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Modelling of thermally induced desiccation of geosynthetic clay liners in double composite liner systems

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A B S T R A C T

Double composite liner systems (DCLSs) for municipal or hazardous waste landfills often include geomembranes (GMBs) and geosynthetic clay liners (GCLs). Heat generated within such landfills due to exothermic degradation of organic matter or hydration of incinerator ash creates thermal gradients across the liner. These thermal gradients have the potential to induce a movement of moisture and create a risk of desiccation of the mineral component of the GCLs. This paper presents the results of a simulation of moisture redistribution and discusses the potential for desiccation of GCLs in DCLSs when subjected to thermal gradients using a numerical model developed by Zhou and Rowe (2003). The results from a series of laboratory experiments previously reported by the authors (Azad et al., 2011) are compared with model predictions. Two alternative soil water characteristic curves (SWCC), proposed by van Genuchten (1980) and Fredlund and Xing (1994), are implemented and their effects on the model's accuracy assessed. The original model is found to predict reasonably well water distribution and the likelihood of thermal desiccation of the GCL.

1. Introduction

Modern landfill barrier systems include a composite liner comprised of a geomembrane (GMB) and a geosynthetic clay liner (GCL) intended to reduce the outward transport of contaminants to a negligible level (Rowe et al., 2004). Although GMBs represent the primary barrier to leachate flow, leakage through perforated wrinkles and other defects in the GMB can occur and a GCL serves to minimize that leakage (El-Zein and Rowe, 2008; Rowe, 1998, 2005, 2012).

In many parts of the world, 50–70% of the dry unit weight of the waste in municipal solid waste is organic matter (USEPA, 2003). The decomposition of organic matter is an exothermic process. The temperature increases due to this decay process have potential undesirable impacts on the long term performance of landfills due to temperature related changes in soil properties, a decrease in the service life of the GMB, and an increase in the risk of desiccation of clay liners (Abu-Hejleh and Znidarcic, 1995; Rowe et al., 1997, 2010; Rowe and Hoor, 2009; Southen and Rowe, 2005a, 2011). Field monitoring of temperature at or near the liner systems has shown that heat generated by waste material can reach 45 °C in the underlying landfill liners (Koerner and Koerner, 2006; Rowe and Islam, 2009; Yesiller et al., 2005; Yoshida and Rowe, 2003), with temperatures of up to 60 °C, and in unusual cases even higher, being reported (Collins, 1993; Koerner et al., 2008; Lefebvre et al., 2000; Rowe, 2005). Since the temperatures within the aquifer are typically 5–25 °C (depending on location), this scenario leads to high temperature gradients. Due to the dependence of vapour density on temperature, this temperature gradient induces downward vapour migration from areas of higher temperature to areas of lower temperature. The resulting decrease in water content in the warmer areas causes liquid water to move upward because of the capillary pressure gradient (matric suction). Air also moves from areas of higher air pressure to those of lower air pressure. The combined effect of liquid water, vapour water, and air flow causes moisture movement and consequently, creates the potential for desiccation of the mineral component of GCL.

Traditionally, two models have been used to simulate soil moisture movement in clay liners under non-isothermal conditions (Milly, 1982; Philip and de Vries, 1957). Milly's model in particular can be applied to both saturated and unsaturated media because it uses capillary pressure, rather than moisture content, and temperature as the primary variables. Döll (1997) developed a numerical model based on two partial differential equations for

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transport of heat and moisture to describe desiccation of mineral liners. Her model was extended by Heibrock (1997) by combining it with a procedure to predict tensile failure taken from Morris et al. (1992). While these models have succeeded to some extent in accounting for observed experimental behaviour, they were all limited in a number of ways including, most importantly, their inability to account for the deformation of the medium (Southen and Rowe, 2005b).

A number of models have been proposed to simulate the thermo–hydro–mechanical behaviour of unsaturated soils (Dakshanamurthy and Fredlund, 1981; Geraminejad and Saxena, 1986; Thomas and He, 1995; Zhou et al., 1998). Zhou and Rowe (2003) have developed one such fully-coupled model, henceforth referred to as ZR3, specifically aimed at modelling the thermo–hydro–mechanical behaviour of landfill liners.

ZR3 incorporates the effects of temperature and stress on moisture transfer, as well as temperature effects on stress and that of air flow on moisture. However, ZR3 has a number of limitations. First, the model does not explicitly simulate cracking but, rather, it predicts the net total horizontal stress and the user can infer that cracking is likely to have occurred when the calculated net total horizontal stress within the clay liner becomes tensile. Second, the model ignores the thermo-plasticity of the GCL. It has been shown that up to temperatures of approximately 40 °C, changes in temperature have a relatively small effect on void ratio (Devillers et al., 1996; Saix et al., 2000). Therefore, this limitation is not likely to be significant in this study because the temperature on the primary geomembrane is between 32 °C and 45 °C and the temperature on PGCL is even lower (Azad, 2011). Third, the model employs a soil water characteristic curve – SWCC – (water retention curve) developed by Lloret and Alonso (1985) that for a given stress level may not offer the most accurate representation of the SWCC of a GCL (Beddoe, 2009; Southen and Rowe, 2007). However it is the only commonly available model that also considers the effect of the change in stress/void ratio on the SWCC of the GCL. The effect of the limitation of the Lloret and Alonso SWCC for GCLs was minimized by selecting the parameters to provide a good fit over the range of suction expected in the cases modelled.

