Effectiveness of drainage blanket for leachate recirculation in bioreactor landfills

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ABSTRACT
Leachate recirculation in a bioreactor landfill helps distribute the moisture, nutrients and microbes required for the enhanced biodegradation of MSW. The moisture distribution is dependent on the leachate recirculation system (horizontal trenches, vertical wells and drainage blankets), hydraulic properties of MSW and leachate injection rate. The main objective of this paper is to evaluate the effect of leachate injection rate and the saturated hydraulic conductivity on moisture distribution using drainage blanket as leachate recirculation system. A two-phase unsaturated flow model is used to compute the leachate and landfill gas flow in MSW using Darcy's law with relative permeabilities computed by van Genuchten function. The model is validated based on published laboratory experiments and mathematical modeling studies. A typical bioreactor landfill cell is selected with a single drainage blanket, and leachate injection is performed continuously until steady-state conditions are achieved. The dynamic changes in the wetted width, wetted MSW area, saturation levels, pore water distribution and outflow into leachate collection system are determined under different hydraulic properties of MSW and leachate injection rates. It is shown that as the hydraulic conductivity decreases, the wetted area increases slowly, but excessive pore water/gas pressures are generated. Higher leachate injection rate under low MSW permeability conditions shows the possibility of leachate migration in both upward and downward directions. Thus, leachate injection should be properly controlled as the permeability of MSW decreases with increased degradation.

1 INTRODUCTION

Proper disposal of municipal solid waste (MSW) has become requirement and challenging among waste management professionals. Though well documented and established waste management alternatives exist, waste disposal in landfills will continue into foreseeable future in the United States. More than 180% increase in the MSW generation occurred in past few decades (USEPA, 2009). On an average, about 4.3 pounds of waste is being generated per person per day (Fig. 1). The waste generation remained the same or slightly decreased recently due to increased recycling efforts. However, large quantities of MSW still requires disposal in landfills.

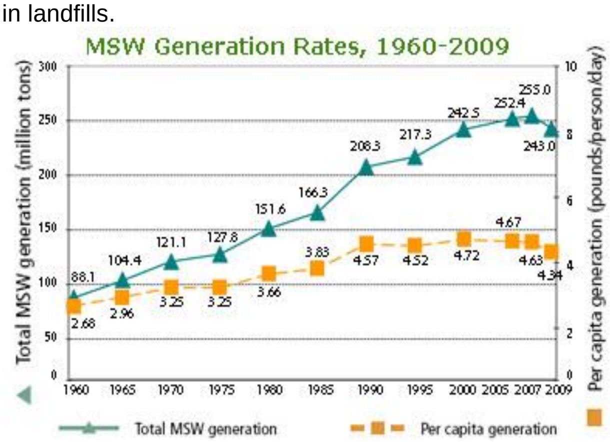

Figure 1. MSW generation in the United States (USEPA, 2009)

Over the past few decades, engineered landfills have been in practice for MSW disposal. An engineered landfill basically consists of a containment system with the leachate collection system. The leachate collected is treated and then discharged into the natural water bodies. This practice requires prolonged duration for the MSW to degrade due to relatively dry conditions in the landfill (around 50 to 100 years), leading to increase in the operational and post-closure monitoring costs. Therefore, recently, bioreactor landfills were introduced to overcome this problem.

Unlike conventional landfill, a bioreactor landfill essentially consists of re-circulation of leachate as well as injection of supplemental liquids, if needed, to increase the moisture in landfill mass and enhance the distribution of nutrients and microbes, which are all essential for the accelerated biodegradation of MSW. Leachate re-circulation system can be a vertical well system, a horizontal drain system, or a drainage blanket system. As a result of increased moisture, waste can be stabilized faster and the costs can be minimized for leachate treatment and post-closure monitoring (Sharma and Reddy, 2004; Reddy, 2006). Moisture content of 40 to 60% on volumetric basis (which corresponds to approximately the saturation level of 60 to 80%) is considered optimal for the enhanced waste degradation (ITRC, 2006).

On the contrary, excess moisture addition may trigger instability of the landfill containment as a whole. Hendron (2006) reported failure of a bioreactor landfill which involved excessive leachate re-circulation (864 to 1296 m^3/day). Therefore, the effects of build-up of pore water pressure on physical stability of the landfill should be properly addressed in the design of bioreactor landfills.

