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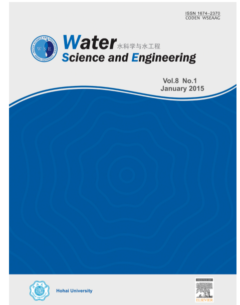

Numerical modeling of solute transport in deformable unsaturated layered soil

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Abstract

The effect of soil stratification was studied through numerical investigation based on the coupled solute transport model in deformable unsaturated soil. The theoretical model implied two-way coupled excess pore pressure and soil deformation based on Biot's consolidation theory as well as a one-way coupled volatile pollutant concentration field developed from the advection-diffusion theory. Embedded in the model, the degree of saturation, fluid compressibility, self-weight of the soil matrix, porosity variance, longitudinal dispersion, and linear sorption were computed. Based on simulation results of a proposed three-layer landfill model using the finite element method, the multi-layer effects are discussed with regard to the hydraulic conductivity, shear modulus, degree of saturation, molecular diffusion coefficient, and thickness of each layer. Generally speaking, contaminants spread faster in a stratified field with a soft and highly permeable top layer; soil parameters of the top layer are more critical than the lower layers but controlling soil thicknesses will alter the results. This numerical investigation showed noticeable impacts of stratified soil properties on solute migration results, further demonstrating the importance of correctly modeling layered soil instead of simply assuming the averaged properties across the soil profile.

Keywords: Solute transport; Layered soil; Consolidation; Unsaturated soil; Deformable media

1. Introduction

Contaminant mass transport through porous media is usually described by well-established conventional advection-dispersion transport models (e.g., Bear, 1972; Barry, 1992) with the ability to account for advection, dispersion, and sorption. Since the mid-20th century, numerous researchers have worked on the advection-dispersion equation (ADE) through analytical approximations (Wang and Zhan, 2015), numerical simulations (Craig and Rabideau, 2006; Boso et al., 2013), and experimental investigations (Rolle et al., 2012) of fully saturated soil environments. Furthermore, solute transport in an unsaturated soil matrix has been studied by several researchers. For example, Fityus et al. (1999) focused on the effects of the degree of saturation and presented pollutant migration in a steady-state unsaturated soil liner under a landfill, and Kumar and Dodagoudar (2010) proposed a stable and convergent two-dimensional (2D) approximate solution using the mesh-free technique.

All the aforementioned studies were based on the assumption of rigid porous media that the volume of the porous media does not change and advective flow is only induced by an external hydraulic gradient. In fact, soil volume change (i.e., soil consolidation) occurs simultaneously with solute transport in many cases. For example, it occurs where the field is under an applied load (self-weight, fill placement, finite size loading, etc.) or experiencing changes in the groundwater table (pumping, artesian wells, etc.). In such cases, the coupled effect of soil deformation and solute transport needs to be considered. Alshawabkeh et al. (2004) showed that the excess pore pressure dissipation produced a transient advective flux of contaminants, which had a strong influence on overall flux. The first attempt at a consolidation-induced solute transport model was formulated by Potter et al. (1994), with errors compared to centrifuge model test results. Later, based on the mass conservation principle, Smith (2000) derived a one-dimensional (1D) contaminant transport equation and provided an analytical solution for a steady-state concentration and a varied porosity circumstance in a fully saturated deformable porous media. The coupled effect of soil consolidation was incorporated into the solute transport model by, first, computing the porosity variation during consolidation and, second, introducing solute migration into the solid phase. To link the two components of solute in pore fluid and solid phases, a linear sorption relationship was postulated. Later, Peters and Smith (2002) extended their previous model (Smith, 2000) to accommodate the time-dependent solute migration process. Recently, adopting Biot's (1941) consolidation theory, Zhang et al. (2012) further developed Peters and Smith's (2002) small strain model to account for the degree of saturation and fluid compressibility. When soil deformation increases, large strain models are required, as reported in Fox (2007a, 2007b) and Zhang et al. (2013). In this study, we only used a small strain model as the first approximation for the case of a multi-layer deformable medium.

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