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Technical note

Breakthrough time-based design of landfill composite liners

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ABSTRACT

Breakthrough time based design methods for determining the design thickness of landfill composite liners are proposed. The composite liners consist of either 1) a geomembrane (GMB) and a compacted clay liner (CCL), 2) a geomembrane (GMB), a geosynthetic clay liner (GCL) and a soil liner (SL), or 3) a GCL and a SL. The design methods are based on analytical solutions developed for solute advection and dispersion of leachate contaminants in composite liners. Both solute concentration and solute flux are considered in the analyses. Two dimensionless parameters involving contaminant concentration and contaminant flux are introduced and the design curves are proposed for breakthrough time based design of composite liners. The results obtained by the proposed analytical solutions are in good agreement with the experimental data published in the literature. Illustrative examples are presented to demonstrate the application of the design methods for composite liners consisting of a GMB and a compacted soil liner and those consisting of a GMB, a GCL, and a SL. The effect of leachate head on the design thickness of composite liners was investigated. It is shown that the design methods presented in this paper is easy to be used to design the landfill composite liners in different leachate head cases.

1. Introduction

Liner systems are often required in modern landfills to prevent groundwater pollution caused by leachate pollutants. Composite liners are very popular. They consist of either a geomembrane (GMB) and a compacted clay liner (CCL), or a GMB, a geosynthetic clay liner (GCL), and a soil liner (SL) (Foose, 2002; Foose et al., 2002; Rowe et al., 2004; Chai et al., 2005; Du et al., 2009; Xie et al., 2009; Cleall and Li, 2011; Park et al., 2012; Rowe, 2012; Xie et al., 2013a; Abuel-Naga and Bouazza, 2014; Hosney and Rowe, 2014). A GMB is an excellent barrier for inorganic contaminants such as heavy metal ions (Rowe et al., 2004; Ewais et al., 2014). A CCL or a SL acts as the diffusion barrier for both organic and inorganic leachate contaminants. The typical three types of standard composite liners specified in China are a GMB with a 0.75 m CCL, a GMB with an attenuation layer, and a GMB with a GCL overlying on an attenuation layer (MCPRC, 2007; MEPPRC, 2008). The hydraulic conductivity of CCL and GCL should be less than 1×10^{-9} m/s and 5×10^{-11} m/s, respectively (MCPRC, 2007). The main mechanism for inorganic contaminant transport in the composite liners is advection through GMB defects and advection-dispersion in the underlying GCL, CCL, or attenuation layer (Rowe, 2005; Varank et al., 2011). Unlike inorganic contaminants, organic contaminants can readily transport through intact GMB by molecular diffusion (Edil, 2003; Chen et al., 2009; McWatters and Rowe, 2009, 2010, 2014; Mendes et al., 2014; Shackelford, 2014).

Cleall and Li (2011) provided an analytical method for the design of landfill composite liners considering pure diffusion. Xie et al. (2013a,b) provided an analytical method for the breakthrough time-based design of composite liners consisting of a GMB, a GCL and a soil liner. However, the advection transport of contaminant through the GMB defects and then the soil liner was ignored in these studies. When the leachate head is low (e.g., <30 cm) and the defects of the GMB are small, the pure-diffusion assumption will not result in large differences. However, the leachate head generated in the landfill tends to be quite high (Guan et al., 2014; Zhan et al., 2014) (e.g., the leachate head exceeds 10 m in Qizishan landfill in China (Zhan et al., 2008; Xie et al., 2009)) and the frequency of geomembrane defects can reach up to hundreds or even thousands per hectare in some developing countries (Xie et al., 2010). In China, the high leachate level in landfills is caused by two main factors. First, the leachate collection systems are not effective and the leachate flow cannot be drained in time due to the

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clogging of the materials in the systems. This is the case in the Shenzhen Xiaping landfill, which had a leachate level of about 30 m. Second, the water content of landfilled waste in China is typically around 50%, which is much higher than that in the municipal solid waste (MSW) of the U.S. and the European countries (20–30%) (Cheng et al., 2007). Furthermore, the hydraulic conductivity of soil liners such as GCLs would be increased when they are permeated with leachate contaminants (Liu et al., 2015). The bentonite in GCLs is sensitive to chemical interactions with the hydrating liquid, and the ion exchange that occurs in bentonite can alter its physical properties. In particular, the exchange of multivalent cations for the native sodium results in an increased hydraulic conductivity and a decreased swell potential (Paumier et al., 2011). The hydraulic conductivity of GCL increased to 1.5×10^{-11} m/s and 4.7×10^{-9} m/s when permeated in 0.01 M and 2 M NaCl solution, respectively (Petrov and Rowe, 1997). The hydraulic conductivity of the 0.01–0.1 M zinc solution polluted compacted natural montmorillonite clay is 1.3–1.6 times higher than that of clay saturated with water (Souli et al., 2008). Under these circumstances, the contaminant flux caused by leakage through geomembrane defects and then by advection through the GCL, CCL or soil liners can be significant. The advective transport of organic compounds through GMB defects cannot be ignored (Xie et al., 2010). To the authors' knowledge, a breakthrough time based design method for landfill composite liners considering both the effect of diffusion and advection is not available.

