by Pedretti et al. (2017) cast doubts on the universality of the use of the NPR indicator to predict the resulting pH of pile drainage.

In the case of increased mineralogical mixing (i.e. piles blended) (Figure 3-right), we observed that in case of NPR =2 the probability that a pile generates acidic pH remains quite high, and comparable with the non-blended scenario. However, for NPR =4, mixing has a much stronger and positive impact on the results. Indeed, we found that the probability of generating acidic pH becomes virtually negligible (<5%), suggesting that the combination of mineralogical mixing and NPR =4 can be more optimal to minimize low acidity drainage conditions from waste rock piles.

Conclusion

A recently developed efficient stochastic modeling tool allows generating process-based Monte Carlo simulations for risk assessment in heterogeneous waste rock piles. Risk is defined here as the likelihood of a pile to generate acidic drainage under uncertainty.

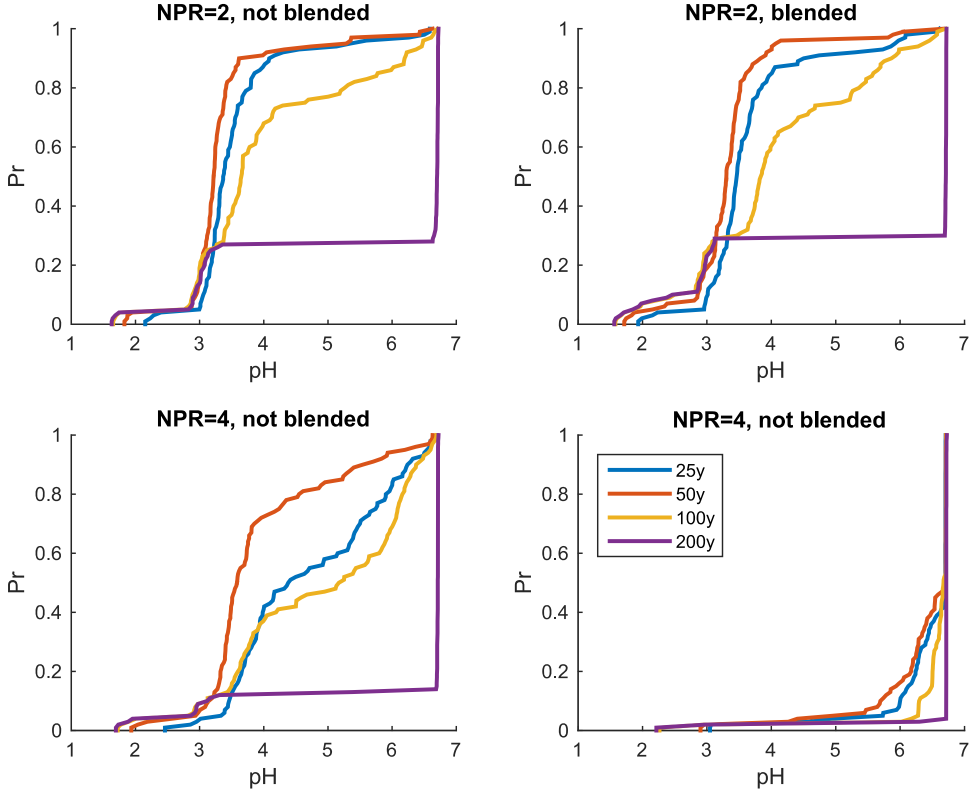

Figure 3 *Cumulative probability of resulting pH from waste rock piles characterized by different bulk NPR ratios and correlation lengths. "Not blended" refer to waste rocks in which mineral correlation is shorter than in the "blended" waste rocks, where the correlation is continuous over the vertical scale of the pile.*

We focused on the NPR metric and evaluated how mineralogical heterogeneity is a relevant source of uncertainty to ensure the validity of NPR values traditionally considered "safe" from operational perspectives in waste rocks. A recent analysis by Pedretti et al. (2017) focusing on similar problems provides a useful conceptual model and analysis to be tested and compared.

Our analysis reveals that the spatial characteristic of mineralogical heterogeneity can play a major a role when defining the actual validity of a specific NPR value. In particular, we found that mineralogical mixing (similar to waste rock "blending") is critical to ensure that NPR =4 works as a proper universal metric to ensure no acidic drainage exfiltrating waste rocks. For the conditions simulated in this analysis, when rocks are not blended, the likelihood of drainage with pH<4 is above 75%, while becoming virtually negligible (<5%) when rocks are blended. On the other hand, NPR =2 is insensitive to blending, and always generate high likelihood of acidic leaching.

Development of this study will target different waste rock conditions and more complex scenarios, which include the implication of additional primary and secondary minerals, variable gas and temperature conditions, and hydraulic heterogeneity.

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