

# Modeling of Moisture Distribution Under Continuous and Intermittent Leachate Recirculation in Bioreactor Landfills

Hanumanth S. Kulkarni (hkulka2@uic.edu) and Krishna R. Reddy (kreddy@uic.edu)  
*Department of Civil and Materials Engineering, University of Illinois at Chicago,  
842 West Taylor Street, Chicago, Illinois 60607, U.S.A*

**ABSTRACT** Bioreactor landfills are popular these days because of their capability to degrade the municipal solid waste (MSW) at faster rate by re-injecting the generated leachate by means of leachate recirculating system. Horizontal trenches (HT) are the common and efficient method used to recirculate the leachate. Since MSW is an unsaturated material, there exist movement of two immiscible fluids; therefore the leachate routing is analyzed as unsaturated two phase flow with the leachate recirculated as wetting fluid and generated landfill gas as non-wetting fluid. Fluid flow is described by Darcy's law, and the unsaturated hydraulic conductivity parameters are modeled by van Genuchten function. The main objective of this paper is to study the effect of different leachate injection rates and injection modes on moisture distribution and maximum pore water pressure developed in the landfill. Results indicated that intermittent leachate injection with high flow rate of  $12\text{m}^3/\text{day}/\text{m}$  sequencing with injection in alternate HT layer proved effective in attaining an optimal environment for MSW degradation without producing excess pore water pressures.

## INTRODUCTION

Bioreactor landfills use enhanced biochemical process to promote the MSW degradation in a short period about 5-10 years, as opposed to 30-100 years demonstrated by conventional landfills (Reddy, 2006). This is accomplished by increasing the moisture content of the MSW by recirculating leachate into the landfill that helps to distribute the microbes and nutrients throughout the landfill. By increasing the waste degradation rate, bioreactor landfills can increase the available volume by 15-30% and thus extends the lifetime of the landfill, allowing it to accept more waste.

Several studies on leachate recirculation methods are available for use in bioreactor landfills. Some of the popular methods include prewetting, surface spraying, surface ponds, vertical wells, and horizontal trenches (Reinhart, 1995). Of all the leachate recirculation techniques available, HTs can be used under both active and post-closure

conditions. They contain perforated pipes through which leachate is recirculated by gravity or injection under pressure. When spaced adequately, HTs can recirculate leachate effectively throughout the landfill (Reinhart, 1995). The leachate injection pressure head, hydraulic conductivity of trench backfill and MSW, dimensions of trench, layout formation of HTs can affect the leachate distribution in a landfill (Haydar and Khire, 2005). It is shown that a logarithmic relation between leachate flux and injection pressure head using a finite element based model HYDRUS-2D. In another study, McCreanor and Reinhart (2000) performed hydrodynamic modeling of leachate recirculation in landfills by including the effect of MSW properties (anisotropic and heterogeneity) and recirculation system on leachate routing. With the help of a modified form of SUTRA, they were able to simulate the forces driving liquid movement through a landfill. Paper presented model validation based on field observations

adopting the leachate injection rate of 8 and 4 m<sup>3</sup>/day/m. Because of limited knowledge on effective leachate distribution to cover the entire landfill, there is a need to study whether the injected leachate is uniformly distributed, and if not, injection rates and modes has to be so regulated to attain an optimal environment that expedite the waste biodegradation process. On the contrary, excess leachate injection develops pore water pressure and hence causes the stability issues. The main objective of our study is to examine the effect of different injection rates, and mode of injection (continuous and intermittent) on the moisture distribution in a landfill to obtain an optimal environment for waste biodegradation.

## NUMERICAL MODELING

### Two Phase Flow Modeling

The two immiscible fluids being filled in the void space of the material. These fluids may be water and gas. Fast Lagrangian Analysis of Continua (FLAC) provides a platform for modeling the flow analysis as a unsaturated two phase flow problem. Fluid flow is described by Darcy's law, and the unsaturated hydraulic conductivity parameters are modeled by van Genuchten (1980) function considering the soil water retention curve (ITASCA 2008). Two phase flow modeling includes the numerical solutions of the derived differential equations that govern the flow of fluids in the porous media that are listed here.

- The transport laws include the Darcy's laws for wetting and non-wetting fluids:

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

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

Where:  $k_{ij}$  = saturated mobility coefficient (tensor) is defined as ratio of intrinsic permeability to dynamic viscosity;  $\kappa_r$  = relative permeability for the fluid (function of saturation);  $\mu$  = dynamic viscosity;  $P$  = pore pressure;  $\rho$  = fluid density and  $g$  = gravity.

