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Comparison of unsaturated flow and solute transport through waste rock at two experimental scales using temporal moments and numerical modeling

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ABSTRACT

This study analyzed and compared unsaturated flow response and tracer breakthrough curves from a 10-m high constructed pile experiment (CPE) in the field (Antamina, Peru) and two 0.8 m high laboratory-based columns. Similar materials were used at both experimental scales, with the exception of a narrower grain size distribution range for the smaller column tests. Observed results indicate that flow and solute transport regimes between experimental scales were comparable and dominated by flow and solute migration through granular matrix materials. These results are supported by analogous breakthrough curves (normalized to cross-sectional area and flow path length) that suggest observation- or smaller-scale heterogeneities within the porous media have been homogenized or smoothed at the transport-scale, long breakthrough tails, and similar recovered tracer mass fractions (i.e., 0.72–0.80) at the end of the experiment. CPE breakthrough curves do indicate a portion of the fluid flow follows rapid flow paths (open void or film flow); however, this portion accounts for a minor (i.e., ~0.1%) component of the overall flow and transport regime. Flow-corrected temporal moment analysis was used to estimate flow and transport parameter values; however large temporal variations in flow indicate that this method is better suited for conceptualizing transport regimes. In addition, a dual-porosity mobile–immobile (MIM), rate-limited mass-transfer approach was able to simulate tracer breakthrough and the dominant transport regimes from both scales. Dispersivity values used in model simulations reflect a scale-dependency, whereby column values were approximately 2× smaller than those values applied in CPE simulations. The mass-transfer coefficient, for solute transport between mobile and immobile regions, was considered as a model calibration factor. Column experiments are characterized by a larger "mobile to immobile" porosity ratio and a shorter experimental duration and flow path, which supports larger mass-transfer coefficient values (relative to the CPE). These results demonstrate that laboratory-based experiments may be able to mimic flow regimes observed in the field; however, the requirement of scale-dependent dispersivities and mass-transfer coefficients indicates that these tests may be more limited in understanding larger-scale solute transport between regions of different mobility. Nevertheless, the results of this study suggest that the reasonably simplistic modeling approaches utilized in this study may be applied at other field sites to estimate parameters and conceptualize dominant transport processes through highly heterogeneous, unsaturated material.

1. Introduction

The construction of waste rock piles is part of the mining process at many mine sites. These piles are generally large, unsaturated structures containing material with grain diameters

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spanning at least six orders of magnitude (i.e., 10^{-6} m–1 m; Nichol et al., 2005; Fala et al., 2005). Predictions of solute loads released at the base of a waste rock pile require the characterization of fluid flow and solute transport. Estimating solute transport parameters for use in predictive models becomes increasingly difficult at larger scales due to the effects of spatial variability in the many factors that control the infiltration of water and the mobility of solutes (e.g., initial/boundary conditions, material properties, preferential flow paths; see Jury and Flühler, 1992; Li and Ghodrati, 1997; Vanderborght et al., 2000; Vanderborght and Vereecken, 2007). These complexities observed at the large scale are generally viewed as difficult, or impossible, to reproduce in smaller experiments (e.g., field barrels, laboratory columns, or humidity cells). For example, a number of studies have compared mineral weathering rates across scales with the intention of determining correction (or scaling) factors (Eriksson et al., 1997; Frostad et al., 2005; Malmström et al., 2000; Otwinowski, 1995). However, the results reveal large discrepancies in behavior among scales, which suggest large field experiments may be necessary to adequately characterize system response (Malmström et al., 2000).

The material characteristics of waste rock can have a substantial impact on its hydrological response (Smith and Beckie, 2003). This observation is supported by the study of Butcher et al. (1995), who state that in stony soil the flow path of water is an intrinsic property of the soil medium (at a given water content). Flow through waste rock can be categorized into two types: preferential flow through either open voids and/or the coarse-sized fraction of the matrix, and matrix flow through finer-grained (or matrix) materials. Preferential flow paths can be expressed as channelized flow whereby the water flux is concentrated into spatially distinct areas smaller than the total cross-sectional flow area (Nichol et al., 2005). In this paper, the term matrix flow describes the movement of water through the granular material present between the cobbles and boulders and is dictated by moisture contents, capillary tension and gravity.

