Modeling of Horizontal Trench Systems for Leachate Recirculation in Bioreactor Landfills

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Abstract: Bioreactor landfills are designed to accelerate degradation of municipal solid waste (MSW) by increasing the moisture content of MSW, most commonly by recirculation of leachate using a horizontal trench (HT) system. Currently, the design of HT system (horizontal and vertical spacing and geometric configuration) is based on empirical approaches, leading to either over-design or under-design of these systems. An ideal HT system should ensure uniform distribution of adequate moisture through the entire MSW without causing a significant increase in pore water pressure. The objective of this study is to perform two-phase flow modeling of HT systems to investigate the effects of horizontal and vertical spacing of HTs, their geometric layout, and optimal leachate recirculation operations on the distribution of moisture within the landfill. Leachate movement in the MSW pores is modeled by unsaturated two-phase flow with the fluid flow described by Darcy's law and the unsaturated hydraulic conductivity MSW defined by van Genuchten function. Several model simulations are performed to investigate the effects of horizontal and vertical spacing and geometric configurations of the HTs, injection modes (continuous versus intermittent), and injection sequencing in alternate HT layers on moisture distribution in the landfill. Simulation results show that the HT layout with horizontal spacing of 30 m and vertical spacing of 6 m resulted in uniform leachate distribution in the landfill within a short period of two weeks. However, to avoid development of high excess pore water pressures under continuous recirculation, intermittent injection mode or leachate sequencing in alternate layers of HTs is shown to be effective in achieving relatively uniform moisture distribution, without causing excess pore water pressures, in landfill.

Keywords: bioreactor landfill; leachate recirculation; modeling; two phase flow; horizontal trench; moisture distribution; layout configuration.

Introduction
Modern bioreactor landfills are aimed to degrade the municipal solid waste (MSW) at a faster rate opposed to conventional landfills (Sharma and Reddy, 2004; Reddy, 2006). Published studies enumerate the empirical methods for the design and operation of leachate recirculation systems in bioreactor landfills which are based on limited laboratory studies and field observations (ITRC, 2006). As a result, these systems yield large variation in the moisture distribution and pore water pressure in the landfill which may affect the stability of landfill slopes. Thus, a design engineer should rationally design and operate the leachate recirculation system to ensure that the leachate is distributed throughout the landfill without causing excess pore water pressure.
Several different leachate recirculation methods are used in practice which include prewetting, surface spraying, surface ponds, vertical injection wells, and horizontal trenches (HTs). Of all these leachate recirculation methods available, HTs are commonly being used in new landfills. Leachate is recirculated through perforated pipes in a gravel trench by gravity or injection under pressure. When spaced adequately, HTs considered to be effective in recirculating leachate, thus enhancing degradation of organic waste (Reinhart, 1995). The leachate injection pressure head, hydraulic conductivities of trench backfill and MSW, dimensions of trench, spacing and geometric formation of HTs can affect the leachate distribution in a landfill (Haydar and Khire, 2005). These researchers showed a logarithmic relation between leachate flux produced and injection pressure head using a finite element based model HYDRUS-2D. In another study, McCreanor and Reinhart (2000) performed hydrodynamic modeling using a finite element model SUTRA to study the effect of MSW properties (anisotropic and heterogeneity) and recirculation system on leachate routing. They simulated the heterogeneity of waste mass by applying statistical relationships to the local hydraulic conductivities, varied MSW hydraulic conductivity from $10^{-1}$ to $10^{-5}$ cm/s and leachate injection rate from 4 to 8 m$^3$/day/m.

To date, a detailed modeling of leachate recirculation systems to determine the moisture distribution as well as pore water pressure generation under different practical bioreactor landfill design and operational scenarios has not been performed. When using HTs for leachate recirculation, the moisture distribution and pore water pressure development in the bioreactor landfill will depend on their vertical and horizontal spacing as well as geometric configuration. Even for a given HT system, leachate injection operations should be optimized to ensure the desired moisture content of 40-60% (by wet weight which is equal to saturation range of 60-80%) throughout landfill to enhance waste biodegradation (ITRC, 2006). The main objective of this paper is to develop an optimal HT system design and operational guidelines to achieve desirable moisture (or saturation) levels in a landfill, while at the same time minimizing development of excess pore water pressure.

**Numerical Modeling**

**Two-Phase Flow Modeling**

Two-phase fluid flow analysis assumes that the pores of the medium are filled by two immiscible fluids – wetting fluid and non-wetting fluid. In a bioreactor landfill modeling, the recirculated leachate is the wetting fluid, while the landfill gas is the non-wetting fluid. Fast Lagrangian Analysis of Continua (FLAC) which provides a platform for modeling two-phase flow in unsaturated media is used in this study (ITASCA, 2008). Fluid flow is described by Darcy’s law, and the unsaturated hydraulic conductivity is modeled by van Genuchten (1980) function considering the water retention curve. Two phase flow modeling includes the numerical solutions of the differential equations that govern the flow of fluids in the porous media.

