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Assessment of consolidation-induced VOC transport for a GML/GCL/CCL composite liner system

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ABSTRACT

In municipal solid waste landfills, a triple-layer composite liner consisting of a geomembrane liner (GML), a geosynthetic clay liner (GCL) and a compacted clay liner (CCL) is commonly used at the landfill bottom to isolate the leachates from surrounding environment. This paper presents a numerical investigation of the effect of liner consolidation on the transport of a volatile organic compound (VOC), trichloroethylene (TCE), through the GML/GCL/CCL composite liner system. The numerical simulations were performed using the model CST3, which is a piecewise linear numerical model for coupled consolidation and solute transport in multi-layered soil media and has been extensively validated using analytical solutions, numerical solutions and experimental results. The performed numerical simulations considered coupled consolidation and contaminant transport with representative geometry, material properties, and applied stress conditions for a GML/GCL/CCL liner system. The simulation results indicate that, depending on conditions, consolidation of the GCL and CCL can have significant impact on the transport results of TCE (i.e., TCE mass flux, cumulative TCE mass outflow, and distribution of TCE concentration within the GCL and CCL), both during the consolidation process and long after the completion of consolidation. The traditional approach for the assessment of liner performance neglects consolidation of the GCL and CCL and fails to consider the consolidation-induced transient advection and concurrent changes in material properties and, therefore, can lead to significantly different results. These differences for with and without the consolidation effects can range over several orders of magnitude. The process of consolidation-induced contaminant transport is complex and involves many variables, and therefore case-specific analysis is necessary to assess the significance of liner consolidation on VOC transport through a GML/GCL/CCL composite liner system.

1. Introduction

For modern sanitary landfills, government regulatory agencies require liner systems to be constructed at the landfill bottom to contain the municipal solid wastes and control the generated leachates such that release of hazardous contaminants into the surrounding environment can be prevented or minimized. These liner systems typically are comprised of a composite liner containing a geomembrane liner (GML) underlain with either a geosynthetic clay liner (GCL) or a compacted clay liner (CCL) or with both GCL and CCL. Conventionally, the contaminant transport analyses for these liner systems were performed using advective-diffusive models which assume that the liners are rigid during a landfill service life such that consolidation of the liners is neglected and so is its impact on the liner performance (Foose, 2002; Shackelford, 1990; Rowe et al., 2004; Cleall and Li, 2011; Park et al., 2012; Xie et al., 2015). In reality, however, vertical stress will be applied on these bottom liners due to placement of the wastes. The height of municipal solid wastes can sometimes exceed a hundred meters (Chen et al. 2009), and thus the vertical stress can be very high, sometimes exceeds 1 MPa and even reaches up to nearly 2 MPa at final closure (Mitchell et al., 2007; Zekkos et al., 2006). When such a high vertical stress is applied on the liner system, the liners (e.g., GCL and CCL) will consolidate and cause transient advective transport and variations in material properties, which subsequently can affect the process of contaminant transport through the liner system. As such, the question to be answered is to what extent, if any, will the consolidation of the liners affect the performance of a liner system? Two of our previous investigations (Pu et al., 2016a, 2016b) focused on the numerical assessment of contaminant transport through the GML/CCL composite liner system and the GML/GCL composite liner system, respectively. The present study aims to focus on contaminant transport through a GML/GCL/CCL composite liner system.

Many researchers have investigated the effect of consolidation on contaminant transport for CCL-based liner systems (e.g., single CCL

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liner and GML/CCL composite liner), including field observations (Othman et al., 1997; Rowe, 1998, 2005; Workman, 1993), analytical method (Xie et al., 2016), and numerical investigations (Fox, 2007b; Lewis et al., 2009a, 2009b; Peters and Smith, 1998, 2002; Smith, 1997, 2000; Pu et al., 2016a; Rowe and Nadarajah, 1995; Zhang et al., 2012, 2013), with the latter more commonly found in the literature. These investigations have generally indicated that CCL consolidation can have significant, lasting impact on the results of contaminant transport, including contaminant mass flux, cumulative mass outflow, contaminant breakthrough time, and contaminant distribution within the CCL. Depending on the specific conditions (e.g., loading conditions, and boundary conditions) and the material properties, CCL consolidation can either significantly accelerate or delay contaminant transport or sometimes have negligible effect.

Besides the studies on CCL-based liner systems, similar evaluation for GCL-based liner system has also been conducted. For example, Pu et al. (2016b) performed a numerical investigation of consolidation-induced contaminant transport for a GML/GCL composite liner, and the results indicate that, although GCL is very thin, consolidation of the GCL can still significantly affect the contaminant transport through the GML/GCL liner system via changing GCL material properties (e.g., reducing the GCL thickness, porosity, and effective diffusion coefficient). Despite the studies on the GML/CCL and GML/GCL liner systems, however, no study has been conducted to evaluate the effect of consolidation-induced contaminant transport for a GML/GCL/CCL composite liner system, although such liner system has been commonly used in practice.