The occurrence of some degree of preferential flow in unsaturated porous media has long thought to be the rule rather than the exception (e.g., Brusseau and Rao, 1990; Flury et al., 1994). In general, three factors exert a strong control on the degree of preferential flow in waste rock: the infiltration rate, the spatial arrangement of matrix-supported and matrix-free zones, and the particle size distribution (PSD). The first factor is dependent upon the local climate and is not pertinent to this study as infiltration conditions are similar for all experiments reported here. For the second factor, Herasymuik (1996) observed that the method of construction controls the spatial orientation of material within the pile. For example, waste rock piles that are created by end-dumping may result in a fining-upwards gradation, as coarser material falls to the base of the lift and finer materials generally remain near the surface (Fala et al., 2005). An alternative is push-dumping, whereby waste rock is deposited in a series of lifts starting at the top of a pile and "pushing" the material to a level surface. This method generally results in a coarse lower zone and a non-uniform upper zone with horizontal traffic surfaces between lifts (Corazao Gallegos, 2007).

The PSD of waste rock is a function of its mineralogical composition, material friability, mine-specific blasting techniques, among other factors. PSD analyses generally encompass size fractions that range over several orders of magnitude and, regardless of the coarse proportions, typically exhibit a long tail at the finer size fractions (Smith and Beckie, 2003).

Structured porous media exhibiting flow heterogeneities, or a combination of preferential and matrix flow paths, are frequently described by multi-domain models (Gerke and van Genuchten, 1993a). In the simplest multi-domain model (i.e., dual-porosity), water/solute are partitioned between a mobile and an immobile domain. Using this approach, the mobile domain constitutes preferential flow and matrix flow paths, and the immobile domain includes stagnant (or non-flowing) waters. The immobile domain is a dynamic region whereby water and/or solute may transfer in and out of this domain, as a result of pressure or concentration gradients (Šimůnek and van Genuchten, 2008). Model formulations using a fixed water content in the immobile domain and solute only transfer between the immobile and mobile domains represent the most basic dual-porosity approach and are termed mobile–immobile (MIM) models (e.g., van Genuchten and Wierenga, 1976). A dual-permeability model also assumes two overlapping pore domains, like the dual-porosity approach, but replaces the immobile domain with a low-permeability domain, which allows active, albeit slow water movement (Gerke and van Genuchten, 1993a, 1993b; Šimůnek and van Genuchten, 2008). Water and solute transport in a dual-permeability model can occur within and between mobile and immobile domains.

In this study, flow and tracer response are examined at two experimental scales, in 0.8 m tall laboratory columns and in a 10 m high experimental waste rock pile constructed using the end-dumping method. This study is akin to previous work in that it compares flow and conservative solute transport at two scales (Eriksson et al., 1997; Strömberg and Banwart, 1994, 1999a, 1999b), but differs in its effort to maintain similar compositions and proportions of the different waste rock types at both scales. The objective of this research is two-fold: 1) to determine the main flow regimes controlling solute transport in these waste rock assemblages under site-specific and laboratory conditions, and 2) to determine if the principal influences on solute transport linked to waste rock flow regimes in larger test piles can be adequately reproduced at more practicable scales by managing "controllable" variables (i.e., material compositions and precipitation inputs).

Both experiments share the same rock type and the rainfall applied to the laboratory columns mimics the daily rainfall recorded at the experimental pile. Flow is recorded from basal lysimeters and a tracer test is used to characterize the partitioning of infiltration among different flow paths. Tracer results are analyzed using a flow-corrected time approach (Eriksson et al., 1997) and numerical modeling. The flow-corrected time approach has been employed in other studies with transient flow behavior (e.g., Destouni, 1991; Jury, 1982; Small and Mular, 1987; Wierenga, 1977). Numerical modeling aimed to apply the simplest multi-domain modeling approach (i.e., the MIM model) to permit the diagnosis of dominant features of solute transport processes, while minimizing the number of model parameters.