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# Parametric sensitivity analysis of coupled mechanical consolidation and contaminant transport through clay barriers

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ABSTRACT

In this paper, an extensive parametric sensitivity analysis of coupled consolidation and solute transport in composite landfill liner systems has been undertaken. The analysis incorporates results of more than 3000 simulations for various combinations of barrier thickness, waste loading rate, initial void ratio, compression index, hydraulic conductivity and dispersion coefficient. However, it is noted that to limit the extent of the study a constant coefficient of consolidation is assumed in the analysis presented here, though this assumption is easily relaxed. Results of the parametric sensitivity analysis are succinctly presented using dimensionless plots, which allow the comparison of results for a large number of parameter values, and so the clear identification of the most important determinants on contaminant transport through the liner system. The dimensionless plots demonstrate a pessimum (for which the 'breakthrough time' is minimised). Numerical results reveal that in cases of extreme liner compressibility an order of magnitude reduction in contaminant transit time may arise due to coupling between solute transport and consolidation, while for barriers of low compressibility and porosity (such as well-engineered composite compacted clay landfill liners), it is found that the contaminant transit time may still be reduced by more than 30%. The numerical results suggest that the use of coupled consolidation–contaminant transport models are sometimes required for informed and conservative landfill liner design.



## 1. Introduction

Modern engineered waste-disposal facilities such as municipal landfills usually employ composite contaminant barrier systems (see Fig. 1). These typically consist of a low hydraulic conductivity clay layer (or equivalent) and an overlying geomembrane. A well-constructed composite barrier limits the migration of pollutants from the waste into surrounding groundwater largely by restricting the passage (leakage) of leachate. This can only occur through defects in the geomembrane and even here is restricted by the low hydraulic conductivity of the underlying clay. Low leachate leakage rates through well-constructed composite barrier systems mean that the advective transport of contaminants is kept to a minimum. As a consequence, diffusion is often considered to be the dominant mode of transport. Ionic contaminants are essentially incapable of diffusing through the organic polymer structure of most geomembrane materials (because of very low diffusion coefficients). However, the diffusion of small non-ionic molecules such as volatile organic compounds (VOCs) can be quite rapid. For this reason, it is the diffusion of small (and often toxic) VOCs that become the main focus of contaminant transport modelling in composite contaminant barriers [10].

Modelling of VOC transport through composite barriers is commonly based upon a relatively simple diffusion analysis. However, results from some field studies involving composite landfill liners have indicated that contaminant transit times may be significantly smaller than those expected from a "diffusion only" contaminant transport analysis. It has also been hypothesized that "consolidation water", expelled from a porous clay liner upon mechanical loading, may lead to advective transport through the clay liner, and higher than expected secondary leachate production beneath the liner. These observations have led to the hypothesis that "consolidation induced advection" may be the cause of the accelerated transit of contaminants [20].

Recently, a number of theoretical investigations of coupled consolidation and contaminant transport in composite barriers have been carried out [2,15,16,18,22]. These investigations have mainly focussed on the development and comparison of different model formulations and constitutive relations. Some of the investigations have incorporated case studies of landfill liners. These have shown that the coupling of consolidation and transport processes can be significant; resulting in contaminant transit times which are substantially lower than those predicted by a traditional "diffusion

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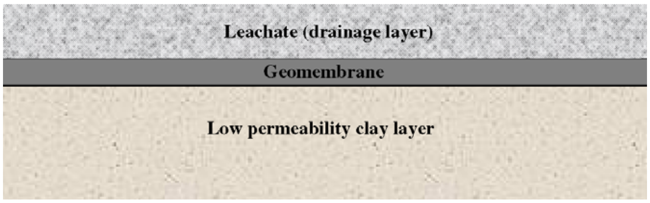


**Fig. 1.** Schematic diagram of a composite contaminant barrier.

only" analysis. However, since the coupled consolidation–contaminant transport models generally require knowledge of various soil and contaminant transport parameters that are either not available or not easy to measure under field conditions, there is some uncertainty regarding the relevance of the results obtained to practical circumstances. For this reason a more extensive investigation of the effects of consolidation on the transport of contaminants through composite barriers such as landfill liners is warranted.

The aim of this paper is to investigate the influence of the choice of model parameters and liner thickness on breakthrough times in composite liner systems. For this purpose an extensive parametric study consisting of over three thousand numerical simulations using the coupled, large-deformation consolidation–transport model of Lewis et al. [15] has been undertaken. Six key design variables are considered in the parametric study: the liner thickness, loading rate of waste in the landfill, and clay soils properties including the initial void ratio, the hydraulic conductivity, the compression index and the dispersion coefficient. Use of non-dimensional time variables allows representation of a vast amount of numerical data in concise form. These plots reveal the regions of the 'parameter space' for which the coupling is most influential in terms of reducing the transit (or breakthrough) time of contaminants across the barrier, so allowing 'worst case' or 'pessimum' scenarios to be identified. In addition, the investigation yields insight into the mechanisms through which consolidation affects contaminant transport in composite barrier systems. These insights contribute to a better understanding of composite liner system behaviour, and may help improve current engineering design.