There is a need for a rational method to design LRS that can achieve uniform distribution of the injected leachate without producing excess pore water pressure. Many parameters effect the moisture distribution in a landfill such as leachate injection rate, hydraulic properties of MSW (saturated and unsaturated hydraulic conductivity of MSW), MSW condition (inhomogeneous and anisotropic MSW), among others.

A comprehensive study has been in progress at the University of Illinois at Chicago to optimize leachate recirculation systems in bioreactor landfills. Recently, the effects of leachate injection rate and mode of recirculation (continuous and intermittent), geometric formation, and configuration of leachate re-circulation systems consisting of horizontal trenches (HTs) and vertical wells (VWs) on the moisture distribution in bioreactor landfills has been investigated (Reddy and Kulkarni, 2010a; Kulkarni and Reddy, 2010; Reddy and Kulkarni, 2010b; Kulkarni and Reddy, 2010c). The effects of unsaturated properties of MSW on moisture distribution due to leachate injection have also been recently investigated (Kulkarni and Reddy, 2011).

The main objective of this paper is to assess the effects of leachate injection rate and hydraulic conductivity of MSW on moisture distribution using drainage blanket (DB) as the leachate re-circulation system. Two-phase flow modeling of unsaturated MSW is performed to predict saturation levels, maximum pore water and gas pressure developed, maximum saturated wetted width and wetted MSW area, and time to reach steady state condition under different leachate injection rates and saturated hydraulic conductivity. The results are useful towards the rational design of effective DB systems.

2 MODELING METHODOLOGY

2.1 Two-Phase Flow Modeling

Two phase flow modeling of the two immiscible fluids (leachate as wetting fluid and landfill gas as non-wetting fluid) is performed. Fluid flow is described by Darcy's law and the unsaturated hydraulic conductivity parameters are modeled by van Genuchten function considering the moisture retention curve (MRC). Two phase flow modeling includes the numerical solutions of the derived differential equations that govern the flow of fluids in the porous media (ITASCA 2008).

The transport of wetting (with superscript "w") and non-wetting (with superscript "g") fluids is described by Darcy's law:

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

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

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

Relative permeabilities are related to saturation (S) and are given by van Genuchten function as

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

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

$$S_e = \frac{S_w - S_r^w}{1-S_r^w} \quad [5]$$

Where: a, b and c are constant parameters for van Genuchten function; S_e = effective saturation; S_r = residual wetting fluid saturation.

Capillary pressure is the pressure difference between the wetting and non-wetting fluids and is given as

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

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

$$S_w + S_g = 1 \quad [7]$$

3 MODEL VALIDATION

3.1 Validation with Laboratory Experiments

Capelo and deCastro (2007) studied transient flow of water in an unsaturated MSW in three laboratory column experiments. Neutron scattering was used to monitor the absolute moisture content variation in the columns. Each column was 3 m deep and 0.6 cm internal diameter (Fig. 2). Drainage was provided at the bottom of the column with a perforated PVC pipe and 10 cm thick crushed bricks. MSW from a sanitary landfill of Fortaleza, Ceara, Brazil, was used. The MSW was compacted in layers of 20 cm to fill the columns to a density of 550 kg/m^3.

The variation of volumetric moisture content with depth was presented in all the three columns during rain simulation condition as well as during the subsequent free drainage condition in the columns one and two. In the column one, flow density for rain simulation was 9.50 cm/h, and the observations were registered for 390 min at every 30 min interval at every 30cm depth; in the columns two and three, flow density for rain simulation was 14.25 cm/h, observations registered for 160 min at every 30 min interval approximately at every 30 cm depth.

These column results were used to validate the two-phase flow model first before applying to the drainage blanket simulations. All three columns tests were modeled using the testing conditions for rain simulations and subsequent free drainage conditions. The rain simulation intensity was assumed based on the absolute moisture content and moisture variation in a sample of MSW produced in city of Fortaleza (Brazil) during a simulated tropical rain event.