The transport of wetting ($w$) and non-wetting ($g$) fluids is described by the Darcy’s law as:

\[
q_i^w = -k_{rw}^w \frac{\partial}{\partial x_j} (P_w - \rho_w g_i x_i)
\]  

\[
q_i^g = -k_{rg}^g \frac{\partial}{\partial x_j} (P_g - \rho_g g_i x_i)
\]
Where: \( k_{ij} \) = saturated mobility coefficient (tensor) of the fluid defined as ratio of intrinsic permeability to dynamic viscosity (\( \mu \)); \( \kappa_r \) = relative permeability of the fluid; \( P \) = pore pressure of the fluid; \( \rho \) = fluid density; and \( g \) = gravity.

The relative permeabilities are related to saturation (\( S_w \)) by the empirical law given by van Genuchten (1980) as:

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

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

\[
S_e = \frac{S_w - S_{w_r}}{1 - S_{w_r}}
\]
(5)

Where: \( a \), \( b \) and \( c \) are constant parameters; \( S_e \) = effective saturation; and \( S_w \) = residual wetting fluid saturation.

The pressure difference between the non-wetting fluid and the wetting fluid is the capillary pressure (\( P_c \)) which is a function of \( S_w \):

\[
P_g - P_w = P_c (S_w)
\]
(6)

Where: \( P_g \) = pressure created by non-wetting fluid; \( P_w \) = pressure created by wetting fluid.

When the pore space is filled with fluids, then the sum of the saturation of wetting fluid (\( S_w \)) and non-wetting fluid (\( S_g \)) is equal to one and it is expressed as:

\[
S_w + S_g = 1
\]
(7)

**Landfill Model**

Fig.1 shows a schematic diagram of the landfill model along with the HT systems with different horizontal and vertical spacing and geometric configurations selected for this study. A bioreactor landfill cell of 150mx30m filled in ten layers, each of 3m height, is considered in this study. Leachate injection system consists of HTs having dimensions of 0.6mx0.6m. An average unit weight of 7.5kN/m\(^3\) is assumed for MSW. A high leachate injection flow rate of 12 m\(^3\)/day/m length of HT is selected. The external boundaries are simulated as the zero-flow boundaries and no infiltration from the landfill cap is assumed since the purpose is to examine the subsurface hydraulics of recirculated leachate. Losses in the pipes, joints, manifolds, and pumps are not considered. The leachate collection and removal system is located at bottom of the landfill.

**Hydraulic Properties of MSW**

The saturated hydraulic conductivity is needed to calculate the intrinsic permeability for the MSW. The permeability of MSW varies within a landfill since the bottom layers are more compacted (Landva and Clark, 1990). Reddy et al. (2009) presented laboratory and field studies on the saturated hydraulic conductivity of MSW for different unit weights and normal pressures and reported that the saturated hydraulic conductivity decreases with increase in unit weight and applied normal pressure. Based on these results, the values of vertical saturated hydraulic conductivity (\( k_v \)) of MSW are determined based on the calculated normal pressure in each layer,
for the assumed average unit weight of 7.5 kN/m$^3$: for layer 1=$8.0\times10^{-5}$ (bottom most layer of MSW in landfill), layer 2=$1.0\times10^{-4}$, layer 3=$1.5\times10^{-4}$, layer 4=$1.7\times10^{-4}$, layer 5=$2.0\times10^{-4}$, layer 6=$2.5\times10^{-4}$, layer 7=$3.0\times10^{-4}$, layer 8=$3.5\times10^{-4}$, layer 9=$4.0\times10^{-4}$, and layer 10=$5.0\times10^{-4}$ cm/s (top most layer of MSW in landfill). Anisotropic waste mass is assumed by taking the horizontal hydraulic conductivity ($k_h$) ten times $k_v$ for each layer (McCreanor and Reinhart, 2000). The unsaturated hydraulic conductivity of MSW is governed by the moisture and matric suction characteristics, which can be modeled by van Genuchten function in terms of degree of saturation as given in equations (3) to (5). Very limited data is published on unsaturated hydraulic characteristics of MSW. Stoltz and Gourc (2007) tested field MSW in laboratory and reported the values of van Genuchten parameters as: $a=0.44$, $b=0.5$ and $c=0.5$, which are used in this study.

