Slope stability of bioreactor landfills during leachate injection: Effects of unsaturated hydraulic properties of municipal solid waste

Rajiv K. Giri and Krishna R. Reddy*

In bioreactor landfill, the leachate flow and moisture distribution depend upon saturated and unsaturated hydraulic properties of municipal solid waste (MSW). The effects of unsaturated parameters have not been studied because of scarcity of the data and variation in unsaturated parameters due to MSW heterogeneity, degree of decomposition, and pore structure. In this study, a numerical two-phase flow model was used to examine the effects of unsaturated hydraulic properties on the moisture distribution, pore fluid pressures, and the stability of a bioreactor landfill slope with horizontal trench as leachate recirculation system. Unsaturated hydraulic parameters were based on the van Genuchten model and obtained from previously published laboratory studies. The unsaturated hydraulic properties of MSW are found to significantly influence the leachate distribution, pore water and capillary pressures, and landfill slope stability during the operations of leachate injection and subsequent gravity drainage. Further research is needed for better understanding and accurate measurement of hydraulic properties and shear strength parameters of unsaturated MSW.

Keywords: Leachate recirculation, Unsaturated hydraulic properties, Municipal solid waste, Moisture distribution, Pore water pressure, Capillary pressure, Slope stability

Introduction

Bioreactor landfills provide a sustainable means of disposing municipal solid waste (MSW) and help in minimizing or preventing the release of contaminated leachate in the environment. In bioreactor landfill, the recirculated leachate in addition to nutrient and microbes are injected back into the MSW in a controlled manner to increase the moisture, which speeds up the biodegradation of MSW because of enhanced microbial activity (Reinhart and Townsend, 1997; Sharma and Reddy, 2004). In landfilled waste, the leachate flow and moisture distribution depend upon the saturated and unsaturated hydraulic properties of MSW, as the landfilled MSW behaves as an unsaturated porous medium with two distinct phases, namely, liquid and air (gas). Saturated hydraulic properties include the determination of saturated hydraulic conductivity of MSW (i.e. hydraulic conductivity at zero suction). In literature, the determination of saturated hydraulic conductivity of MSW has been reported based on field studies (Landva and Clark, 1986; Oweis et al., 1990; Jain et al., 2006) as well as laboratory studies (Korfiatis et al., 1984; Beaver and Powrie, 1995; Powrie and Beaver, 1999; Jang et al., 2002; Reddy et al., 2009a). Unsaturated hydraulic properties of MSW are based on estimating water retention curves (WRCs) and unsaturated hydraulic conductivity function. The WRCs describe different sets of known values of matric suction (difference in pore air and pore water pressure) and corresponding volumetric moisture content (ratio of volume of water to the total volume of sample) at equilibrium and are invariably given by the van Genuchten model (1980). Whereas, unsaturated hydraulic conductivity is represented by the van Genuchten–Mualem model (Mualem, 1976) and is a function of volumetric moisture content and saturated hydraulic conductivity.

Numerical modeling of bioreactor landfills simulating saturated and unsaturated leachate flow and moisture distribution in MSW requires knowledge of unsaturated hydraulic properties (McCreanor and Reinhart, 2000; Haydar and Khire, 2005; Jain et al., 2010; Reddy et al., 2013; Giri and Reddy, 2013). However, very limited data are available on unsaturated hydraulic properties of MSW. This is because of the fact that estimation of unsaturated hydraulic properties of MSW depends upon the waste heterogeneity and anisotropy, degree of decomposition, and pore structure and the particle size distribution, but variations in these factors with landfill depth and age make
it difficult to correctly determine unsaturated hydraulic properties of MSW (Kazimoglu et al., 2006; Zekkos, 2011; Wu et al., 2012). Furthermore, the limited available data on unsaturated hydraulic properties are based on experimental studies, wherein tests have been carried on either synthetic MSW or shredded samples which may have not been true representative of field conditions, and thus, could lead to varied unsaturated parameters. To the author’s knowledge, no study has been carried out to determine the effects of unsaturated hydraulic properties on the leachate distribution, and generation and distribution of pore fluid pressures (i.e. water and gas) in landfilled waste. In addition, leachate injection using leachate recirculation system, such as horizontal trench (HT) near landfill side slope can generate excessive pore fluid pressures, reduce shear strength of MSW, and may endanger the stability of bioreactor landfill slope. Also, the current design of horizontal trench systems (HTs) is empirical, and a rational design methodology is needed for effective, controlled leachate recirculation that ensures the physical stability of bioreactor landfills.