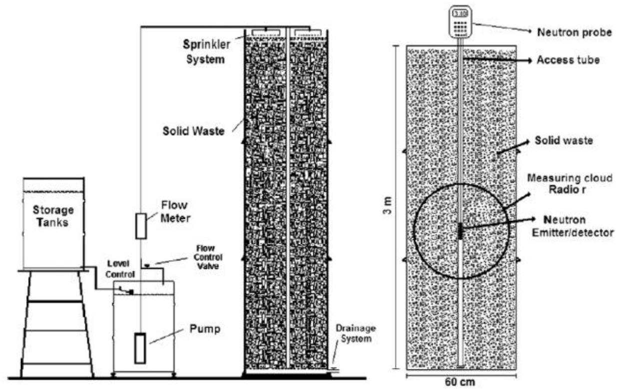

Figure 2. Experimental column setup to measure the moisture distribution in a laboratory scale testing (Capelo and deCastro, 2007)

3.1.1 Model and Initial and Boundary Conditions

To simulate the moisture distribution in the experimental column, a model size of 3 m height and 0.6 m in diameter was assumed. To understand the effect of grid size on moisture distribution, the ratio of model size to the smallest grid size was varied as 40, 30, 20 and 10. Based on the grid size results obtained, the experimental column was divided into small square mesh size of 0.06m to represent the ratio of model size to grid size of 10. All the boundaries were assumed as impermeable boundaries. During rain simulation, the bottom valve in the experiment was closed to allow the accumulation of leachate from the bottom. During the second stage of testing, the experiments included free drainage condition for column two. This condition was simulated by assigning zero pore pressure for the bottom most grid points in the model.

MSW in the column was assumed isotropic, but inhomogeneous. Initial condition parameters for the model validation are summarized in Table 1. The initial pore water pressures of leachate and landfill gas were assumed as zero at all grid points.

Flow in unsaturated porous media depends on the unsaturated hydraulic parameters of the media; therefore, the respective van Genuchten fitting parameters that include the residual saturation, saturated moisture content, matric suction, fitting parameters "a", "b", "c" and "P_0" were selected based on representative values for the fresh MSW (Stoltz and Gourc, 2007 (amended parameters)). Though the MSW tested in this study were different from those used by Capelo and deCastro, (2007), the MSW in both cases was fresh MSW and using the same properties was considered appropriate.

The initial porosity of the MSW was not reported; therefore, it was varied from 40% to 80% in model simulations, and the porosity of 77% provided good fit with the measured initial volumetric moisture content (Table 1). The viscosity ratio is defined as the ratio between the viscosity of wetting fluid and non-wetting fluid. The viscosities of wetting and non- wetting fluids assumed were the typical values for water and air.

Saturated hydraulic conductivity is one of the important hydraulic properties of MSW that greatly influences the moisture distribution during leachate re-circulation. Since the MSW was compacted in layers as specified by Capelo and deCapro (2007), having the layer height of 20 cm in column, the bottom layers possess high unit weight and therefore are relatively less permeable compared to the near top layers (Reddy et al., 2009).

Based on the results presented by Reddy et al. (2009), the k_{sat} values were selected for each layer as a function of overburden (normal) stress. Assuming an average bulk unit weight of MSW as 5.4 kN/m^3, and the values of k_{sat} in cm/s for different layers were as follows: Layer 1=9.0x10^{-2} (bottom most layer of MSW in landfill); Layer 2=0.5x10^{-1}; Layer 3 = 2.5x10^{-1}; Layer 4=3.0x10^{-1}; Layer 5=6.0x10^{-1}; Layer 6=7.0x10^{-1}; Layer 7=8.0x10^{-1}; Layer 8=9.0x10^{-1}; Layer 9=1.0; and Layer 10=2.0 (top most layer of MSW in landfill).