![Figure 1. Different horizontal trench configurations modeled in this study](image)

**Model Simulations**

Three different series of simulations are conducted to investigate the optimal design and operation of HT systems, as explained below:

**Series I: HT Configurations**

Four different HT configurations as shown in Fig.1 (HT-C1 to HT-C4) are selected for this study:

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HT-C1: uniform layout with horizontal spacing of 60m and vertical spacing of 12m  
HT-C2: staggered layout with the same horizontal and vertical spacing as HT-C1  
HT-C3: staggered layout with horizontal spacing of 30m and vertical spacing of 12m  
HT-C4: staggered layout with horizontal spacing of 30m and vertical spacing of 6m.

The above horizontal spacing, the vertical spacing, and the geometric layout are assumed based on the typical designs adopted at the actual bioreactor landfills in the United States. The moisture (or saturation) distribution and pore water pressure generation are predicted with time for a total duration of four weeks under continuous injection of leachate at a maximum injection rate of 12 m³/day/m.

Series II: Intermittent Leachate Injection
Leachate injection is considered effective if the moisture content in the MSW is increased to 40-60% (by wet weight), which is equivalent to the saturation level of approximately 60-80%, uniformly through the entire landfill. It is not desirable to completely saturate the MSW because it will not allow easy removal of generated gas and any excess moisture accumulation will increase the pore water pressures, thus jeopardizing the effectiveness and stability of bioreactor landfills. The intermittent leachate injection rather than continuous leachate injection may provide the optimal moisture conditions without generating excess pore water pressures and this aspect is investigated by using the HT-C4 configuration under the following different leachate injection scenarios:
- HT-C4-C: Four weeks continuous flow in all wells (baseline comparison case)
- HT-C4-1O1S: One week on and one week off- repeated to total four weeks duration
- HT-C4-1O2S: One week on and two weeks off-repeated for total four weeks duration

Series III: Leachate Injection in Alternate HTs
It may be possible to further optimize moisture and pore pressure conditions by injecting leachate intermittently, but sequencing leachate injection in alternate levels of HTs. For example, intermittent leachate injection may be performed in deep HTs for a certain time period during which no injection is performed in any other shallow HTs. Following this, intermittent leachate injection may be performed in shallow HTs while no injection is performed in deep HTs. This procedure may be then repeated. In order to investigate this injection scheme, HT-C4 configuration is selected and the following three different scenarios are simulated:
- HT-C4-C: Four weeks continuous flow in all wells (baseline comparison case)
- HT-C4-1OM1O&T&B: 1st week, flow in HT layer 2 (L2) only; 2nd week, flow in HT layers 1 (L1) and 3 (L3) only; 3rd week, flow in L2 only; 4th week, flow in L1 and L3 only. Subsequent gravity flow in all HTs for four weeks without any leachate injection.
- HT-C4-1OT&B1OM: 1st week, flow in L1 and L2; and gravity flow without injection in all HTs during the 4th week. Subsequent four weeks gravity flow without any leachate injection.

Results and Discussion

**HT configurations**
Figure 2 shows the saturation contours in landfill after two weeks of continuous leachate injection for four different configurations shown in Fig. 1. It is clear from the simulation results
that HT layout does affect the moisture distribution. The maximum saturation level near the HT locations in all four configurations is 100% (fully saturated); however, the zone of influence differs for each configuration. In HT-C1, HTs are not staggered and they have horizontal spacing of 60m and vertical spacing 12m, thus making two layers of HT. This configuration resulted in less influence area (Fig. 2(a)), making it ineffective option to distribute the leachate throughout the landfill. Configuration HT-C2 involves the staggering of HTs, but with the same horizontal and vertical spacing as HT-C1 and the results for this configuration (Fig. 2(b)) shows an increased influence area compared the HT-C1. Thus staggering of the HTs improves the moisture distribution in the landfill as compared to the regular spacing of them. In HT-C3 configuration, the horizontal spacing is reduced to 30m while keeping the same vertical spacing, thus having two layers of HTs. As shown in Fig. 2(c), reducing the HT spacing has improved the influence area in the landfill compared to the other two configurations HT-C1 and HT-C2. Results obtained from configuration HT-C4, which has the horizontal spacing of 30m and vertical spacing of 6m making it three layers of HTs, showed that the injected leachate is distributed throughout the landfill covering around 70% of the total area of MSW just after two weeks of leachate injection (Fig. 2(d)).