Therefore, this study focuses on investigating the effects of unsaturated hydraulic properties on the moisture distribution, generation and distribution of pore water and capillary pressures, and the resulting impacts on the stability of bioreactor landfill slope incorporating heterogeneous and anisotropic MSW (HTAW) using a numerical two-phase flow modeling. The validation of numerical two-phase flow modeling and reasoning behind selecting HTAW during leachate injection using HTs have been presented elsewhere (Giri and Reddy, 2013).

**Unsaturated hydraulic properties of MSW**

Literature containing data on unsaturated hydraulic properties of MSW is very limited. To the author’s knowledge, only five major experimental studies estimating unsaturated hydraulic properties of MSW have been reported (Benson and Wang, 1998; Kazimoglu et al., 2006; Breitmeyer and Benson, 2011; Stoltz et al., 2012; Wu et al., 2012). In these studies, the determination of unsaturated hydraulic properties included first measuring the WRCs and unsaturated hydraulic conductivities, and thereafter, curve fitting the measured WRCs of MSW with the van Genuchten model (1980). Table 1 shows the unsaturated hydraulic parameters of MSW obtained from previous studies.

Benson and Wang (1998) performed laboratory tests based on ASTM D 2325 method and used a pressure plate extractor cell to determine the soil water characteristic curve (SWCC) of MSW. In their study, the MSW samples were obtained from a landfill in California, USA and were compacted to a dry unit weight of 7 kN m$^{-3}$. Similarly, Kazimoglu et al. (2006) used a modified pressure-plate extractor method with a maximum suction of 500 kPa to experimentally determine the WRCs of MSW. They used synthetic MSW samples (25 cm in diameter and 14 cm in height) with a unit weight of 5.5 kN m$^{-3}$. Breitmeyer and Benson (2011) obtained relatively fresh MSW samples (4 months old) from a landfill in Wisconsin, USA. In their study, the collected MSW samples having a maximum particle size of 25 mm were compacted to three different dry densities. They used the hanging column method to

<table>
<thead>
<tr>
<th>Researchers</th>
<th>Unit weight/ weight content ($\rho$)</th>
<th>Residual volumetric moisture content ($\theta_r$)</th>
<th>Saturated volumetric moisture content ($\theta_s$)</th>
<th>Air-entry pressure ($\psi_{ae}$)</th>
<th>Steepness of WRC ($n$)</th>
<th>Inverse of air-entry pressure ($\psi_{ae}^{-1}$)</th>
<th>Fitting parameters</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benson and Wang (1998)</td>
<td>7.0</td>
<td>0.53</td>
<td></td>
<td>1.11</td>
<td>2.30</td>
<td>0.05</td>
<td>0.11</td>
<td>Laboratory experiments on MSW obtained from California landfill.</td>
</tr>
<tr>
<td>Kazimoglu et al. (2006)</td>
<td>7.8</td>
<td>0.48</td>
<td>0.41</td>
<td>0.13</td>
<td>2.20</td>
<td>0.05</td>
<td>0.13</td>
<td>Laboratory experiments on synthetic MSW.</td>
</tr>
<tr>
<td>Stoltz et al. (2012)</td>
<td>6.8</td>
<td>0.59</td>
<td>0.41</td>
<td>1.59</td>
<td>2.30</td>
<td>0.05</td>
<td>0.37</td>
<td>Laboratory experiments on fresh MSW from French bioreactor landfill.</td>
</tr>
<tr>
<td>Wu et al. (2012)</td>
<td>6.98</td>
<td>0.69</td>
<td>0.41</td>
<td>1.59</td>
<td>2.30</td>
<td>0.05</td>
<td>0.37</td>
<td>3 years old shallow-layered MSW from Chinese landfill.</td>
</tr>
</tbody>
</table>
measure WRCs for each of the three MSW samples, in which the maximum suction of 29 kPa was applied based on the moveable water columns. In addition, they used multistep outflow method (Gardner, 1956) to determine the unsaturated hydraulic conductivity.

Stoltz et al. (2012) carried out laboratory tests to determine the effects of dry density of MSW on unsaturated hydraulic parameters depending upon the level of compaction. In their study, three different MSW samples collected from French bioreactor landfills were examined based on different gravimetric moisture contents. For compacted MSW specimens, a hanging column method equipped with controlled suction odometer and ceramic porous plate was employed in order to maintain a relatively low matric suction (<10 kPa) because of the presence of large void spaces (pores) in the selected MSW samples. Moisture retention curves (MRCs) of MSW samples were evaluated by first saturating the porous ceramic plate using carbon dioxide (CO2) followed by saturation of MSW (placed inside the odometer) with zero suction, and finally draining and oven drying the selected MSW samples. For non-compacted specimens, Stoltz et al. (2012) used soil moisture extraction plate, based on the principle of axis translation (i.e. matric suction), which could maintain matric suction as high as 450 kPa.

