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Effect of heterogeneity and anisotropy related to the construction method on transfer processes in waste rock piles

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ABSTRACT

Waste rock piles producing acid mine drainage (AMD) are partially saturated systems involving multiphase (gas and liquid) flow and coupled transfer processes. Their internal structure and heterogeneous properties are inherited from their wide-ranging material grain sizes, their modes of deposition, and the underlying topography. This paper aims at assessing the effect of physical heterogeneity and anisotropy of waste rock piles on the physical processes involved in the generation of AMD. Generic waste rock pile conditions were represented with the numerical simulator TOUGH AMD based on those found at the Doyon mine waste rock pile (Canada). Models included four randomly distributed material types (coarse, intermediate, fine and very fine-grained). The term "randomly" as used in this study means that the vertical profile and spatial distribution of materials in waste rock piles (internal structure) defy stratigraphy principles applicable to natural sediments (superposition and continuity). The materials have different permeability and capillary properties, covering the typical range of materials found in waste rock piles. Anisotropy with a larger horizontal than vertical permeability was used to represent the effect of pile construction by benches, while the construction by end-dumping was presumed to induce a higher vertical than horizontal permeability. Results show that infiltrated precipitation preferentially flows in fine-grained materials, which remain almost saturated, whereas gas flows preferentially through the most permeable coarse materials, which have higher volumetric gas saturation. Anisotropy, which depends on pile construction methods, often controls global gas flow paths. Construction by benches favours lateral air entry close to the pile slope, whereas end-dumping leads to air entry from the surface to the interior of the pile by secondary gas convection cells. These results can be useful to construct and rehabilitate waste rock piles to minimize AMD, while controlling gas flow and oxygen supply.

1. Introduction

Waste rock piles producing acid mine drainage (AMD) have been the subject of a wide body of research. Interest is primarily related to the importance of waste rock piles in terms of economic and environmental impacts. The focus on research also reflects that waste rock piles are complex systems that have required significant developments in terms of characterization and numerical modelling in order to understand their dynamics, thus allowing better understanding of processes that enables better management of existing piles and guidelines on constructing new piles with minimal AMD production.

The complexity of waste rock piles is mainly due to materials of varied grain size, the physical and chemical heterogeneity of these materials and the coupled transfer processes prevailing in these non-isothermal partially saturated

Abbreviation: AMD, acid mine drainage.

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systems (Amos et al., 2015). Efforts to characterize conditions in waste rock piles have been made by using vertical profiles of temperature and oxygen to provide information on AMD production rates that involve the exothermic oxidation of sulphides (Harries and Ritchie, 1981, 1985; Jaynes et al., 1983; Lefebvre, 1994; Dawson et al., 2009). Aubertin et al. (2005) and Amos et al. (2015) present overviews of waste rock pile characterization methods, including the lab measurement of capillary properties of varied grain size material. Various aspects of these processes in waste rock piles have been the object of specific work, including water infiltration in partially saturated heterogeneous media (Smith and Beckie, 2003) and oxygen supply caused by thermal convection of the gas phase (Lefebvre et al., 2001a, 2001b; Ritchie, 2003; Pham et al., 2013). Lefebvre et al. (2001a) compared the transfer processes controlled by the physico-chemical properties of two different piles (Doyon Mine in Canada and Nordhalde in Germany). Lefebvre et al. (2001b) have shown by numerical modelling that the same physical processes lead to different transfer conditions due to the different physical properties of the two piles.

The heterogeneity of waste rock piles has been recognized in most characterization and monitoring studies (Morin et al., 1994; Martin et al., 2005; Smith et al., 2013b), infiltration tests on a large scale test pile (Nichol et al., 2000, 2005) and with numerical modelling (Lefebvre et al., 2001b; Fala et al., 2003; Lahmira et al., 2007; Dawood and Aubertin, 2009; Lahmira, 2010; Lefebvre et al., 2011a, 2011b, 2012; Fala et al., 2012; Lahmira and Lefebvre, 2014; Dawood and Aubertin, 2014; Broda et al., 2014). There is no conceptual physical model capable of describing the spatial distribution of properties in waste rock piles. However, it is possible to identify factors that influence the internal structure of waste rock piles, including material properties, mineralogy, mining operations, and construction methods (Aubertin et al., 2002a; Fala et al., 2003; Smith et al., 2013c). Azam et al. (2007) reported that the pile construction method by end-dumping leads to segregation of coarse material at the bottom of the slope and the creation of fine and coarse layers. The creation of layers of different grain sizes is the result of gravity effects and traffic of heavy equipment. During construction, materials of various loads are dumped into the same pile; the fine fraction of a load can be mixed with the coarse fraction of a previous load and vice versa. The presence of fine-grained layers increases the water retention capacity, while the coarse-grained layers are largely non-saturated, hence facilitating gas flow. The formation of a zone of coarse material at the base of a pile promotes air inflow that brings more oxygen along the foundation of the pile, as observed at the Questa mine (Lefebvre et al., 2002).