Table 1. Initial model input parameters

Parameter	Value	Remarks	Source
Wetting fluid pore water pressure	0	Initial Values	---
Non-wetting fluid pore pressure	0	Initial Values	---
Wetting fluid bulk modulus (Pa)	2x10^9	Typical	---
Non-wetting fluid bulk modulus (Pa)	1x10^5	Typical	---
Residual moisture content (θ_r) (%)	12	Laboratory experiments conducted on fresh MSW collected from French Bioreactor Landfill	Stoltz and Gourc (2007) (amended)
van Genuchten parameter (α) (/kPa)	2.9		
van Genuchten parameter (a)	0.358		
van Genuchten parameter (b)	0.50		
van Genuchten parameter (c)	0.50		
Porosity (n) (%)	77	40% to 80%	Model matching
Coefficient of pore water pressure increment due to volumetric strain (β)	0	Typical	ITASCA (2008)
Viscosity ratio	37.5	Typical	---
Saturated hydraulic conductivity (k_{sat}) (cm/s)	Varied	2.0 to 9.0x10^{-2} cm/s (varied with depth)	Reddy et al. (2009)

3.1.2 Results

Rain simulation was modeled in the column two with rain intensity 14.25 cm/hr. Figure 3 shows the evolution of moisture distribution in the column with respect to column depth during the rain simulation. Based on the saturation contours, the volumetric moisture content in the column at different depths was computed during the rain simulation and free drainage condition. The model results are compared to that of the published experimental values as given by Capelo and deCastro (2007).

The initial moisture content of MSW in the column was 13.2% before injecting the leachate into the column. When the leachate was injected in the column one, a minor variation in the moisture content was observed in the shallow layers of the column. When the leachate injection was continued further, a general trend of accumulation of high moisture was seen in the deep layers between 1.5 m to 3.0 m, which was due to the low permeability in these layers. The data points plotted in Fig. 3 represents the published results from the column experiments.

During the free drainage condition in the column two, the column was saturated. During the rain simulation in the column two, the moisture content was recorded using the neutron probe for every 30 min at 30 cm depth from the top of the column. Results obtained for free drainage in the column two indicated less moisture content after 14 days in the column.

The volumetric moisture content plotted in Fig. 3 consists of few data points not in agreement with the model predictions, and this may be due to the heterogeneity of the MSW. Overall, the model results indicate a fair agreement with the published experimental results, demonstrating the capability of the two-phase flow model to predict moisture distribution in MSW.

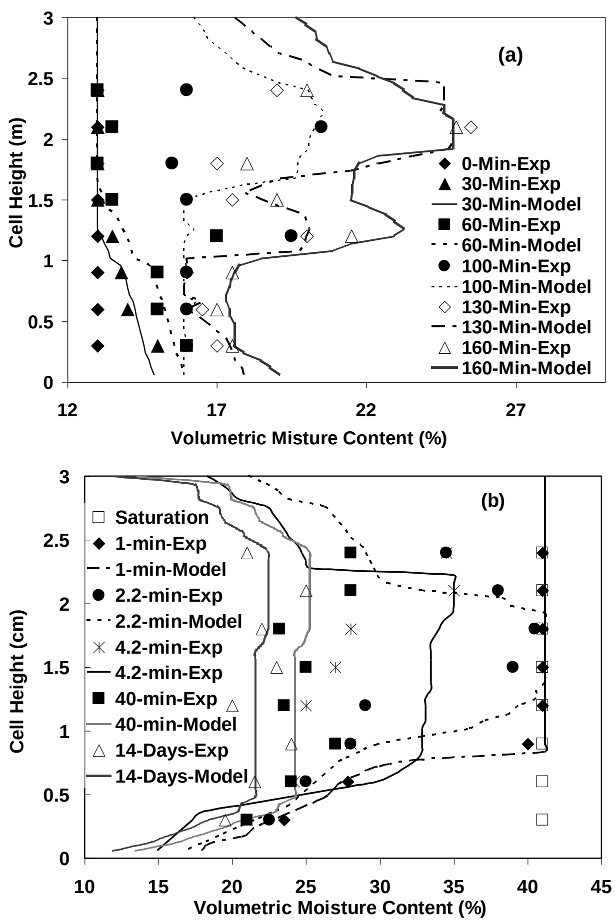

Figure 3. Volumetric moisture content in column two (a) during rain simulation; (b) during free drainage condition

3.2 Validation with Previous Mathematical Modeling

Haydar and Khire (2007) reported mathematical modeling of leachate recirculation using drainage blanket in a bioreactor landfill. Homogeneous and isotropic silt loam was assumed to represent MSW. Leachate was re-circulated in the DB at injection rate of 26 m^3/d/m length of leachate injection pipe embedded in a gravel backfilled DB until the injected leachate migrated within the DB only for first eight hours of operation.