Wu et al. (2012) conducted laboratory experiments to determine the unsaturated hydraulic properties of MSW with varying landfill depth and age. The MSW samples were collected up to a depth of 25 m from a bioreactor landfill in Beijing, China. The collected samples were disturbed and of relatively small size (12 cm high and 15-6 cm in diameter) with varying unit weight with landfill depth, ranging from 6-98 kN m⁻³ for shallow depth to 14-32 kN m⁻³ for deep layered depth. Wu et al. (2012) used a modified Tempe cell and carried out pressure plate tests to measure WRCs for collected MSW samples.

Modeling methodology

Numerical two-phase flow

The unsaturated pores of MSW are filled with two immiscible fluids, namely, landfill leachate (i.e. wetting fluid) and gas (i.e. non-wetting fluid), and their flow is influenced by degree of saturation, capillary pressure, and relative hydraulic conductivity. The numerical two-phase flow model incorporates modeling the flow of these two immiscible fluids. In the numerical two-phase flow model, the governing equations of unsaturated MSW are given by the linear momentum balance and the fluid balance laws (based on mass balance) and are represented as

\[ \rho = \rho_d + n(S_L \rho_L + S_G \rho_G) \] (1)

\[ \frac{n}{K_L} \left[ \frac{\partial S_L}{\partial t} + \frac{\partial q_L}{\partial t} \right] = - \frac{\partial q_L}{\partial x_1} \] (2)

\[ \frac{n}{K_G} \left[ \frac{\partial S_G}{\partial t} + \frac{\partial q_G}{\partial t} \right] = - \frac{\partial q_G}{\partial x_1} \] (3)

where \( n \) is the porosity, \( S_L \) is the wetting leachate (liquid) saturation, \( S_G \) is the non-wetting gas saturation, \( P_L \) is the wetting pore liquid pressure, \( P_G \) is the non-wetting pore gas pressure, \( \rho_L \) and \( \rho_G \) are the fluid densities, \( \rho_d \) is the matrix dry density, \( K_L \) and \( K_G \) are the liquid and gas bulk modulus, respectively, \( q_L \) and \( q_G \) are the flow rate of wetting liquid and non-wetting gas given by Darcy’s law. The governing equations of the two-phase flow model (1)–(3) are solved numerically with the Fast Lagrangian Analysis of Continua (FLAC) program using the finite difference method. Two-phase flow model using FLAC program was selected as it enables the realistic generation and distribution of moisture and pore pressures through porous MSW. The detailed mathematical formulation including governing equations and numerical formulations related to the two-phase flow model are explained elsewhere (ITASCA Consulting Group, 2011; Reddy et al., 2013).

Slope stability model

Strength reduction technique is adopted to analyze the stability of bioreactor landfill slope in terms of factor-of-safety (FOS) using FLAC program (Dawson et al., 1999). Mohr–Coulomb failure criterion is combined together with strength reduction approach for stability analyses. The main advantage of using this method is that it takes into consideration transient varying pore water and pore gas pressures while computing the FOS at any given instant. The computation of FOS is carried out by successively reducing the shear strength parameters (cohesion and friction angle) of MSW until the slope reaches the verge of failure. FLAC uses a bracketing approach to determine initial stable and unstable bracketing state solutions for a given FOS trial (\( F_{\text{trial}} \)) value. Wherein, stable bracketing state refers to \( F_{\text{trial}} \) value for which solution converges and unstable bracketing state corresponds to \( F_{\text{trial}} \) value for which the solution does not converge. The difference between the stable and unstable solutions is continuously reduced until the difference reaches below a specified tolerance limit (ITASCA Consulting Group, 2011). Successful application of this technique has been presented elsewhere (Giri and Reddy, 2013).

Landfill configurations

A simplified two-dimensional bioreactor landfill model, 175 m wide and 50 m deep with a side slope of 3H:1V was created in FLAC using graphical interface to investigate the effects of unsaturated hydraulic properties of HTAW condition under pressurized leachate addition. Figure 1 shows the simplified bioreactor landfill cell configuration. The landfill model configuration and overall modeling approach is similar to that reported by Xu et al. (2012) and Giri and Reddy (2013). The main components of the landfill cell incorporating HTs were modeled: HTAW, HTS, and leachate collection and removal system (LCRS). In the present study, the physical properties of leachate were considered to be similar as pure water and the results obtained from this study could be used for liquids with similar characteristics. The conceptual landfill model does not consider the effects of landfill cover system because this study is mainly focused on pressurized leachate injection and flow through landfilled waste during active
condition in landfills. External factors such as precipitation and infiltration have not been considered. The effect of dynamic (seismic) activity on the stability of landfill slope is neglected. Also, the temperature effects, mechanical compression, and biological processes in bioreactor landfill are not taken into consideration.