Aubertin et al. (2002a, 2002b, 2005) have also presented a conceptual model showing the internal structure of a waste rock pile which includes two main zones: a first zone in the centre of the pile with sub-horizontal layers resulting from the deposition method of materials during construction and the movement of heavy equipment on the surface of benches. A second zone, located near the edge of the pile, where the waste rock materials are typically dumped down the slope producing segregation often accompanied by an inclined stratification typical of construction by end-dumping (Aubertin et al., 2002a, 2002b; Nichol, 2002). The internal structure resulting from the construction method directly affects the water saturation and flow inside the pile. It also controls the geotechnical stability and susceptibility to produce acid mine drainage in the presence of sulphides (Fala et al., 2003, 2005, 2006; Molson et al., 2005; Smith et al., 2013a; Dawood and Aubertin, 2014). Recent studies have used geophysical methods to map the spatial distribution of material properties in waste rock piles (Anterrieu, 2006; Anterrieu et al., 2007, 2010; Finsterle and Kowalsky, 2008; Phillip et al., 2009; Dawood et al., 2011). These authors associated the electrically conductive areas to fine-grained material (high water retention capacity) while electrically resistive areas were associated with coarse-grained materials. The results confirmed the existence of the above-mentioned internal structure.

Although hydrogeological data provide information on the hydraulic properties that control flow and transport processes (Neuner et al., 2013), these data alone are not sufficient to capture the behaviour of a complex system. Pruess et al. (1999) noted that heterogeneity is the source of flow complexity at different scales. Recent work has nevertheless provided a valuable perspective on the behaviour of heterogeneous systems, including the presence of the capillary barrier effect and localized flow (Fala et al., 2005; Molson et al., 2005; Dawood and Aubertin, 2009; Fala et al., 2012), which can be caused by high permeability layers (Li, 2000; Zhan, 2000). Bussière et al. (2003) and Fala et al. (2006) also noted that the combination of a fine-grained layer overlaying a coarse material layer could act as a capillary barrier and retain water by capillary action in the former.

In soil physics, flow paths are often described as systems of interconnected pores (Beven and Germann, 1982; Flury et al., 1994; Li, 2000). The relationship between flow paths, permeability and heterogeneity has been represented numerically (Birkholzer and Tsang, 1997; Eriksson and Destouni, 1997; Fala et al., 2003, 2005, 2006; Lahmira et al., 2007; Lahmira, 2010; Dawood et al., 2011; Dawood and Aubertin, 2014) and observed experimentally (Eriksson and Destouni, 1997; Fines et al., 2003; Nichol, 2002). Small-scale heterogeneity has also shown its effect on flow and solute transport in the unsaturated zone (Hangen et al., 2004). At small scales, preferential flow can result from the passage of fluid from fine-grained material to coarser material (Parlange and Hill, 1976; Baker and Hillel, 1990). This phenomenon was observed in materials without obvious physical heterogeneity (Ghodrati and Jury, 1992; Jury et al., 2003; Wang et al., 2003; Cho et al., 2005). Preferential flow that is not directly connected to material properties can occur during the redistribution of the wetting front when the hydraulic gradient is reversed due to an infiltration event into a dryer zone (Wang et al., 2003). Jury et al. (2003) and Wang et al. (2004) suggest that all soils are susceptible to such a preferential flow, usually related to immiscible fluid flow. Wang et al. (2003) observed that this phenomenon tends to reappear at the same locations for subsequent infiltration events. Covered waste rock piles may also exhibit this type of preferential flow (Nichol, 2002), which was highlighted by Hangen et al. (2004) using chemical tracers.

A complex dynamic of coupled physical processes occurs in waste rock piles. The representation of all these processes in a single numerical model is very difficult without using some simplifications. Furthermore, physico-chemical reactions and the distribution of fluids in such a system represent a major challenge, especially since multiphase flow of two fluids occurs simultaneously. This study used the code TOUGH2 as a numerical