The main purpose of this paper is to provide a simple method for the design of landfill composite liners including GMB/CCL, GCL/SL and GMB/GCL/SL on the basis of contaminant breakthrough time. The combined effects of diffusion and advection transport in the composite liners are considered. Non-dimensional design charts were proposed based on the analytical solutions for contaminant transport through GMB/CCL and GCL/SL. The design procedure and illustrating examples were then presented to demonstrate the application of the method.

2. Materials and methods

2.1. Breakthrough time analysis

The concept of contaminant breakthrough time based design method is shown in Fig. 1, where h_w is the leachate head acting on the liner system and L is the thickness of the landfill liner system. The concentration of contaminant in the leachate is assumed to be a constant C_0. The concentration of contaminants in the groundwater, C_b, is assumed to be the limit concentration of the contaminant specified in the drinking water standard, since groundwater is an important source of drinking water in many Chinese cities. The breakthrough time is defined as the time required for the contaminant with a concentration of C_0 in the leachate to reach the limit concentration of C_b in the groundwater. The breakthrough time should be greater than 30 years for a landfill site.

2.1.1. Composite liners consisting of GMB and CCL

As GMB is much thinner (1.5–3 mm) when compared to CCL (≥0.75 m), steady-state transport of contaminant through it was assumed. The mathematical model for contaminant transport through composite liner with geomembrane defects can then be developed on the basis of the steady state assumption (see Fig. 2). z is the spatial dimension in the direction of transport with its origin at the top surface of the geomembrane. L_g is the thickness of the GMB and L_s is the thickness of CCL.

The governing equation of contaminant transport through the GMB of the composite liner can be described by (Xie et al., 2010):

$$D_g \frac{d^2 C_g}{dz} - v_a \frac{dC_g}{dz} = 0 \tag{1}$$

where D_g is the diffusion coefficient of the contaminant in the geomembrane; and v_a is Darcian velocity in the composite liner. It can be obtained by (Rowe et al., 2004):

$$v_a = mQ/A \tag{2}$$

where Q is the leakage rate through one defect in the composite liner (m^3/s); m is the number of defects in GMB per square meter; and A is the transversal surface area of flow (m^2).

Rowe (1998) developed a simple equation to predict leakage through a hole in a GMB coincident with (or adjacent to) to a wrinkle, which, in its simplest form (assuming no interaction between adjacent wrinkles), can be written as (Chappel et al., 2012; Rowe, 1998, 2012; Rowe et al., 2012):

$$Q = 2L\left[kb + (kL_S\theta)^{0.5}\right] h_d/L_S \tag{3}$$

where L is the length of the connected wrinkles (m); $2b$ is the width of the wrinkle (m); L_S is the thickness of the CCL (m); θ is the transmissivity of the interface between GMB and the underlying soil liner (m^2/s); k is hydraulic conductivity of the underlying soil liners (m/s); and h_d is the head loss across the composite liner (m).

The seepage velocity in the underlying soil liner is given by:

$$v_s = v_a/n_s \tag{4}$$

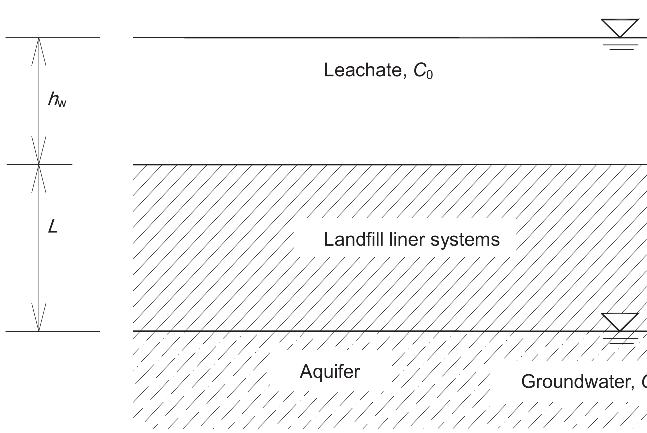

Fig. 1. Schematic of breakthrough time-based design of landfill liner system.

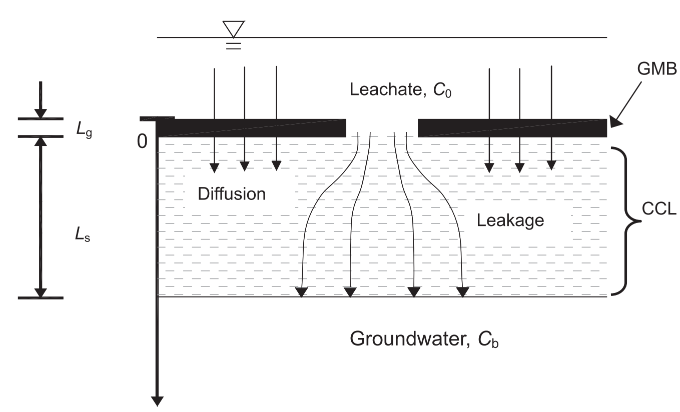

Fig. 2. Mathematical model for contaminant transport through GMB/CCL.