Leachate collection and removal system was located at the base of the 50 m deep landfill with a thickness of 0·3 m. For all simulations, the LCRS is assumed to be made of free draining granular soil, and friction angle and cohesion of 22° and 0 kPa, respectively, were selected to simulate the interface between the MSW and underlying drainage media in LCRS (GeoSyntec Consultants, 2007; Xu et al., 2012). A HT (1 m x 1 m) is located at an elevation of 30 m above the base of the LCRS, and at a setback of 15 m from the side slope. The setback distance of 15 m was selected based on the recommendation made by USEPA (2007) for typical required distance (15–30 m) of leachate recirculation systems from side slope. Horizontal trench system was backfilled with high permeability material such as gravel or shredded tires in order to maintain higher backfill permeability when compared to the MSW used in the study. The top boundary is free to extend laterally away from the side slope up to any location, however, in this study, it is assumed to be extended to a width of 25 m away from the side slope. Furthermore, the 50 m deep landfill model was divided into ten different layers, each with a thickness of 5 m to incorporate HTAW with varied unit weight and saturated hydraulic conductivity with depth.

The landfill model is discretised into cells, and all external boundaries are simulated as zero flow boundaries. For all modeling cases, a grid cell size of 1 m x 1 m is selected to produce accurate results. To simulate LCRS at the bottom, zero pressures are defined for all cells in the bottom-most model layer and the sum of outflow from these cells is calculated as outflow through LCRS (Reddy et al., 2013).

Model input parameters and initial and boundary conditions
Boundary conditions are divided into mechanical and hydraulic boundary conditions. Mechanical boundary conditions are taken into consideration by fixing the base in both horizontal and vertical directions, so that the lateral and vertical deformations of the landfill at the base are zero. The lateral deformation is restrained on the right side boundary of the model, whereas the side slope is free to move in both directions, and the top boundary is free to move only in the vertical direction. Hydraulic boundary conditions are taken into consideration by fixing the pore gas pressure and seepage at the top boundary and at the side slope. The pore gas pressure is atmospheric at the seepage boundary and it is impermeable to the liquid (water) as long as the liquid pressure (water pressure) is negative: the gas pressure is taken as zero at boundary nodes where the condition is not satisfied (ITASCA Consulting Group, 2011). The right-side boundary and the bottom of the landfill model are considered to be impermeable (i.e. free pore pressures and free saturation).

All grid points were initially free to vary based on the net inflow and outflow from the neighboring zones. Pore water pressure was fixed to zero for the grid points at the LCRS (located 0·3 m above the base) to represent the drainage layer. The pore gas pressures were fixed to be zero initially at all grid points in order to establish initial mechanical equilibrium, which was used further to calculate baseline (no leachate injection) FOS. The initial pore water pressure was calculated based on the initial gas pressure by default. Thereafter, the gas pressures were set to vary for different flow conditions (ITASCA Consulting Group, 2011). The initial volumetric moisture content of 15% (v/v, by volume) at all grid points and an initial porosity of 40% at all zones were considered.

Material properties
In this study, MSW is considered to be heterogeneous and anisotropic in nature with varied unit weight and saturated hydraulic conductivity with landfill depth, as this represents the most realistic field condition. Also, the stability of bioreactor landfill slope is influenced by the unit weight, saturated hydraulic conductivity, unsaturated hydraulic properties, and shear strength of MSW (i.e. cohesion, and friction angle). Varied unit weight with depth is represented based on Zekkos et al. (2006)

\[ \gamma = \gamma_1 + \frac{z}{\alpha + \beta z} \]  

where \( \gamma \) is the unit weight of MSW at depth \( z \), \( \alpha \) is the modeling parameter = 3·0 m\(^3\) kN\(^{-1}\) for typical MSW, \( \beta \) is the modeling parameter = 0·2 m\(^3\) kN\(^{-1}\) for typical MSW, \( \gamma_1 \) is the near surface in-place unit weight (kN m\(^{-3}\)).
The saturated hydraulic conductivity of MSW decreases with depth because of the increase in normal stress caused by overlying MSW and is calculated based on Reddy et al. (2009a)

\[ k_s = k_{s0} \left[ 1 + \left( \frac{\sigma}{p_a} \right) \right]^{-5.3} \]

where \( k_{s0} \) is the initial saturated hydraulic conductivity at zero normal stress (10^-2 cm s^-1), \( k_s \) is the saturated hydraulic conductivity under effective normal stress of \( \sigma' \), and \( p_a \) is the atmospheric pressure (101.3 kPa).