Notwithstanding the limitations of ZR3, predictions made with the model have been found to be in good agreement with experimental results and observed field behaviour of single lined landfill barrier systems (Southen, 2005; Zhou and Rowe, 2003, 2005) and it is, presently, the only available model potentially suitable for examining desiccation cracking of GCLs in composite liners at the base of MSW landfills.

The primary objective of this present study is to examine the ability of the ZR3 model to explain moisture changes under thermal and mechanical stress in a double composite liner system (DCLS) containing two GCLs. The results of four laboratory experiments specifically designed to examine the potential for desiccation of GCLs in DCLSs (Azad et al., 2011), will be compared with model predictions for the ZR3 model using the Lloret and Alonso (1985) representation of the SWCC. Then, the predictions obtained by incorporating the soil water characteristic curve equations proposed by van Genuchten (1980) and Fredlund and Xing (1994) will be examined to assess their ability to improve (or not) the accuracy of the results.

2. Thermal consolidation model

2.1. Non-linear thermo-poro-elastic theory

2.1.1. Background and assumptions

In a deformable unsaturated soil medium, there are three different phases (solid, liquid and gas) and transfer of heat, moisture and air in this medium involves interaction among three different fields (thermal, mechanical and hydraulic). To establish the equations of this complex system, various assumptions are made:

(1) the porous medium is deformable, homogeneous and isotropic;
(2) deformations are small and strains are infinitesimal;
(3) thermal equilibrium exists between different phases;
(4) vapour movement is due to convection and diffusion;
(5) the velocities of liquid water and air both follow Darcy's law;
(6) heat flow is due to heat conduction, heat convection and latent heat transfer;
(7) soil grains are incompressible and their density is constant.

The governing equations in the ZR3 model are based on the equations of equilibrium, water mass balance, air mass balance, and heat energy balance. Vertical displacement, capillary pressure, air pressure and temperature are chosen as basic variables in this model. In what follows, the full set of equations for the ZR3 model are presented. A detailed derivation of these equations is beyond the scope of this paper and can be found in Zhou and Rowe (2003).

2.1.2. Mechanical equations

The equilibrium, volumetric strain and thermo-poro-elastic constitutive equations can be written respectively as:

$$(\mathrm{d}\sigma_{ij})_{,j} + \mathrm{d}b_i = 0 \tag{1}$$

$$\mathrm{d}\varepsilon_v = \frac{\mathrm{d}\sigma^*}{K} + B_1 \mathrm{d}p_c + B_2 \mathrm{d}T \tag{2}$$

$$\mathrm{d}\sigma_{ij} = 2G\left(\mathrm{d}\varepsilon_{ij} + \delta_{ij}\frac{\mu}{1-2\mu}\mathrm{d}\varepsilon_{kk}\right) - KB_1\delta_{ij}\mathrm{d}p_c - \delta_{ij}\mathrm{d}p_a - KB_2\delta_{ij}\mathrm{d}T \tag{3}$$

where σ_{ij} and ε_{ij} are the stress and strain tensors, respectively; b_i are the body forces; ε_v is the volumetric strain; σ^* is the net mean stress $(=(\sigma_1+\sigma_2+\sigma_3)/3+p_a)$; p_a is the air pressure; p_l is the pore water pressure; p_c is the capillary pressure $(=p_l-p_a)$; T is the temperature increase; G is the shear modulus; δ_{ij} is the Kronecker's delta; μ is the Poisson's ratio; K is the bulk modulus of the medium with respect to change in net mean stress $(=(\partial e/\partial\sigma^*)/(1+e_0))$; B_1 is the compressibility of the soil structure with respect to a change in capillary pressure $(=(\partial e/\partial p_c)/(1+e_0))$; and B_2 is the thermal expansion coefficient of the unsaturated medium $(=(\partial e/\partial T)/(1+e_0))$.

2.1.3. Water mass balance

The fluxes of liquid (q_l) and vapour (q_v) water can be expressed by the following relationships:

$$q_l = -\rho_l\kappa_l\nabla(p_c+p_a+\rho_l gz) \tag{4}$$

$$q_v = -D^*\nabla\rho_v + \rho_v v_a \tag{5}$$

where ρ_l and ρ_v are the liquid and vapour water densities, respectively; κ_l is the mobility coefficient of liquid water $(=K_l/(\rho_l g))$; K_l is the hydraulic conductivity; g is the gravitational acceleration; z is the vertical coordinate (positive upward) in a Cartesian coordinate system (x,y,z); D^* is the effective molecular diffusion coefficient of water vapour; and v_a is air velocity. Both liquid and vapour densities are allowed to change with temperature and capillary pressure according to:

$$\rho_l = \rho_{l0}[1+\beta_l(p_c+p_a)-\alpha_l T] \tag{6}$$