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Design of drainage blankets for leachate recirculation in bioreactor landfills using two-phase flow modeling

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ABSTRACT

Drainage blankets (DB) are used for leachate recirculation in bioreactor landfills and consist of highly permeable material placed over a large area of the landfill with the leachate injection pipe embedded in the material at specified locations. DBs are generally installed at different depth levels during the waste filling operations. Very limited information is reported on performance of DBs, and that which exists is based on a small number of field monitoring and modeling studies. A rational method for the design of landfills using DBs has not been developed. This study performs a parametric analysis based on a validated two-phase flow model and presents design charts to guide the design of DBs for given hydraulic properties of MSW, the leachate injection rate and the dimensions and locations of the DB as measured from the leachate collection and recirculation system (LCRS) located at the bottom of the landfill cell. Numerical simulations were performed for the two established MSW conditions: homogeneous–isotropic and heterogeneous–anisotropic waste. The optimal levels of leachate saturation, wetted width, wetted area and developed pore water and pore gas pressures were determined, and design charts using the normalized parameters were developed. An example is presented on the use of design charts for typical field application.

1. Introduction

Landfills are used commonly to dispose of municipal solid waste (MSW) [1]. Generally, an engineered landfill consists of a bottom liner, leachate collection and removal system (LCRS) and final cover system that prevents moisture infiltration and promotes the removal of leachate from the landfill cell. As a result, the MSW exists in a dry condition and undergoes a very slow biodegradation process that can exceed 50–100 years. The bioreactor landfills that use the injection or recirculation of generated leachate or additional foreign fluids that are introduced back into the landfill have an increased moisture level and means to distribute the nutrients and microbes that result in accelerated waste biodegradation [2–9].

A small number of studies have examined the moisture distribution in these bioreactor landfills using numerical flow models, such as SUTRA, HYDRUS2D, and SEEP. However, those numerical modeling often assumed a single phase flow or a simple MSW condition in which the waste was assumed to be homogeneous and isotropic. Haydar and Khire [10] investigated moisture distribution in such homogeneous and isotropic MSW where a drainage blanket (DB) was used as the leachate recirculation system (LRS) using HYDRUS2D as the modeling tool and a single flow (e.g., liquid) process. They examined the migration of injected leachate within the DB only and concluded that the area of influence beneath the DB, influenced by the injected leachate, would be the same size. Moreover, they selected the known properties of silt loam to represent the MSW under that DB, whereas it is well established that MSW exists in an unsaturated condition and that it is also highly heterogeneous and anisotropic material [9]. Therefore, it is of utmost importance to model the study using two-phases and considering MSW as unsaturated heterogeneous and anisotropic material, whether the leachate injection system is a DB or other recirculation methods.

The main objective of this study is to develop a rational method for planning bioreactor landfills that use a DB as the LRS in the form of design charts. FLAC (Fast Lagrangian Analysis of Continua) is used to model the two-phase flow in landfill to analyze the moisture distribution for a wide range of MSW properties, DB dimensions and leachate injection rates until the steady-state condition is reached in the course of the experiments. Steady-state is defined as the state when the outflow from the LCRS is equal to inflow of

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leachate into the landfill. Modeling is presented assuming the MSW as (i) homogeneous and isotropic MSW (HAW) and (ii) heterogeneous and anisotropic MSW (HTAW). Modeling was conducted by varying the width of the DB (W_B), depth of the DB from LCRS (D_B), leachate injection rate (Q_i), and saturated hydraulic conductivity of the MSW (k_{sat}) below the DB. This model determines the lateral extent of the injected leachate or wetted width (W_{Wmax}), wetted MSW area (W_{Amax}) and developed pore water pressure (Pw_{max}).

2. Modeling methodology

2.1. Numerical two-phase flow model

The two-phase model assumes the flow of two immiscible fluids, in this case, leachate as wetting fluid and landfill gas as non-wetting fluid, to fill the pore spaces between the solids in the MSW. The flow of each fluid is described by Darcy's law with the unsaturated hydraulic conductivity represented by van Genuchten function [11–13]. FLAC manual [13] provides the detailed mathematical formulation and numerical implementation of the two-phase flow and the main governing equations are presented in this section. According to Darcy's law, the transport of wetting (with superscript "w") and non-wetting (with superscript "g") fluids is given by:

$$q_i^w = -k_{ij}^w \kappa_r^w \frac{\partial}{\partial x_j}(P_w - \rho_w g_k x_k) \tag{1}$$

$$q_i^g = -k_{ij}^w \frac{\mu_w}{\mu_g} \kappa_r^g \frac{\partial}{\partial x_j}(P_g - \rho_g g_k x_k) \tag{2}$$

where k_{ij} = saturated mobility coefficient (tensor) defined as ratio of intrinsic permeability to dynamic viscosity; i = number of zones in horizontal (x) direction; j = number of zones in vertical (y) direction; κ_r = relative permeability for the fluid (function of saturation); μ = dynamic viscosity; P = pore pressure; ρ = fluid density, and g = gravity.