The geotechnical properties of MSW were similar to that reported by Xu et al. (2012) who considered homogeneous and anisotropic MSW with a unit weight (\( \gamma \)), cohesion (c), friction angle (\( \phi \)), vertical saturated hydraulic conductivity \( (k_v) \), and anisotropy \( (a) \) of 15 kN m^-3, 15 kPa, 35^\circ, 10^-3 cm s^-1, and 10, respectively throughout the entire landfill depth. However, to simulate HTAW condition, in this study, the unit weight of the MSW at the mid depth (25 m) of the landfill cell is taken to be exactly the same as that of Xu et al. (2012) (i.e. \( \gamma = 15 \) kN m^-3), and unit weights for rest of the layers vary with depth according to the equation (4). In addition, saturated hydraulic conductivity of each waste layer decreases with depth because of the increase in normal stress caused by overlying MSW with changing unit weights, and is calculated using equation (5). Shear strength and anisotropy (value 10) of MSW were constant throughout the landfill cell. Municipal solid waste properties for HTAW condition are also shown in Table 2. More information regarding HTAW material properties, selection, and its effects on leachate distribution and stability of bioreactor landfill slope can be found elsewhere (Giri and Reddy, 2013).

In this study, five major laboratory based studies focusing on the unsaturated hydraulic properties of field-collected MSW are simulated (Table 1). The unsaturated hydraulic properties of the MSW included the van Genuchten fitting parameters for the WRCs and unsaturated hydraulic conductivity function wherein, the WRCs are given by the empirical laws of van Genuchten (1980)

\[ \theta = \theta_s + \frac{\theta_a - \theta_s}{\left[1 + \left( \frac{K_s}{S_s} \right)^{1/n} \right]^{m}} \]

where \( \theta \), \( \theta_s \), and \( \theta_a \) are the actual, residual, and saturated volumetric moisture content (cm^3 cm^-3) respectively, \( \alpha \) is the inverse of air entry pressure (kPa^-1), \( n \) is the steepness of the WRC, and \( m \) is assumed to be equal to \((1-1/n)\).

Unsaturated hydraulic conductivity, \( K(\psi) \), is generally described in the form of relative permeabilities, \( k_r(\psi) \), of the fluids and are expressed by the van Genuchten function as (Mualem, 1976; van Genuchten, 1980)

\[ k_r^L = K(\psi)/K_s = S_s^{\alpha} \left[ 1 - \left( 1 - S_s^{1/\alpha} \right)^{2a} \right] \]

\[ k_r^G = K(\psi)/K_s = (1 - S_s)^c \left[ 1 - S_s^{1/\alpha} \right]^{2a} \]

where \( k_r^L \) and \( k_r^G \) are the relative permeabilities of leachate and gas respectively, \( K_s \) is the saturated hydraulic conductivity (cm s^-1), \( S_s \) is the effective saturation as a function of matrix suction head, \( a \) and \( m \) are equal, \( b \) and \( c \) are the van Genuchten parameters (=0.5).

For the present study, the unsaturated hydraulic properties of the MSW were not varied with respect to the depth because: (1) very little published information is available on the evolution of unsaturated hydraulic properties of MSW as a function of overburden pressure and (2) unsaturated hydraulic properties have relatively small impact on the key design parameters at steady-state conditions (Haydar and Khire, 2005; Reddy et al., 2013).

**Model simulations**

Five different sets of unsaturated hydraulic parameters of MSW based on laboratory testing were used to examine the effect of unsaturated properties on the moisture distribution, generation and distribution of pore water and capillary pressures, and the resulting impacts on stability of bioreactor landfill slope. All simulations were performed for HTAW (more representative of field condition) with varied unit weight and saturated hydraulic conductivity with depth. Continuous leachate injection with an injection pressure of 196 kPa was used until steady-state condition was achieved or slope failure occurred, whichever took place first. This injection pressure was selected based on the maximum water column head of 20 m (vertical distance from the top boundary surface to the HT=20 m). Results were obtained in terms of wetted area (area corresponding to degree of liquid saturation \( \geq 60\% \)), pore water pressure, capillary pressure, and FOS with time.