The same conditions were simulated using the two-phase flow model. The model size of 100 m width and 20 m height was selected, and DB was located at 5 m above the LCRS. All the initial and boundary conditions, and material properties are assumed to be the same as those given by Haydar and Khire (2007).

Haydar and Khire (2007) defined the saturated wetted width (W_w) as the distance of leachate migrated from the center of the injection pipe to the maximum leachate movement within the DB. Fig.4 shows the wetted width as a function of the time of leachate recirculation. The saturated wetted width, representing the saturation greater that 90%, as predicted by the two-phase flow model is compared to that predicted by Haydar and Khire (2007), and it can be seen that the results from both the models are in close agreement.

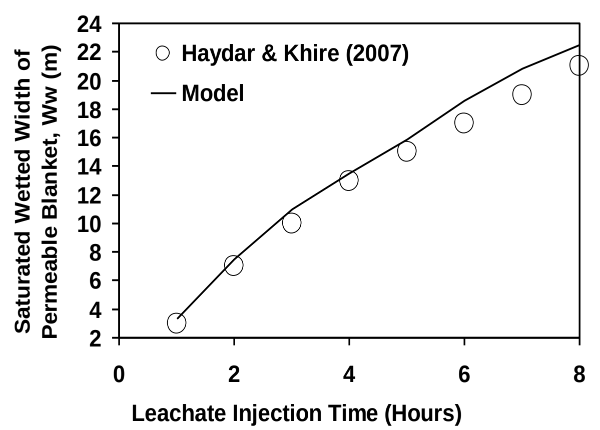

Figure 4. Comparison of predicted saturated wetted width of blanket with the published modeling results

4 DRAINAGE BLANKET AS LEACHATE RECIRCULATION SYSTEM IN BIOREACTOR LANDFILL

Moisture distribution using a drainage blanket (DB) was evaluated for different leachate injection rates and unsaturated MSW (Fig. 5). Leachate injection rates in the injection pipes in the DB was assumed to vary as 26, 56 and 86 m^3/d/m length of the injection pipe in a DB. Saturated hydraulic conductivity of MSW was varied as 10^{-3}, 10^{-4} 10^{-5} and 10^{-6} cm/s. These values were selected based on the published literature and the typical injection rates practiced in the field.

Haydar and Khire (2007) presented the wetted width within the DB, which does not represent the effectiveness of DB to recirculate the leachate in MSW. Therefore, the definition of saturated wetted width is modified as the maximum influence width in MSW due to leachate recirculation (Fig. 5).

4.1 Model and Boundary and Initial Conditions

A bioreactor landfill cell of 100 m width and 30 m height (Fig. 5) was selected. The grid size was chosen based on the sensitivity studies on the grid size, varying the different grid sizes from 1.0 to 0.1 m. Based on the accuracy and the computation time, the square grid size of 0.25 m was selected. Bioreactor landfill was assumed to contain a single DB layer with homogeneous and isotropic MSW. A single DB was located 27 m above the LCRS and it had the dimensions of 60 m width and 0.25 m depth. The DB was assumed to consist of high permeability granular material having ksat = 10^{-2} cm/s. The maximum saturated width of MSW and area were measured with respect to the saturation greater than 45% (initial degree of saturation of MSW is 45%). All the boundaries were assumed impermeable. The bottom most grid points in the landfill model were assumed to have zero pore water pressure, simulating the leachate removal by LCRS. All initial properties of MSW were assumed to be the same as those shown in Table 1 except the saturated hydraulic conductivity.

