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Transient analytical solution for one-dimensional transport of organic contaminants through GM/GCL/SL composite liner

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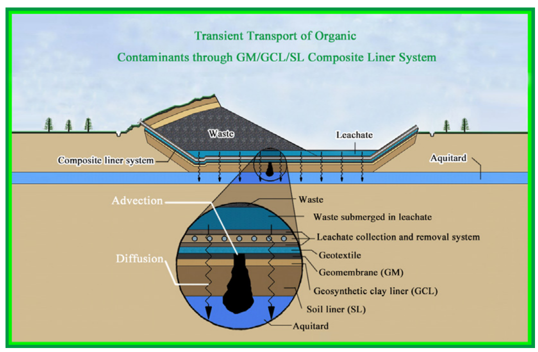
HIGHLIGHTS

- Analytical solution is given for solute transport in GM/GCL/SL composite liner.
- The transient diffusion-advection processes in composite liner can be simulated.
- The rationality of the steady-state and semi-infinite assumptions are studied.
- The two assumptions cause overestimation of breakthrough time.
- The method is able to properly conduct the equivalency assessment.

GRAPHICAL ABSTRACT



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ABSTRACT

Analytical solution for transport of organic contaminants through composite liner consisting of a geomembrane (GM), a geosynthetic clay liner (GCL), and a soil liner (SL) with finite thickness is presented. The transient diffusion-advection processes in the whole composite liner and adsorption in GCL and SL can be described by the present method. The method is successfully verified against analytical solution to a coupling transient diffusion-advection problem in double-layer porous media. The rationality of the steady-state transport assumption in GM and GCL and the semi-infinite bottom boundary assumption, which are widely adopted in the existing works, is comprehensively investigated. The overestimated zone, underestimated zone and no difference zone caused by the two assumptions under various conditions are identified. With the increase of elapsed time, the overestimated zone disappears, and the underestimated zone becomes smaller and smaller and finally is overwhelmed by the no difference zone. Moreover, the equivalency between GM/GCL/SL and GM/CCL composite liners is also properly assessed by the present method. GM/GCL/SL composite liner performs better than GM/CCL composite liner under high leachate level condition.

1. Introduction

Municipal Solid Waste (MSW) landfills and hazardous waste landfills are important sources of groundwater pollution (Qiu, 2011; Han et al., 2016; Postigo et al., 2018). Organic contaminants are among the most hazardous constituents in landfill leachate (Kjeldsen et al., 2002), because they are generally toxic at lower concentration than many inorganic compounds (Edil, 2003; Islam and Rowe, 2008).

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Composite liner, which generally consists of a geomembrane (GM) layer, a compacted clay liner (CCL) or a geosynthetic clay liner (GCL) and a soil liner (SL), has been widely used in landfills to protect surrounding environment and groundwater from landfill leachate pollution (Barroso et al., 2006; Bouazza and Bowders Jr., 2010; Varank et al., 2011a; El-Zein et al., 2012; Park et al., 2012; Hoor and Rowe, 2013; Guan et al., 2014; Xie et al., 2015a). Therefore, it is substantially essential to study the transport of organic contaminants in composite liners.

The prediction of organic contaminant transport through composite liner, however, is quite difficult and intricate for three main reasons. First, composite liner inherently consists of two or even more layers with distinctly different transport properties (Rowe, 2012). Second, the potential mechanisms involved in the transport process are various and complicated, mainly including diffusion, advection and adsorption (Lake and Rowe, 2005; Chen et al., 2015; Xie et al., 2015b). Third, the concentration at a certain point in composite liner changes over time until equilibrium is reached (Foose, 2002; Edil, 2003; El-Zein, 2008). For these reasons, accurately estimating the performance of composite liner system is a challenging work, and great efforts have been made to solve the problem. This study will focus on analytical solutions.

In the past decades, numerous solutions have been proposed for contaminant migration in composite liners (Liu and Ball, 1998; Foose, 2002; Shackelford and Lee, 2005; Chen et al., 2009; Liu et al., 2009; Cleall and Li, 2011; Zhan et al., 2013). However, only diffusion is considered in these solutions. Extensive literature indicates that apart from diffusion, leakage through the geomembrane defects and the underlying SL should also be considered when assessing the performance of landfill composite liners (El-Zein, 2008; Du et al., 2009; El-Zein et al., 2012; Rowe, 2012; Rowe and Abdelatty, 2013), especially in cases with high frequency of holes and high hydraulic leachate head.