- Relative permeability laws are related to saturation ( $S_w$ ) and are given by van Genuchten:

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

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

$$S_e = \frac{S_w - S_r}{1 - S_r} \quad (5)$$

Where:  $a=0.44$ ,  $b=0.5$  and  $c=0.5$  (Stoltz and Gourc, 2007) are constant parameters;  $S_e$  = effective saturation;  $S_w$  = residual saturation.

- Capillary pressure laws are related to the pressure difference between the wetting and non-wetting fluids and is given as  $P_g - P_w = P_c(S_w)$  (6)

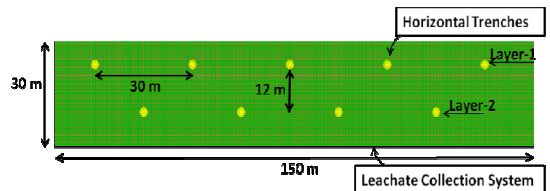
Where:  $P_g$  = Pressure created by non-wetting fluid;  $P_w$  = Pressure created by wetting fluid.

- Saturation law corresponds to the saturation in the medium and is expressed as the sum of the saturation of wetting fluid ( $S_w$ ) and non-wetting fluid ( $S_g$ ) and is given by

$$S_w + S_g = 1 \quad (7)$$

### Landfill Model

A schematic diagram of the landfill model is shown in Fig.1. A bioreactor landfill cell of 150m x 30m filled in ten layers, each of 3m height is considered for our study. Leachate injection system consists two layers of HTs having dimensions of 0.6m x 0.6m with horizontal spacing of 30 m and vertical spacing of 12 m. An average unit weight of 7.5 kN/m<sup>3</sup> is assumed. The external boundaries are simulated as zero-flow boundaries and no flow from the landfill cap is assumed since only the subsurface hydraulics of the recirculated leachate is focused. Losses in the pipes, joints, manifolds, and pumps are not considered. Leachate collection system is located at bottom of landfill.



**Fig.1** Landfill model for numerical simulation of leachate recirculation in MSW using HTs (For colour figure, refer to CD)

## Hydraulic Properties

The hydraulic conductivity varies within a landfill since the bottom layers are more compacted (Landva and Clark 1986). Reddy et al. (2009) presented laboratory results on the hydraulic conductivity of field collected MSW samples which are about 1.5 years old, using rigid wall and flexi wall permeameters. Authors observed decrease in hydraulic conductivity with increase in unit weight and normal pressure applied. The values for vertical saturated hydraulic conductivity ( $k_v$ ) are extracted based on the normal pressure for the assumed unit weight of  $7.5 \text{ kN/m}^3$  for layer 1= $8.0\text{E-}5$ , layer 2= $1.0\text{E-}4$ , layer 3= $1.5\text{E-}4$ , layer 4= $1.7\text{E-}4$ , layer 5= $2.0\text{E-}4$ , layer 6= $2.5\text{E-}4$ , layer 7= $3.0\text{E-}4$ , layer 8= $3.5\text{E-}4$ , layer 9= $4.0\text{E-}4$ , and layer 10= $5.0\text{E-}4 \text{ cm/s}$ . Anisotropic waste mass has been simulated assuming the horizontal hydraulic conductivity ( $k_h$ ) varying ten times  $k_v$  (McCreanor and Reinhart, 2000). Since the waste media is unsaturated, the pores between the solids are filled with leachate and landfill gas. Based on the limited data available, the unsaturated hydraulic conductivity parameters of MSW for the van Genuchten fitting function are chosen from Gourc and Stoltz (2007).

## Modeling Scenarios

### *Continuous leachate injection*

The effect of injection flow rate on moisture distribution is studied by injecting the leachate continuously for four weeks in all wells with different injection rates of 12, 8, 4, 2, and  $0.5 \text{ m}^3/\text{day/m}$ .

### *Intermittent leachate injection*

Leachate injection rates of 12, 4, and  $2 \text{ m}^3/\text{day/m}$  are assumed for the following four modes of injection scenarios:

- i. Continuous injection for four weeks
- ii. One week on and off in all wells
- iii. Two weeks on and off in all wells
- iv. Three weeks on and one week off in all wells

### *Intermittent leachate injection in alternate HT layer*

Effect of intermittent leachate injection in alternate HTs on moisture distribution within MSW is

considered with flow rate of  $12\text{m}^3/\text{day/m}$  for the following injection scenarios:

- a. Four weeks continuous in both layers of HTs.
- b. First week flow in Layer2 (L2) only; flow in Layer1 (L1) only in second week; injection in only L2 for third week; and for fourth week, injection only in HTs in L1 is allowed.
- c. First week flow in HTs of L1 only; second week injection only in L2; flow in only L1 HTs for third week; and for the fourth week, injection only in HTs of L2 is allowed.
- d. First two weeks flow in only L2 HTs; for third and fourth weeks, injection only in HTs of L1.
- e. First two weeks flow in only HTs of L1; for third and fourth weeks, injection only in HTs located at L2.
- f. Effect of gravity flow for the four weeks following the scenario (d) and (e) above is assessed.