Figure 2. Saturation contours after two weeks of continuous leachate injection for different HT configurations

Pore water pressure within the influenced area varied significantly (Fig.3). Maximum pore water pressure was developed within the close vicinity of the injection location and it decreased with
increased distance from the injection location. In HT-C1, the developed maximum pore water pressure is 60kPa. With the same vertical and horizontal spacing, but staggering the HTs locations resulted in reduced pore water pressure to maximum of 50kPa. In HT-C3 with reduction in horizontal spacing, the maximum pore water pressure slightly increased to 55kPa. Configuration HT-C4 resulted in full saturation of the entire landfill and induced pore water pressure as high as 140kPa only after two weeks flow.

![Pore pressure distribution](image)

(a) HT-C1
(b) HT-C2
(c) HT-C3
(d) HT-C4

**Figure 3.** Pore water pressure distribution after two weeks of continuous leachate injection for different HT configurations

In order to better delineate the effect of HTs configuration, leachate injection was continued for four weeks. Saturation contours after four weeks of leachate injection are plotted in Fig. 4 for different configuration. From Fig. 4(a), it is clear that HTs configured without staggering cannot distribute the leachate throughout the landfill even after four weeks of leachate injection, thus configuration HT-C1 is considered to be ineffective for moisture distribution. In case of HT-C2, staggering HTs has helped to increase the influence area in the landfill compared to HT-C1; however, some areas of the landfill remain unaffected by leachate injection. HT-C3, where in the horizontal spacing is reduced to 30m, but with the same vertical spacing, has shown improvement in distributing the moisture throughout the landfill having influence area more than 80% of the total landfill area. In HT-C4, with reduced horizontal and vertical spacing, when leachate is injected up to four weeks has created fully saturated (flooded) the entire landfill;
however, such over-saturation of the landfill is not preferred due to generation of excess pore water pressures and associated potential geotechnical stability issues.

Figure 4. Saturation contours after four weeks of continuous leachate injection for different HT configurations

The pore water pressure within the influenced area increased significantly for all configurations due to continued injection for four weeks (Fig.5). Maximum pore water pressure occurred within the close vicinity of the injection location and it decreased with increased distance from the injection location. The developed maximum pore water pressure increased from 60 to 90kPa, 50 to 60kPa, 55 to 150kPa and 140 to 250kPa with continued leachate injection from two weeks to four weeks for the configurations HT-C1, HT-C2, HT-C3, and HT-C4, respectively. Such high pore water pressures will be a concern from the stability of the landfill point of view.

The optimal configuration is the one which distributes the leachate uniformly to result in saturation levels of 60-80% (equivalent to 40-60% moisture content by wet weight) and induce low pore water pressures. HT-C1 is ineffective to distribute the moisture throughout the landfill. Staggering the HTs as in HT-C2 is effective; however, because of the higher spacing between the HTs, moisture was not distributed throughout the landfill. Staggered, but decreased horizontal spacing of HTs as in HT-C3 yielded better moisture distribution when the leachate is injected for four weeks continuously. However, it is impractical to inject the leachate continuously for four
weeks. Thus, further reduction in both the horizontal and vertical spacing as in HT-C4 covered more than 70% of the total landfill area within two weeks of flow with maximum saturation of 100%. However, continued injection caused fully saturated conditions and high pore water pressures. Therefore, a better control of leachate injection in configuration HT-C4 may reduce the over-saturation and pore water pressure conditions and create optimal conditions needed for bioreactor landfills.

![Image](image1.png)

![Image](image2.png)

![Image](image3.png)

![Image](image4.png)

**Figure 5.** Pore water pressure distribution after four weeks of continuous leachate injection for different HT configurations

**Intermittent leachate injection**

Injecting leachate intermittently (some days on and some days off) instead of continuous injection was investigated to optimize the moisture distribution in landfill using HT-C4 configuration. As stated earlier, two intermittent injection scenarios were modeled: (1) one week injection and one week of no injection, which was repeated for total duration of four weeks (denoted HT-C4-1O1S), and (2) one week injection, two weeks of no injection and one week of injection again (total duration of four weeks, denoted HT-C4-1O2S). The results of the intermittent leachate injection are compared with the results of continuous injection for four weeks. Figure 6 compares the saturation contours in the landfill with intermittent and continuous injection after four weeks. HT-C4-1O1S resulted in reduced saturation levels between 60-90% (Fig.6(b)) in the vicinity of HTs and the saturation levels greater than 90% in most of the other
areas of the influence zone. On the other hand, HT-C4-1O2S indicated the maximum saturation throughout the landfill as 90-100% (fully saturated) as seen in Fig. 6(c).