Furthermore, the effects of intermittent modes of leachate injection were also considered as it is not common

<table>
<thead>
<tr>
<th>Layer</th>
<th>Depth/m</th>
<th>Depth to mid layer/m</th>
<th>Unit weight/kN m^-3</th>
<th>Vertical hydraulic conductivity/m s^-1</th>
<th>Cohesion/kPa</th>
<th>Friction angle/degree</th>
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<tbody>
<tr>
<td>10 (Topmost)</td>
<td>0-5</td>
<td>2-5</td>
<td>12.6</td>
<td>2.4 x 10^-5</td>
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<td>35</td>
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<td>7-5</td>
<td>13.5</td>
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<td>1.3 x 10^-7</td>
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<td>8</td>
<td>10-15</td>
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<td>14-6</td>
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<td>4-1 x 10^-9</td>
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</tr>
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<td>7</td>
<td>15-20</td>
<td>17-5</td>
<td>15-6</td>
<td>1-8 x 10^-8</td>
<td>8-2 x 10^-9</td>
<td>1-3 x 10^-9</td>
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<td>47-5</td>
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<td>1-3 x 10^-9</td>
<td>1-3 x 10^-9</td>
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</table>
to inject pressurized leachate in bioreactor landfill, continuously. Therefore, intermittent modes of leachate injection with few hours of injection followed by rest period (gravity drainage) are preferred. Two different modes of intermittent injection were carried out: (a) one day on followed by one day off (one-day-on-off) and (b) 1 week injection followed by 1 week of rest period (one-week-on-off). The simulations were performed for HTAW condition with an injection pressure of 196 kPa using five different sets of unsaturated hydraulic properties. The obtained results are compared to the continuous injection mode to differentiate the wetted area, degree of saturation, pore fluid pressure, and FOS with injection time.

Results and discussions

Moisture distribution

Various site-specific parameters and MSW conditions, such as degree of decomposition, unit weight, unsaturated hydraulic properties, temperature, and meteorological parameters affect the target degree of leachate saturation in landfills. However, this study does not focus on achieving the target degree of saturation, but the wetted area of MSW in landfills, which is the area corresponding to 60% or higher degree of leachate saturation as recommended by ITRC (2006).

The wetted area resulting from the five different sets of unsaturated hydraulic parameters, over 4 weeks of continuous leachate injection with injection pressure of 196 kPa, is shown in Fig. 2a. All simulations were carried out under HTAW condition. The wetted area comparisons are made during 1 week, 2 weeks, and 4 weeks injection period. For each set of unsaturated hydraulic properties of MSW, there is noticeable difference in the wetted area, and the difference becomes more prominent as the leachate is continuously injected from the beginning to 4 weeks period. This is because of continual lateral spreading of moisture away from the trench location and more toward the side slope in the lateral direction in response to injection pressure, as the MSW is heterogeneous and anisotropic in nature with higher saturated hydraulic conductivities laterally than vertically (i.e. $k_h = 10k_v$). During the initial first week of continuous leachate injection, the injected leachate covered approximately 41–53 m². Similarly, for 2 weeks of leachate injection the wetted area was approximately 70–96 m².
and the same after 4 weeks was around 127–181 m² for the five different sets of unsaturated hydraulic parameters. The wetted area varied from approximately 29% during first week of injection to around 37% after 2 weeks of continuous injection. Furthermore, successive leachate injection over 4 weeks increased that variation to 43%, for different sets of unsaturated hydraulic properties. The relative permeabilities of MSW for leachate and gas phases are different for each set of unsaturated hydraulic properties (Table 1), which affect the migration of leachate in MSW during the initial stages and this is shown by the variation in the wetted area after the first 4 weeks of leachate injection. Hence, it implies that the unsaturated hydraulic properties of MSW influence the leachate migration within the landfill during the transition state from unsaturated to saturated condition.

Figure 2b compares the wetted area for different modes of leachate injection (continuous as well as intermittent modes) after 4 weeks of injection, resulting from different sets of unsaturated hydraulic properties of MSW (HTAW condition). The wetted area of MSW resulting from the one-day-on-off mode of intermittent injection is larger than that for one-week-on-off intermittent simulations because, once the injection is stopped and the gravity drainage is allowed for longer time period (more than a day), the wetted area increases at a lower rate as the degree
of leachate saturation reduces considerably with time under gravity drainage. When compared with continuous injection mode, the percentage reduction in wetted area ranges from 40 to 48% for one day-on-off simulations and 46 to 60% for one-week-on-off simulation for different sets of unsaturated hydraulic parameters.