The relative permeabilities of the fluids are related to wetting fluid saturation (S_w) and are expressed by the van Genuchten function as:

$$\kappa_r^w = S_e^b\left[1 - \left(1 - S_e^{1/a}\right)^a\right]^2 \tag{3}$$

$$\kappa_r^g = (1 - S_e)^c\left[1 - S_e^{1/a}\right]^{2a} \tag{4}$$

where a, b and c are constants; S_e = effective saturation. The van Genuchten function is used to relate P_c and S_e by:

$$P_c(S_L) = \frac{\rho_L g}{\alpha}\left[S_e^{-1/a} - 1\right]^{1-a} \tag{5}$$

where ρ_L = wetting fluid density; g = gravity; α = coefficient related to the intrinsic permeability (κ); porosity = (n); and surface tension of matrix = (σ), and is given by $\alpha = \frac{\rho_L g\sqrt{\kappa/n}}{\sigma}$

$$S_e = \frac{S_w - S_r^w}{1 - S_r^w} \tag{6}$$

where S_r^w = residual leachate saturation (i.e., the leachate saturation below which the drainage will not occur). The sum of the saturation of leachate (S_w) and gas (S_g) should be:

$$S_w + S_g = 1 \tag{7}$$

Capillary pressure is related to the pressure difference between the wetting and non-wetting fluids as:

$$P_g - P_w = P_c(S_w) \tag{8}$$

where P_g = pressure created by non-wetting fluid; P_w = pressure created by wetting fluid; $P_c(S_w)$ = capillary pressure, which is a function of degree of saturation (S_w).

Fluid balance laws are available for the slightly compressible fluids and give the variation of fluid content (variation of fluid volume per unit volume of porous material) with respect to the volumetric fluid source intensity. The balance laws for wetting and non-wetting fluid are:

$$\frac{\partial \xi_L}{\partial t} = -\frac{\partial q_i^L}{\partial x_i} + q_v^L \tag{9a}$$

$$\frac{\partial \xi_G}{\partial t} = -\frac{\partial q_i^G}{\partial x_i} + q_v^G \tag{9b}$$

where ξ = variation of fluid volume per unit volume of porous material and q_v = volumetric fluid source intensity.

Constitutive laws for fluids are solved for the pressures in wetting and non-wetting fluids, and saturation in wetting and non-wetting fluids:

$$S_L\frac{\partial P_L}{\partial t} = \frac{K_L}{n}\left[\frac{\partial \xi_L}{\partial t} - n\frac{\partial S_L}{\partial t} - S_L\frac{\partial \in}{\partial t}\right] \tag{10a}$$

$$S_G\frac{\partial P_G}{\partial t} = \frac{K_G}{n}\left[\frac{\partial \xi_G}{\partial t} - n\frac{\partial S_G}{\partial t} - S_G\frac{\partial \in}{\partial t}\right] \tag{10b}$$

By combining these equations with fluid balance laws,

$$n\left[\frac{S_L}{K_L}\frac{\partial P_L}{\partial t} + \frac{\partial S_L}{\partial t}\right] = -\left[\frac{\partial q_i^L}{\partial x_i} + S_L\frac{\partial \in}{\partial t}\right] \tag{11a}$$

$$n\left[\frac{S_G}{K_G}\frac{\partial P_G}{\partial t} + \frac{\partial S_G}{\partial t}\right] = -\left[\frac{\partial q_i^G}{\partial x_i} + S_G\frac{\partial \in}{\partial t}\right] \tag{11b}$$

This produces a nonlinear system of four equations that will be solved for four unknowns: P_L, P_G, S_L, and S_G. In the fluid flow only calculation, the term $\left[\frac{\partial \in}{\partial t}\right]$ is omitted.

The above governing Eqs. (11a) and (11b) of two-phase unsaturated flow are solved numerically in FLAC program using the finite difference method [13]. It should be noted that all the above mentioned equations Eqs. (1)–(11) as well as the variable nomenclatures are the same as that presented in FLAC manual [13]. The use of the FLAC model is validated by reported laboratory and field studies as well as previous modeling studies by Kulkarni [14] and it is found that the FLAC model can predict the laboratory, field and previous modeling results reasonably well.

2.2. Model implementation

2.2.1. Conceptual model

The conceptual model assumed a bioreactor landfill cell that is 100 m wide by 30 m high for the two-phase flow numerical model (Fig. 1). A 0.3 m thick DB was assumed to be placed in the middle of the model located 25 m above the LCRS. The width (W_B) of DB was varied from 10 to 80 m, and it was considered to have a single leachate injection pipe located at the center the blanket. Moisture distribution, a significant factor in the design charts, was evaluated considering the MSW as homogeneous–isotropic waste and heterogeneous–anisotropic waste.

Since the grid size used in the model affects the moisture distribution, a sensitivity analysis was carried out for the model to grid size ratios of 40, 30, 20 and 10, which represent the square grid sizes varying from 1.0 m to 0.1 m. A square grid size of 0.30 m was found to be optimal based on the accuracy of the results and the computation time required. External infiltration from the boundaries into the landfill cell was not examined, since the study focused on subsurface hydraulics. The LCRS was represented by