This paper presents a numerical investigation of the impact of liner consolidation on the transport of trichloroethylene (TCE), a volatile organic compound (VOC) common in landfill leachates (Lake and Rowe, 2004), through a GML/GCL/CCL composite liner system. The CST3 numerical model developed by Pu and Fox (2016) is used to simulate the coupled large strain consolidation and solute transport. The CST3 model is first briefly described, and then numerical simulation results by model CST3 are compared on the basis of three baseline simulation cases (one considers the effect of liner consolidation and the other two neglect such effect by assuming the GCL and CCL are both rigid with constant properties). Then, a parametric study is carried out to assess the effect of several important variables on the transport of TCE through the GML/GCL/CCL liner system. The differences of results between conventional advective-diffusive transport versus consolidation-induced transport are discussed.

2. Numerical model

CST3 is a numerical model for the simulation of coupled large strain consolidation and solute transport in saturated multi-layered soils (Pu and Fox, 2016), which is developed on the basis of the CS2 method (Fox and Berles, 1997; Fox and Pu, 2012). The consolidation module of CST3 accounts for large strain, soil self-weight, general constitutive relationships, changing compressibility and hydraulic conductivity during consolidation, relative velocity of fluid and solid phases, unload/reload, time-dependent loading schedule and boundary conditions, externally-applied hydraulic gradient, depth-dependent preconsolidation stress profile, and multiple soil layers with different transport properties and material properties. Soil constitutive relationships are defined using either equations or discrete data points to better adapt to user's need. CST3 does not account for the effects of strain rate, secondary compression, or aging on the compressibility or hydraulic conductivity of the soil. The solute transport module of CST3 accounts for advection, diffusion, mechanical dispersion, linear and nonlinear sorption, equilibrium and nonequilibrium sorption, porosity-dependent effective diffusion coefficient, and first-order decay reactions. Contaminant transport is consistent with temporal and spatial variations of soil porosity and seepage velocity, which is the key to the success of the coupling between soil consolidation and solute transport. Depending on the values of input parameters, CST3 can simulate diffusion-controlled, advection-controlled, or combined advective-diffusive contaminant transport (Fox, 2007b). The key to the transport module is the definition of two Lagrangian fields of elements that separately follow the motion of solid phase and that of fluid phase. This approach improves numerical stability and simplifies transport computations to dispersive mass flow between contiguous fluid elements (Fox, 2007a). Top and bottom boundaries with respect to transport conditions can be prescribed concentration (Type I), prescribed concentration gradient (Type II), or prescribed solute mass flux (Type III). The CST3 model and its predecessors have been validated extensively, including comparisons with analytical solutions, numerical solutions and experimental data (e.g., Bonin et al., 2014; Fox, 2007b; Fox and Berles, 1997; Fox and Lee, 2008; Fox and Pu, 2015; Lee and Fox, 2009; Meric et al., 2010, 2017; Pu and Fox, 2016). The main advancement of the CST3 model relative to the CST1 and CST2 models is its capability to account for multiple soil layers with different consolidation properties and transport properties, and thus CST3 is well suited for the modeling of consolidation-induced transport through the GML/GCL/CCL triple-layer liner system.

3. Numerical simulations

3.1. Baseline conditions

3.1.1. Liner system

Baseline simulation conditions use representative consolidation properties and transport properties of liners and stress conditions which were taken from the experimental data reported in the literature, and the baseline conditions then serve as the basis for the subsequent parametric study. Fig. 1 shows the initial configuration of the GML/GCL/CCL composite liner system, which is comprised of, from top to bottom, a leachate collection and removal system (LCRS), a GML, a GCL, a CCL and a subgrade layer. The subgrade can represent an underlying leachate detection system or natural geological layer at atmospheric pore pressure, and is assumed to be fully drained. Same as in the previous studies of Pu et al. (2016a, 2016b), the CCL, GCL, and GML have an initial thickness of 1 m, 10 mm, and 1.5 mm, respectively, with the vertical coordinate z directed upward from the bottom of the CCL. The high-density polyethylene (HDPE) GML is intact and in intimate contact with the upper surface of the GCL, such that there is no GML/GCL interface transmissivity (Harpur et al., 1993; Mendes et al., 2010) and it is undrained under the GML. The LCRS is 1 m thick and contains a constant leachate height of 0.3 m above the GML.

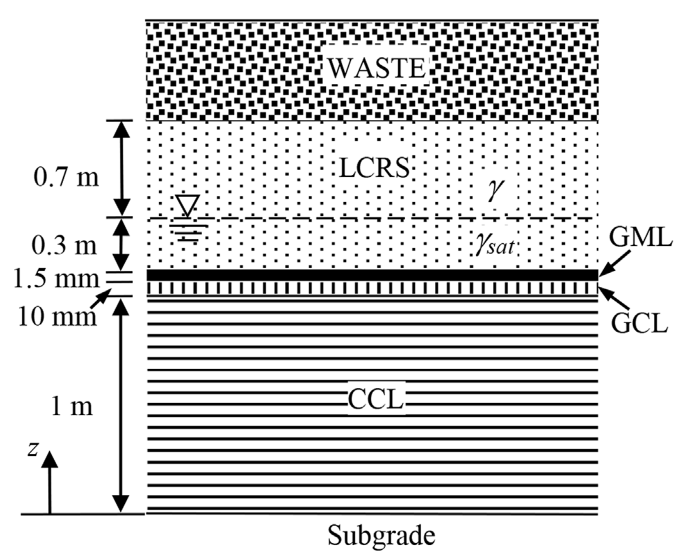

Fig. 1. Initial configuration for GML/GCL/CCL composite liner system.