Evolution of degree of leachate saturation and maximum developed saturation for different sets of unsaturated hydraulic properties using continuous and intermittent modes of injection are shown in Figs. 3 and 4, respectively. All observations were made at a location 5 m left of the HT (i.e. setback = 10 m from the side slope) during 4 weeks injection period with injection pressure of 196 kPa. For continuous injection mode, the leachate saturation increased continually from the initial 40% until the MSW became fully saturated (saturation = 100%) and remained the same thereafter. The time required to reach 100% saturation varied from 2–7 days for different sets of unsaturated hydraulic properties in the case of continuous injection. More prominent effects on the leachate saturation were observed during intermittent injection strategies, as during gravity drainage, the MSW remains in unsaturated state and this governs the flow and moisture distribution in landfill. For different sets of unsaturated hydraulic properties, the degree of saturation after 4 weeks of injection varied approximately 45% and 13%, when one-week-on-off and one-day-on-off injection modes were carried out, respectively.

**Pore fluid pressures**

The generation and distribution of pore water pressure as a function of unsaturated hydraulic properties for different modes of leachate injections, during 4 weeks injection, are shown in Figs. 5 and 6. All observations were made at 5 m left of the trench system with an injection pressure of 196 kPa for HTAW condition. During initial stages of the continuous leachate injection, the difference in pore water pressure (approximately 15%) was not significant for the five different sets of unsaturated studies. As the leachate is continuously injected during 4 weeks, the developed pore water pressure increases (87–105 kPa) considerably, however, the variation as a result of different sets of unsaturated parameters was found to be relatively small (approximately 20%). Nevertheless, large drop in pore water pressures, around 32%, was observed for different sets of unsaturated hydraulic properties, using one-week-on-off intermittent simulations, rather than one-day-on-off injection strategy. This is because of the fact that when the leachate injection was stopped and gravity drainage was allowed for longer duration, the developed pore water pressure in unsaturated MSW gets sufficient time to dissipate and results in reduced pore water pressure. This is significant as invariably landfill designers and operators are concerned about excess pore pressures near landfill slope because of leachate injections which may endanger its stability, however, intermittent mode of injection, especially, 1 week on followed by 1 week off could result in considerable reduction in pore pressure and ensure the stability of landfill slopes.

Figure 7 compares the maximum developed capillary pressure as a result of different sets of unsaturated hydraulic properties of MSW (HTAW) resulting from intermittent modes of leachate injection. The MSW remains in unsaturated state during initial stages, and therefore, large variation in the initial capillary pressure (4–38 kPa) was obtained for different sets of unsaturated hydraulic parameters. This also indicates the presence of relatively high pore gas pressures in MSW during early stages, and the need for accounting pore gas pressure while carrying out slope stability analysis for bioreactor landfills. Capillary pressure decreases considerably as the leachate is injected because of increase in pore water
pressure and reduction in pore gas pressure. The variation in capillary pressure for the two modes on intermittent leachate injection (one-week-on-off and one-day-on-off) after 4 weeks was found to be minimal.

**Slope stability analyses**

Shear strength parameters and unit weight of MSW, transient varying pore fluid pressures, unsaturated hydraulic properties, and MSW heterogeneity and anisotropy were taken into consideration for the slope stability of bioreactor landfill during leachate injections. Figure 8 compares the effects of five different sets of unsaturated hydraulic properties of MSW on landfill slope stability in terms of FOS with injection duration. The baseline FOS (no leachate injection) varied from 2.06 to 2.32 amongst different sets of unsaturated hydraulic properties and accounts for large variation (approximately by 12%). This is attributed to significant difference in capillary pressures (4–38 kPa) during initial stages in which the MSW remains in unsaturated state, depending upon the unsaturated hydraulic properties, and thus resulted in varied baseline FOS. Numerical simulations were carried out...
using continuous leachate injection with an injection pressure of 196 kPa to determine the stability of landfill slope during first 4 weeks or the time period when the slope failed, whichever occurred first (Fig. 8a). Results show that the different unsaturated parameters significantly affect the stability of landfill slope, as the time to failure (e.g., time for the FOS<1.5) varied from 13 days (Benson and Wang, 1998) to 28 days (Wu et al., 2012). This implied the effects of unsaturated hydraulic properties on landfill slope stability during continuous leachate recirculation. However, in practice, continuous leachate addition is rarely practiced. Therefore, simulations were performed using intermittent modes of injection. Figure 8b and c compare the FOS for different sets of unsaturated hydraulic properties using different modes of leachate injection during 2 weeks and 4 weeks of injection period, respectively. It is evident that the reduction in the values of FOS is minimal during intermittent leachate injection strategies (both one-day-on-off and one-week-on-off) because of significant drop in pore pressures. Therefore, intermittent injection mode is recommended for leachate operations in bioreactor landfill, rather than continuous addition to maintain the stability of landfill slopes.