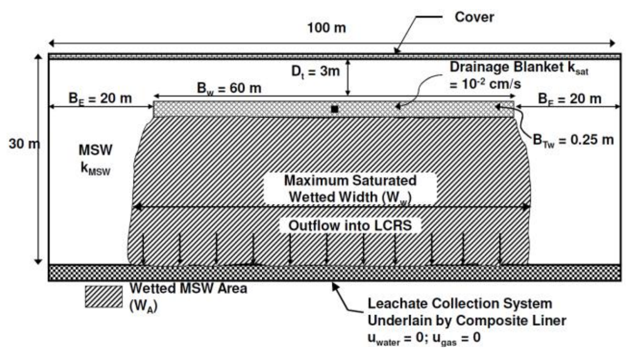

Figure 5. Landfill model with drainage blanket for leachate recirculation in MSW

4.2 Modeling Scenarios

Leachate recirculation rates were varied from 26 to 86 m^3/d/m for different saturated hydraulic conductivity ranging from 10^{-3} to 10^{-6} cm/s. Leachate was re-circulated until the steady state condition reached in all the cases. The saturation levels, maximum saturated wetted width and area of MSW, maximum pore water and gas pressure, and time to reach the steady state condition were compared as a function of leachate injection rate.

4.3 Saturation Levels

Figure 6 shows the saturation levels for simulations with leachate injection rate as 26 and 86 m^3/d/m, for saturated hydraulic conductivity of 10^{-3} and 10^{-6} cm/s. Evidently, the higher the leachate injection rate, the larger was the saturated area. Furthermore, the injected leachate migrated more laterally with decrease in the saturated hydraulic conductivity. It is clear from Fig. 6a that the injected leachate migrated only below the DB and reached LCRS at steady state condition when the k_{sat} of MSW was 10^{-3} cm/s. As the k_{sat} value of MSW decreased, the saturated MSW area increased and the leachate continued to spread laterally in the landfill. At steady state condition, the injected leachate partly migrated vertically upward with decrease in k_{sat} value (Fig. 6a). From Fig. 6b, it is clear that the higher leachate injection rate increased the saturated wetted width. Besides, for lower k_{sat} value, the injected leachate migrated to the top of the landfill above the DB.

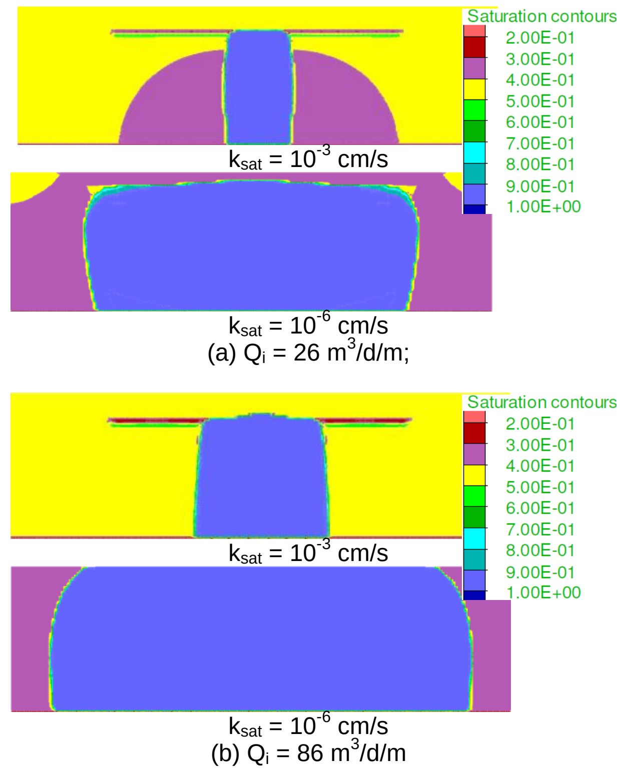

Figure 6. Saturation contours for varied leachate injection rates and saturated hydraulic conductivity

4.4 Wetted Width and Wetted Area of MSW

The predicted saturated wetted width of the MSW is shown in Fig. 7a. The maximum saturated wetted width decreased with increase in saturated hydraulic conductivity of MSW. The maximum saturated wetted width for k_{sat} of 10^{-6}, 10^{-5}, 10^{-4}, and 10^{-3} was 93, 84, 72 and 29 m, respectively. These results show that the injected leachate migrates within the DB if the underlying MSW possesses low hydraulic conductivity; therefore, it increases the saturated wetted width of MSW. Figure 6a indicates that the wetted width increased up to the saturated hydraulic conductivity of 10^{-5} cm/s, and further decrease in saturated hydraulic conductivity of MSW did not increase the wetted width considerably.