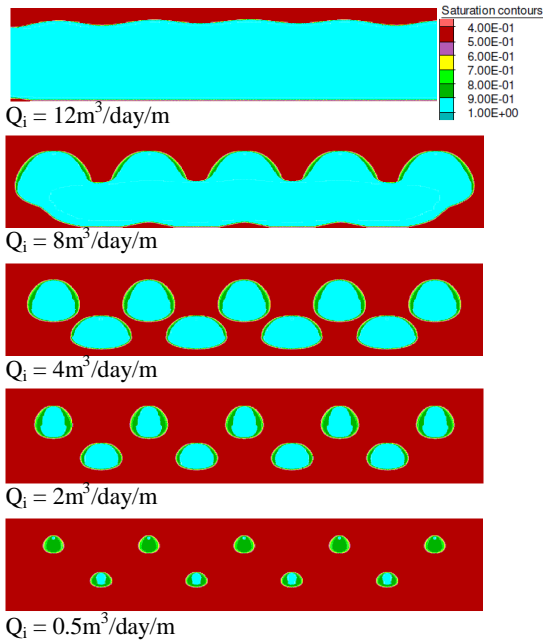
## RESULTS AND DISCUSSION

### **Effect of Continuous Leachate Injection**

Leachate injected continuously for four weeks showed considerable difference on influence area for different injection rates (Fig.2). After four weeks of flow, landfill was observed to get flooded with  $Q_i=12\text{m}^3/\text{day/m}$ , and in case of  $Q_i=8\text{m}^3/\text{day/m}$ , the moisture got distributed throughout the entire landfill. However in the case of low injection rates of 4, 2, and  $0.5 \text{ m}^3/\text{day/m}$ , more dry areas are found. Maximum saturation levels in the landfill for different injection rates varied with 100% for  $Q_i=12\text{m}^3/\text{day/m}$  to 90% for  $Q_i=0.5\text{m}^3/\text{day/m}$ .

The maximum pore water pressure developed in landfill with respect to leachate injection rate indicated as high as 140 kPa for  $Q_i=12 \text{ m}^3/\text{day/m}$ , then reduced to 60kPa for  $8 \text{ m}^3/\text{day/m}$ , 20kPa for  $4 \text{ m}^3/\text{day/m}$ , 13kPa for  $2 \text{ m}^3/\text{day/m}$ , and 5 kPa for  $0.5 \text{ m}^3/\text{day/m}$ . The high pore water pressure development reduce the resisting force against sliding of the landfill slope and hence makes the bioreactor landfill slope to be more prone for failure. In order to attain larger influence area, higher injection rates are preferable; however, it is important to maintain an optimum saturation level (60-80%) in the system to enhance the waste

biodegradation and also to avoid excess development of pore water pressure. This might be possible with the intermittent liquid injection modes.

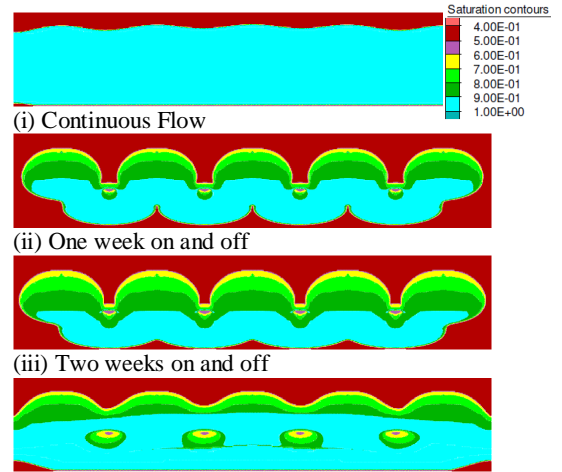


**Fig.2** Saturation contours for different leachate injection rate (continuous injection for four weeks). (For colour figure, refer to CD)