Limitations of the study

Apart from the aforementioned general assumption regarding the numerical model, the present study has
some additional limitations that need to be discussed. Shear strength of MSW were kept constant throughout the entire depth because of lack of information on variation in shear strength properties of unsaturated MSW. Proper knowledge of shear strength parameters (cohesion and friction angle) of unsaturated MSW is important for the accurate computation of bioreactor landfill slope stability and mechanical settlement. Since, leachate recirculation leads to elevated moisture level and fast degradation of MSW, resulting in change in particle size and waste composition. Therefore, it is essential to determine the effect of such changes on shear strength properties of landfilled MSW. Unfortunately, not much information is available in literature in this regard.

Reddy et al. (2009b) performed the direct shear tests on fresh MSW as well as 1.5 years old landfilled waste.
(obtained from Orchard Hills landfill, IL, USA) to determine the effects of moisture content and biodegradation on shear strength parameters of MSW; however, they could not find any specific correlation between shear strength properties and biodegradation because of difference in waste composition and level of degradation. Hettiarachchi and Thani (2011) carried out direct shear tests on laboratory manufactured synthetic MSW with cooked pasta (readily biodegradable organic waste) at unsaturated moisture levels (close to field capacity) and found out that increase in biodegradation leads to reduction in friction angle and increase in cohesion of MSW. However, the tests were conducted on synthetic MSW and therefore the obtained results could be considerably different than the true field MSW condition. Hence, just like unsaturated hydraulic properties, the shear strength parameters of unsaturated MSW could be influenced by the sample disturbance (difference in the in-situ waste and laboratory samples), sample size, MSW heterogeneity, and rate of degradation. Therefore, further research is required to address these issues. Nevertheless, the numerical modeling results presented in this study seem to be reasonable and could provide useful information to landfill operators and engineers.

Conclusion

In this study, numerous modeling simulations were performed to investigate the effects of unsaturated hydraulic properties of MSW during leachate injection over time. Unsaturated hydraulic properties were selected based on the five major laboratory studies reported in literature. The landfill waste was considered to be heterogeneous and anisotropic in nature with varied unit weight and saturated hydraulic conductivity (representing field conditions). A numerical two-phase flow modeling was used to predict the moisture distribution, generation and distribution of pore-water and capillary pressures, and their resulting impacts on the stability of bioreactor landfill slopes during pressurized leachate addition with a relatively high injection pressure. Simulations were also carried out for different leachate injection strategies (i.e. continuous as well as intermittent injection). Following conclusions are drawn from this study:

1. Large variation in the predicted wetted area of MSW (a measure of moisture distribution and is corresponding to the area with leachate saturation ≥60%) was observed because of unsaturated hydraulic properties during continuous leachate injections over time. This can be attributed to each set of unsaturated hydraulic properties having different relative fluid permeabilities and this affected the leachate migration in landfilled MSW. The time to reach 100% saturation varied during continuous leachate injection. However, more predominant effects were seen during intermittent simulations and the leachate saturation of 60–80% was observed after 4 weeks.

2. High pore water pressures with lesser variations amongst the selected sets of unsaturated hydraulic properties were observed during continuous injection mode. Nevertheless, large drop in pore water pressures were found during intermittent injection strategies with the one-week-on-off simulation found to be most suitable as it provides sufficient time for pore pressures to dissipate. Furthermore, large difference in capillary pressures (4–38 kPa) was obtained during initial unsaturated MSW condition amongst different sets of hydraulic parameters.

3. The values of FOS were considerably reduced for unsaturated hydraulic properties during continuous leachate injection because of the generation of excessive pore pressures near side slope, and therefore, endangering the stability of slope. However different intermittent leachate injection strategies including leachate injection followed by gravity drainage resulted in much safer conditions for bioreactor landfill slope because of reduced pore pressures.

Overall, it was concluded that the unsaturated hydraulic properties of MSW considerably influenced the moisture distribution, pore water and capillary pressures, and the stability of bioreactor landfill slope during leachate recirculation. Undertaking of further research in this area is needed to accurately determine unsaturated hydraulic properties of MSW, as large variation in unsaturated hydraulic parameters may be found because of waste degree of decomposition, overburden stress, MSW pore structures and particle size distribution, and leachate complexities with landfill depth and age. Also, shear strength parameters of unsaturated MSW need to be studied for the analyses of landfill slope stability and MSW settlement.

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References


GeoSyntec Consultants. 2007. Reviewers checklist: slope stability analysis. Prepared as part of the fundamentals of slope stability and settlement for solid waste disposal facilities, University of Florida, TREEO Center, Orlando, FL, USA.


Variation of shear strength properties with the organic fraction in unsaturated synthetic municipal solid waste, Proc. ‘Geofrontiers 2011’, ASCE, Geotechnical Special Publication, 211, Dallas, TX, USA, 1411–1422.