Figure 7b shows the predicted maximum saturated wetted area of MSW indicating decrease in saturated wetted area with increase in saturated hydraulic conductivity. Higher leachate injection rate in low permeable MSW caused the injected leachate to migrate in both vertically upward and downward directions, thus causing greater saturated MSW area for low permeability of MSW. More interestingly, the computed saturated wetted width of MSW was observed more or less the same for different leachate injection rates at steady state condition. However, the time to reach steady state condition varied significantly for different leachate injection rates and saturated hydraulic conductivity (Fig. 7c).

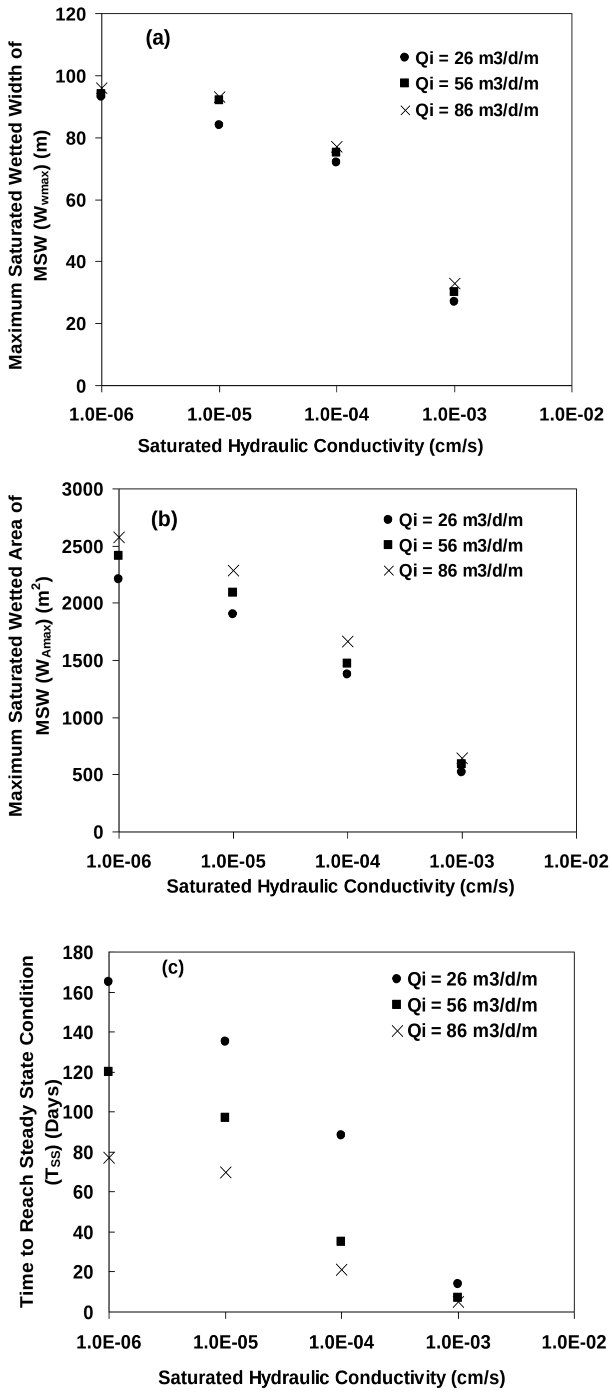

Figure 7. (a) Maximum saturated wetted width (W_w); (b) maximum saturated wetted area (W_A); (c) time to reach steady state condition for varied leachate injection rates and saturated hydraulic conductivity

4.5 Maximum Pore Pressure

At steady state condition, the predicted maximum pore water and gas pressures are shown in Fig. 8. As the saturated hydraulic conductivity of MSW increased, the maximum pore water pressure in the MSW decreased (Fig. 8a). For example, the maximum pore water pressure developed in the landfill for leachate injection rate of 26 m^3/d/m were 204, 101, 63 and 6 kPa for k_{sat} of 10^{-6}, 10^{-5}, 10^{-4}, and 10^{-3}, respectively (Fig. 8a).