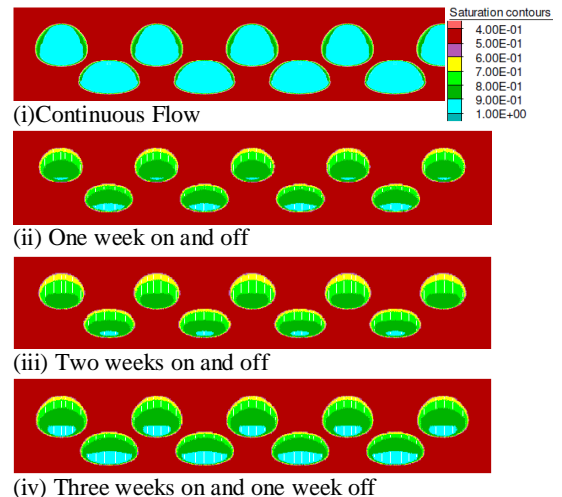
**Effect of Intermittent Injection in all HTs**

In order to assess the effect of intermittent injection on the optimum saturation levels and the maximum pore water pressure development in the system, injection flow rates of 12, 4, and 2 m<sup>3</sup>/day/m are considered for the scenarios (i to iv) as explained before. It is clear from the results (Fig.3) that intermittent liquid injection reduces the influence area compared to the continuous liquid injection. However, the pore pressure developed in the system has reduced which is important, in stability point of view. It can also be observed that in scenario (ii) and (iii), after four weeks of liquid injection, the saturation level has dropped to 60-90% in the landfill with the flow rate of 12m<sup>3</sup>/day/m, having larger influence area (Fig. 3a). Results with low flow rates (4 and 2 m<sup>3</sup>/day/m) indicates more dry areas compared to the former case. Figure 4 summarizes the maximum pore

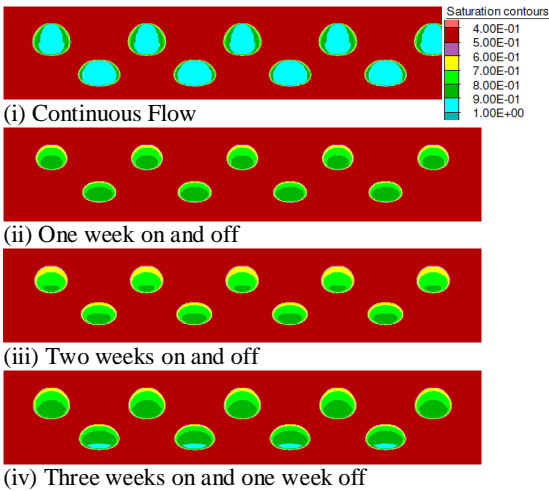
water pressure developed in the landfill for the scenario (iii) with two weeks on and off injection mode. A significant reduction in pore pressure more than 85% (from 140kPa with the continuous injection to 19 kPa with intermittent liquid injection) in the landfill was observed. Thus scenario (iii) proves the best suited combination of liquid injection mode having  $Q_i=12\text{m}^3/\text{day}/\text{m}$ . Further, reduction in saturation levels and maximum pore water pressure was assessed by adopting intermittent liquid injection in alternate HT layers.



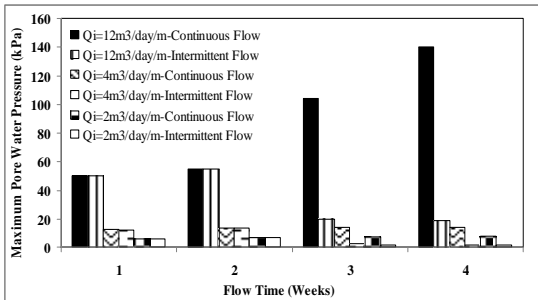
**Fig.3a**  $Q_i = 12 \text{ m}^3/\text{day}/\text{m}$  (For colour figure, refer to CD)



**Fig.3b**  $Q_i = 4 \text{ m}^3/\text{day}/\text{m}$  (For colour figure, refer to CD)



**Fig.3c**  $Q_i = 2 \text{ m}^3/\text{day}/\text{m}$   
**Fig.3** Saturation contours for intermittent leachate injection with three different injection rates

