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Research Paper

Failure probability assessment and parameter sensitivity analysis of a contaminant’s transit time through a compacted clay liner

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ABSTRACT

This paper presents failure probability assessment and parameter sensitivity analysis of a contaminant’s transit time through a compacted clay liner. Monte Carlo simulation (MCS) was used to assess failure probability, and the failure samples generated in the MCS were used to investigate the sensitivity of various uncertain parameters to the failure probability. To facilitate the MCS, a database on various transport parameters was developed by collecting and analyzing measurement data reported in literature. Failure probability assessment and parameter sensitivity analysis showed that the uncertainties in adsorption parameters, longitudinal dispersivity, and hydraulic conductivity have the most significant effects on failure probability.

1. Introduction

In a modern landfill, it is essential to construct an engineered liner system at its bottom to separate the waste and the associated leachate from the groundwater system (e.g., [61,46]). Compacted clay liner is a type of commonly used liner worldwide (e.g., [62]). For example, a 2-m-thick compacted clay liner is a typical liner prescribed by the Chinese national standards [53]. A key performance index of a liner is transit time (TT), which is defined as the time required for the concentration, C_b, of a contaminant in the aquifer at the bottom of the liner to reach an unacceptable level (see Fig. 1). A liner is considered failed when its TT is smaller than the expected service life (SL) of the liner.

Estimation of TT through a compacted clay liner in engineering practice unavoidably involves various uncertainties in transport parameters that arise from their inherent spatial variability and measurement errors (e.g., [28,43]). It is therefore important to incorporate these uncertainties into the analysis of contaminant transport using probabilistic analysis. Some probabilistic methods have been used for evaluating the performance of a compacted clay liner, including the first-order reliability method [28,1], stochastic finite element method [13], Bayesian method [8], and Monte Carlo simulation (MCS) [17,5,45,49]. Among these methods, the MCS provides a robust and conceptually simple way to evaluate failure probability (e.g., [47]).

Different performance criteria have been used when evaluating the failure probability of a liner. For example, the previous studies mentioned above used either hydraulic conductivity, which only considers advection [8,17,5,1], or the concentration of contaminants (i.e., C_b) at the bottom [45,49], which considered advection, diffusion, and adsorption. It is worthwhile to note that TT is a widely used performance criterion in traditional or deterministic liner performance evaluation (e.g., [65,35,25,15]). Shackelford [65] defined TT as the time required for the concentration of a specific leachate component at the bottom of the liner to reach a prespecified unacceptable level. Using TT as the performance criterion not only allows the consideration of advection, diffusion, and adsorption simultaneously but also relates the performance of the liner to its SL. However, to date, TT-based probabilistic analysis has not been performed, and the effect of various uncertainties on TT-based failure probability has not been explored systematically through sensitivity analysis.

The results of sensitivity analysis are of significant practical value as they quantify the contribution of the various sources of uncertainty to the overall design uncertainty (e.g., [22]). Resources, whether intellectual or physical, can thus be rationally allocated toward reducing the uncertainty of the variables with significant impacts on design. For example, Bieda [7] conducted a sensitivity analysis with an approximated analytical solution to determine the relative influence of input parameters on solute transport in

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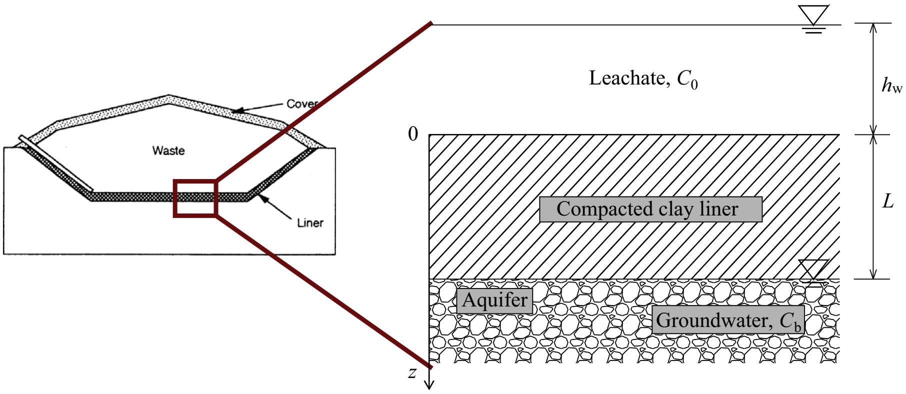

Fig. 1. Schematic of transit time-based design of compacted clay liners.

the saturated soil of a landfill. However, only advection and diffusion were considered in this previous study and adsorption was ignored. Therefore, further work is needed to consider advection, diffusion, and adsorption simultaneously and provide insight into the relative contributions of various uncertainties to TT-based failure probability.