## 2. Method

### 2.1. Barrier characteristics

The composite contaminant barrier system investigated here is typical of those employed in many large-scale solid waste landfills. The "single composite" barrier system is composed of a geomembrane and an underlying clay layer of low hydraulic conductivity. A schematic cross-section of the barrier is shown in Fig. 1.

During operation, leachate from the waste accumulates above the geomembrane in the overlying drainage layer. Removal of leachate is generally facilitated by a network of perforated leachate collection pipes incorporated within the drainage layer. It is assumed that leachate leakage through the geomembrane is negligible in terms of the contribution to contaminant transport across the barrier, that is, contaminant advection through the geomembrane is negligible compared to diffusion. It should be noted that this assumption does not preclude consolidation induced advection of contaminants within the clay layer, after they have diffused across the geomembrane. To both provide a conservative analysis and limit the complexity of the parametric investigation described here, a constant contaminant concentration in the leachate is assumed [12]. In other words, it is assumed that the leachate is 'well mixed' and contaminant decay over time is negligible (i.e., a constant contaminant concentration, $c_0$, is maintained in the leachate).

### 2.2. Consolidation–transport model

The theoretical investigation is based on a material coordinate (that is, Lagrangian coordinates: material displacement – $a$, time – $t$) large-deformation consolidation–transport model formulation. The model and its advantages over a variety of other model formulations have been described in detail previously [15] and so these arguments are not reproduced here. However, for reference, the governing equations, constitutive relations and boundary conditions are presented without derivation below together with relevant references. To keep the scope of the investigation manageable and provide conservative estimates of contaminant transit times, the effect of sorption on contaminant transport is neglected. Also, in considering the consolidation of the liner, the effect of the self-weight is neglected due to its relatively small magnitude for a thin clayey liner in comparison to the mechanical loading it is likely to carry. The model equations were solved using the multiphysics finite element software package FEMLAB 2.3 [8].

#### 2.2.1. Governing equations – consolidation

The equations describing soil consolidation can be formulated as follows:

$$\frac{1}{1+e_0}\frac{\partial e}{\partial t}=\frac{\partial}{\partial a}\left(\frac{k(1+e_0)}{\rho_f g a_v(1+e)}\frac{\partial e}{\partial a}\right) \quad (1)$$

where $e$ is the void ratio, $e_0$ the initial void ratio (constant, since self-weight is neglected), $k$ the hydraulic conductivity, $g$ the acceleration due to gravity, $\rho_f$ the mass density of the fluid phase, $a_v(\equiv \frac{de}{d\sigma'})$ is the coefficient of compressibility, and $\sigma'$ is the effective stress.

#### 2.2.2. Governing equations – contaminant transport

Transport of contaminants through porous soil can be readily described as

$$\frac{e}{1+e_0}\frac{\partial c}{\partial t}=\frac{k(1+e_0)}{\rho_f g a_v(1+e)}\frac{\partial e}{\partial a}\frac{\partial c}{\partial a}+(1+e_0)\frac{\partial}{\partial a}\left(\frac{e}{(1+e)^2}D\frac{\partial c}{\partial a}\right) \quad (2)$$

where $c$ is the solute concentration in the fluid phase and $D$ is the coefficient of hydrodynamic dispersion. In Eq. (2) the first term on the right-hand side (rhs) describes transport due to advection caused by soil consolidation. The second term on the rhs is the contribution due to diffusion. The Darcy velocity is commonly introduced as $q = k(1+e_0)/(\rho_f g \ a_v)/(1+e)\partial e/\partial a$. Advective and diffusive flux can be expressed as $f_a = c\cdot q$ and $f_d = (1+e_0)e/(1+e)^2 D\,\partial c/\partial a$.

In order to describe the dependence of the compressibility coefficient, hydraulic conductivity, and dispersion coefficient on the void ratio the following constitutive relations have been used:

$$a_v=\frac{C_c}{\sigma'_p\cdot\ln 10}\exp\left(\ln 10\cdot\left(\frac{e-e_p}{C_c}\right)\right),$$
$$k=k_p\exp\left(\ln 10\cdot\left(\frac{e-e_p}{C_k}\right)\right),\quad D=D_e=\text{const} \quad (3)$$

where $e_p$ and $\sigma'_p$ are the void ratio and effective stress values, respectively, corresponding to the preconsolidation stress, $C_c$ is the soil compression index (defined as absolute value of the slope of the idealised virgin compression line), $k_p$ is the hydraulic conductivity of the soil corresponding to $e_p$ and $C_k$ is the hydraulic conductivity (or 'permeability') index. Note that in Eq. (2) we assumed that the coefficient of hydrodynamic dispersion ($D$) is equal to the effective diffusion coefficient ($D_e$) and constant. This assumption generally holds for fine-grained soils where the Darcy velocity is low.

#### 2.2.3. Boundary conditions – consolidation

$$\frac{\partial e}{\partial a}(0,t)=0;\quad e(L,t)=\begin{cases} e_p, & \sigma_a\leqslant\sigma'_p\\ e_p-C_c\log\left(\frac{\sigma_a}{\sigma'_p}\right), & \sigma_a>\sigma'_p\end{cases} \quad (4)$$