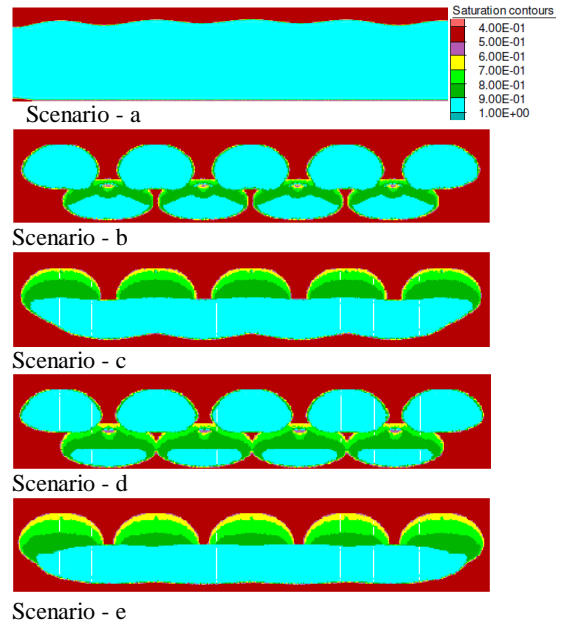


**Fig.4** Variation of maximum pore water pressure for two weeks on and off mode of injection.

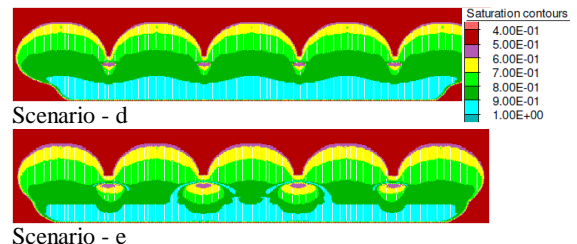
**Intermittent Leachate Injection in Alternate HT Layers**

Figures 5 and 6 illustrate the moisture distribution and maximum pore water pressure in the landfill with intermittent injection in alternate HT layers for the six scenarios considered herein. Saturation levels are varying from 60-100% for different scenarios (a) to (e) (Fig.5a). Figure 5b shows the saturation levels for scenario (f), following scenarios (d) and (e). Scenario (a) which is continuous injection in all wells, shows the landfill getting flooded for four weeks flow. Scenario (d) and (e) proves more efficient for distributing moisture throughout the landfill with saturation levels between 60-90% in some areas. Search for

an optimum saturation was further proceeded for eight weeks flow by adopting gravity flow only following four weeks flow in scenario (d) and (e). Simulations indicated that the influence area for the saturation level between 60-80% increased compared to the first four weeks flow in the scenario (d) and (e). Maximum pore water pressure developed in these six scenarios are plotted in Fig.6 justifies the effectiveness of intermittent injection in reducing the pore water pressure around 84% in scenario (d) and (e) compared to

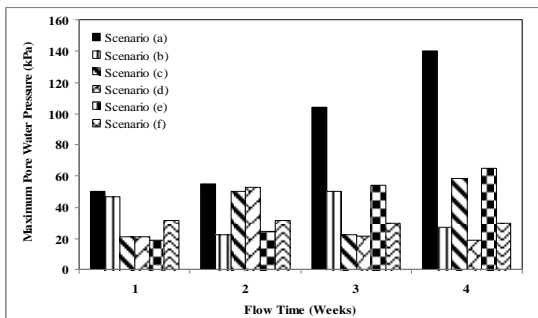


**Fig.5a** Saturation contours for four week flow with leachate injection in alternate HT layers (For colour figure, refer to CD)



**Fig.5b** Saturation contours for eight weeks flow in scenario (f) following the scenario (d) and (e)  
**Fig. 5** Saturation contours for the effect of intermittent leachate injection in alternate layers with different scenarios (For colour figure, refer to CD)

scenario (a) (from 140 kPa in scenario (a) to 19.2 kPa in scenario (d) and (e)). Hence scenario (e) i.e. leachate injection for the first two weeks only in L1 HTs and then followed by two weeks liquid injection in L2 HTs only, then ceasing the liquid injection in all wells, allowing the flow by gravity (scenario (f)) ensures an optimal environment for waste biodegradation.



**Fig. 6** Maximum pore pressure variations for the effect of intermittent leachate injection in alternate HT layers with different scenarios

## CONCLUSIONS

The numerical study performed consists of designing liquid recirculation system using HTs. Study included the comparison between continuous and intermittent leachate injection modes on saturation levels and the developed pore water pressure. Following are the major findings of this study:

1. Higher the injection rate, the greater is the influence area. The saturation levels ranged between 100-70% with different injection rates. The maximum and minimum pore water pressure 140kPa and 5kPa for  $Q_i=12$  and  $0.5 \text{ m}^3/\text{d}/\text{m}$  respectively.
2. Intermittent liquid injection reduces the saturation level between 60-80% in scenario (iii) with two weeks on and off mode, having a larger influence zone. Around 86% of pore water pressure has reduced.
3. Scenarios (d) or (e) prove to be better to have optimal environment wherein two weeks of injection is allowed at a time in one layer of HT.
4. Effect of gravity flow, scenario (e) showed good results to have an optimal environment for waste

degradation without producing excess pore water pressure in the landfill cell.

## ACKNOWLEDGEMENT

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