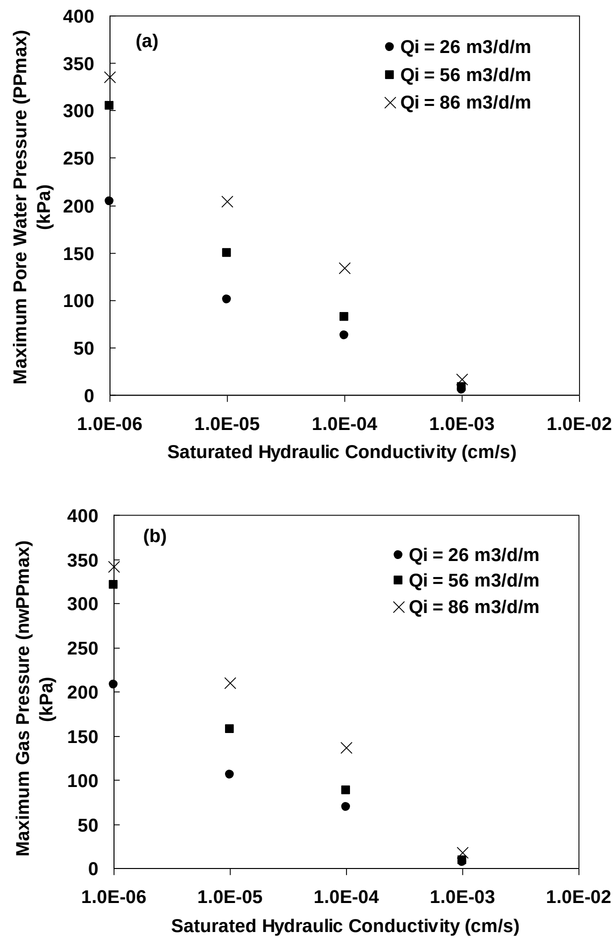

Figure 8. (a) Maximum pore water pressure; (b) maximum gas pressure for varied leachate injection rates and saturated hydraulic conductivity

Fig. 8 indicates that the increase in pore pressures was gradual until the saturated hydraulic conductivity of MSW of 10^{-5} cm/s, and further, there was a sudden increase in the pore pressure value for the saturated hydraulic conductivity of MSW less than 10^{-6} cm/s. This indicates that, when the MSW degrades, the chances of development of pore water pressure in the landfill are high at a given leachate injection rate. When MSW is initially placed in the landfill, MSW possesses high permeability and therefore, the pore water pressure in fresh MSW for a new landfill is expected to be low; however, the long term concerns regarding the stability of bioreactor landfill containment system is critical due to development of high pore pressures.

Since the MSW placed in landfill is under unsaturated condition, the pore gas pressure is also important and needs to be evaluated. The developed maximum pore gas pressures are plotted in Fig. 8b at steady state condition. The developed maximum pore gas pressures are slightly more than that of maximum pore water pressure at steady state condition. The capillary pressure is the difference of pore gas pressure and pore water pressure. The capillary pressure decreased with the continued injection of leachate. The developed maximum pore gas pressure for leachate injection rate of 26 m^3/d/m are 208, 106, 69 and 6.5 kPa for k_{sat} of 10^{-6}, 10^{-5}, 10^{-4}, and 10^{-3}, respectively (Fig. 8b).

Furthermore, the developed maximum pore gas pressure follows a similar trend to that of pore water pressure. The pore gas pressure developed is high when the saturated hydraulic conductivity of MSW is low. The developed maximum values of pore water and gas pressures are observed only near the leachate injection point in the DB itself. Besides, the developed pore pressures in the bioreactor landfill may be controlled by following the intermittent leachate recirculation (Reddy and Kulkarni, 2010a; Kulkarni and Reddy, 2010).

5 CONCLUSION

Moisture distribution in a bioreactor landfill due to leachate injection in drainage blanket is predicted using a two-phase flow model. A typical landfill cell with DB is considered, and leachate injection is performed until the steady-state condition is reached. Simulations are performed with different leachate injection rates and saturated hydraulic conductivity of MSW. MSW is assumed to be homogeneous and isotropic. Increase in the leachate injection rate increased the saturated wetted width and area of MSW and pore water and gas pressures in MSW, but decreased the time to reach the steady state condition. Decrease in saturated hydraulic conductivity of MSW increased the saturated wetted width and area of MSW, maximum pore water and gas pressure, and time taken to reach steady state condition.

6 ACKNOWLEDGEMENTS

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