Figure 6. Saturation contours after four weeks with HT-C4 configuration under continuous and two different intermittent leachate injection scenarios

Figure 7. Pore water pressure distribution after four weeks with HT-C4 configuration under continuous and two different intermittent leachate injection scenarios
A substantial reduction in pore water pressure is observed by adopting intermittent leachate injection (from 250kPa in scenario HT-C4-C to 130kPa in scenario HT-C4-1O1S and 150kPa in scenario HT-C4-1O2S) after four weeks of leachate injection (Fig. 7). There is around 48% reduction in pore water pressure in the system from HT-C4-C to HT-C4-1O1S which proves that the intermittent mode of leachate injection is more effective than continuous injection. Though the scenario HT-C4-1O1S with intermittent leachate injection mode of one week on and off is shown to be better than continuous leachate injection, further optimization of the leachate injection operations is necessary to achieve optimal saturation (about 60-80%) and reduce pore water pressures.

**Leachate injection in alternate HT layers**

Intermittent leachate injection in alternate HT layers is analyzed to optimize moisture (saturation) and pore water pressure distribution in the landfill. The saturation levels for two different such scenarios considered are compared with the continuous injection scenario, all for total duration of four weeks, in Fig.8. Scenario HT-C4-1OM1OT&B indicated the saturation of 100% after first four weeks of flow, while significant area of the landfill experienced saturation levels of 60-80% in scenario HT-C4-1OT&B1OM.

![Saturation contours](image)

*Figure 8. Saturation contours after four weeks with HT-C4 configuration with continuous versus two scenarios with intermittent leachate injection in alternate level HTs*

The pore water pressure distribution in Fig. 9 indicates that the intermittent leachate injection in alternate HT layers has reduced the excess pore water pressure in the landfill compared to continuous injection. In HT-C4-1OM1OT&B, after first four weeks of flow, the maximum pore water pressure of 120kPa is developed and in HT-C4-1OM1OT&B it was 55kPa (around 80% reduction compared to HT-C4-C).
It may be possible that optimal conditions will exist if the leachate injection is ceased in all HTs and only gravity flow is allowed for few weeks. In order to assess this option, leachate is allowed to flow under gravity alone for four weeks immediately upon the leachate injection intermittently for the first four weeks is completed (total eight weeks duration from the beginning). Because of the gravity flow, the saturation levels in the landfill have reduced significantly (Fig. 10). Scenario HT-C4-1OT&B1OM resulted in larger influence area with the saturation levels between 60-80% which is necessary for the waste biodegradation.

Further, due to the gravity flow for four weeks subsequent to the first four weeks of intermittent leachate injection in alternate layers of HTs as in scenarios HT-C4-1OM1OT&B and HT-C4-1OT&B1OM, the maximum pore water pressure in the landfill is reduced significantly to 54kPa in HT-C4-1OM1OT&B and 44kPa in HT-C4-1OT&B1OM (Fig. 11). This shows that such operational scheme, especially in the scenario HT-C4-1OT&B1OM, is effective in achieving optimum environment in the landfill without producing excess pore water pressure.

Conclusions
The purpose of this study was to perform two-phase flow modeling to optimize the design and operation of HTs. Three series of simulations were performed to study the effects of: (I) HT layout design; (II) intermittent leachate injection; and (III) leachate injection in alternate HT layer on moisture and pore water pressure distribution in a typical landfill. Based on the results, the following conclusions can be drawn:

1. HT layout has a considerable effect on moisture and pore water pressure distribution in a landfill. The staggered arrangement of HTs with horizontal spacing of 30m, vertical spacing of 6m, and having three layers of HTs appear to be an optimal HT layout for the
selected landfill to result a better distribution of the injected leachate in the landfill within a short period of two weeks.

![Saturation contours](image1)

(a) HT-C4-1OM1OT&B

(b) HT-C4-1OT&B1OM

**Figure 10.** Saturation contours after four weeks of gravity flow subsequent to the leachate injection conditions

![Pore water pressure contours](image2)

(a) HT-C4-1OM1OT&B

(b) HT-C4-1OT&B1OM

**Figure 11.** Pore water pressure contours after four weeks of gravity flow subsequent to the leachate injection conditions

2. Intermittent leachate injection mode of one week on and one week off, proved effective in reducing the moisture saturation between 60-80% along with reducing the pore water pressure in the landfill, when compared to the continuous leachate injection mode.

3. Leachate injection in alternate HT layers for one week on and one week off mode for a total duration of four weeks showed better distribution of moisture. Subsequent four weeks gravity flow without any leachate injection yielded saturation 60-80% and reduced pore water pressures which are optimal for waste degradation.

It should be noted that the results of this study are based on one selected high injection rate and a set of unsaturated hydraulic properties of MSW. The effects of these variables on moisture and pore water pressure distributions are currently being investigated.
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References