This paper aims to (a) perform a TT-based failure probability assessment for a compacted clay liner using the MCS and (b) conduct parameter sensitivity analysis using the failure samples generated in the MCS and a probabilistic failure analysis approach [70]. To facilitate the probabilistic analysis, a database on various transport parameters was developed by collecting and synthesizing laboratory and field measurement data reported in the literature. After this introduction, a deterministic model was introduced for estimating the TT through a compacted clay liner, followed by probabilistic approaches for assessing failure probability and performing parameter sensitivity analysis. Then statistical analysis of transport parameters (e.g., hydraulic conductivity, effective diffusion coefficient, adsorption parameters) was performed according to the measured data collected from the literature. As an illustration, the proposed TT-based failure probability assessment was then performed for a typical compacted clay liner. Finally, parameter sensitivity analysis was conducted to identify an important uncertainty that significantly affects the failure probability. In addition, the effects of leachate head and SL were investigated.

2. Transit time analysis

The concept of TT-based design method is shown in Fig. 1, where h_w is the leachate hydraulic head acting on the liner and L is the thickness of the compacted clay liner. The concentration of contaminant in the leachate is denoted as C_0. The maximum allowable concentration of the contaminant specified in the drinking water standard is taken as the maximum allowable C_b in groundwater as groundwater is an important source of drinking water in many regions. The TT of a compacted clay liner is defined as the minimum time required for the contaminant with a concentration C_0 on top of the liner to transport through the liner and reach the maximum allowable C_b in the ground water, and it is adopted as the performance index of a compacted clay liner in this study.

The governing equation of contaminant transport through a compacted clay liner can be expressed by the following one-dimensional advection-dispersion equation (e.g., [62]):

$$R_d \frac{\partial C}{\partial t} = \left[D_h \frac{\partial^2 C}{\partial z^2} - v_s \frac{\partial C}{\partial z} \right] \tag{1}$$

where z is the vertical coordinate, C is the contaminant concentration, and R_d is the retardation factor and can be determined as (e.g., [62])

$$R_d = 1 + \frac{\rho_d K_p}{n} \tag{2}$$

where ρ_d is the dry density, n is the porosity, and K_p is the partition coefficient. When the soil exhibits a behavior of linear adsorption, K_p becomes the distribution coefficient, K_d [66]. D_h is the hydrodynamic dispersion coefficient for the contaminant and can be obtained as (e.g., [62])

$$D_h = D^* + \alpha v_s \tag{3}$$

where D^* is the effective diffusion coefficient, α is the longitudinal dispersivity, and v_s is the seepage velocity given by

$$v_s = k * (hw + L)/L/n \tag{4}$$

where k is the hydraulic conductivity.

From Eq. (1), TT can be obtained by the following analytical solution [57]:

$$\frac{\mathrm{C_b}}{\mathrm{C_0}} = \frac{1}{2}\left[erfc\left(\frac{L\mathrm{R_d} - \mathrm{v_s}TT}{2\sqrt{\mathrm{D_h R_d}TT}} \right) + \exp\left(\frac{\mathrm{v_s}L}{\mathrm{D_h}} \right) erfc\left(\frac{L\mathrm{R_d} + \mathrm{v_s}TT}{2\sqrt{\mathrm{D_h R_d}TT}} \right) \right] \tag{5}$$

where erfc() is the complementary error function. The initial and boundary conditions for the solution given by Eqs. (1) and (5) are

$$\begin{aligned} &C(\mathrm{z} \geqslant 0, \mathrm{t} = 0) = 0 \\ &C(\mathrm{z} = 0, \mathrm{t} > 0) = C_0 \\ &C(\mathrm{z} = \infty, \mathrm{t} > 0) = 0 \end{aligned} \tag{6}$$

Note that Eqs. (5) and (6) are based on the following assumptions: (i) the clay liner is homogeneous, fully saturated, and semi-infinite; (ii) steady-state flow has been established; and (iii) the contaminant concentration on top of the clay liner is constant. Because groundwater level is not always at the bottom of the liner, the leachate concentration probably fluctuates significantly over the SL of a liner, and the underlying aquifer also affects contaminant transport, Eq. (5) tends to provide conservative results [65,24,35].

As the parameters (e.g., D^* and R_d) for different contaminants vary greatly, the TT of a liner depends on the contaminants that are transported through the liner. Consider, for example, two frequently detected contaminants in leachate: toluene and Cd^{2+}. Toluene is a representative toxic and volatile organic compound in leachate [56,63,38,19,41]. Cd^{2+} is a representative heavy metal in leachate (e.g., [23,67,68,18,69]), and it has been listed in the Chinese national drinking water standards as a toxic element and is considered a highly mobile inorganic contaminant. According to the Chinese national drinking water standard [55], the maximum allowable concentrations of toluene and Cd^{2+} in groundwater are