Fortunately, several analytical solutions considering diffusion and advection through single layer porous media (Guerrero and Skaggs, 2010; Varank et al., 2011b; Guerrero et al., 2013; Singh and Das, 2015; Singh et al., 2017), double-layer porous media (Li and Cleall, 2011) and composite liners (Guan et al., 2014; Chen et al., 2015) have been developed. For example, Li and Cleall (2011) presented a transient analytical solution for solute transport in double-layer porous media. Guan et al. (2014) and Chen et al. (2015) presented quasi-steady-state analytical solution for solute transport through composite liner consisting of a GM layer or a GCL overlaying a SL. However, the solutions proposed by Li and Cleall (2011), Guan et al. (2014) and Chen et al. (2015) are only applicable for two-layer liners and cannot be directly applied for composite liners with multiple layers. In fact, composite liner consisting of a GM layer overlaying GCL and SL has been widely used in landfills. However, there is scanty analytical solution available for solute transport through a multilayered composite liner considering the coupling effect of diffusion and advection.

Recently, Xie et al. (2015a) has proposed an analytical solution for diffusion and advection transport through a composite liner consisting of GM, GCL and SL, which is the state-of-the-art for this problem (denoted as Steady-state and Semi-infinite Method (SSM)). However, there are still some limitations. First, steady-state transport in GM and GCL is assumed, namely, it is assumed that the contaminant concentration in GM and GCL do not change over time (denoted as steady-state assumption). In fact, contaminant transport through the whole composite liner is a transient process (Foose, 2002). Second, the bottom boundary condition cannot be properly modeled since the SL is assumed to be semi-infinite (denoted as semi-infinite assumption). However, the thickness of SL is definitely finite rather than semi-infinite. The above two assumptions highly simplify the problem, but the rationality of the hypotheses is still questionable and the applicable conditions should be thoroughly investigated.

The main purpose of this paper is to develop transient analytical solution for transport of organic contaminants through a GM/GCL/SL composite liner considering finite thickness of SL. A particular focus of this paper is to identify the limitation of the semi-infinite assumption and the steady-state assumption on evaluating the performance of the composite liner. In addition, the equivalence of performance between GM/CCL and GM/GCL/SL composite liners is also analyzed using the proposed solution.

2. Mathematical model development

2.1. Basic assumptions

As shown in Fig. 1, the liner system is composed of three individual horizontal layers, namely a GM, a GCL and a SL. Advection and diffusion occur in all the three layers, and adsorption of the contaminant occurs in the GCL and SL layers. L_{gm}, L_{gcl} and L_{sl} represent the thicknesses of the GM, the GCL and the SL, respectively; L_{cl} is the thickness of the composite liner; h_w is the hydraulic leachate head mounding on the GM surface. Several assumptions are adopted to facilitate developing the mathematical model: (1) contaminant concentration in the leachate is assumed to be constant at C_0 (Chen et al., 2009); (2) the GCL and the SL are both saturated and homogeneous (Benson et al., 1999; Stark, 2017); (3) contaminant transport is one-dimensional along z axis (Chen et al., 2015); (4) degradation of the organic contaminants is neglected (Chen et al., 2015); (5) adsorption of the contaminant in GCL and SL is a linear and equilibrium process (Rowe, 1998).

2.2. Governing equations and boundary conditions

As the governing equation for GM is not exactly the same as that for GCL and SL, which results in much difficulty in obtaining the solution for the whole composite liner, a normalization method is proposed to deal with the governing equations and boundary conditions for GM. Consequently, a normalized general governing equation that is applicable for all the three layers is finally obtained, which is the key to get the transient solution for the whole composite liner.

(1) GM layer

The transient transport of contaminants through GM can be described by the following equation:

$$\frac{\partial C_{gm}(z,t)}{\partial t} = D_{gm}\frac{\partial^2 C_{gm}(z,t)}{\partial z^2} - \frac{v_a}{K_g}\frac{\partial C_{gm}(z,t)}{\partial z} \tag{1}$$

where $C_{gm}(z,t)$ is the contaminant concentration in GM at any position z and any time t; D_{gm} is the diffusion coefficient of GM; K_g is the partition coefficient between GM and the landfill leachate, which is the ratio of the contaminant concentration at equilibrium in GM to that in the leachate; v_a is the Darcy velocity of contaminant in the composite

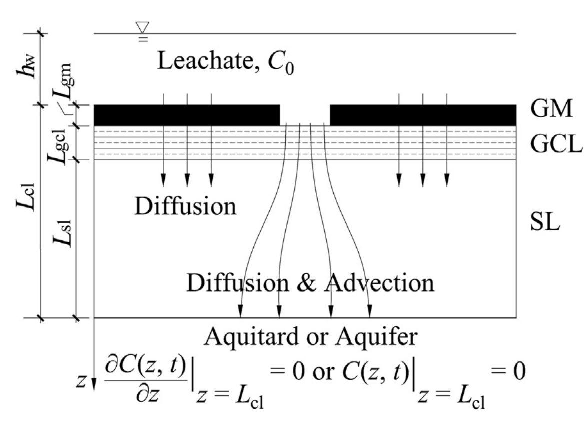

Fig. 1. Mathematical model for contaminant transport through composite liner.