Origin of preferential flow and its controlling factors on emission potential using numerical simulations and lab experiments.

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ABSTRACT

We believe the unsaturated and heterogeneous nature of landfills leads to the emergence of preferential pathways of water and dissolved compounds through the waste body. In this research we explore the origin of preferential flow in a porous media with a deterministic numerical model. In this model water flow is modeled with the Richards' equation and non-sorbing, single component, solute transport with the advection dispersion equation. We compare results from systematic heterogeneous soils with known hydraulic properties driven by a range of different infiltration patterns with a homogeneous soil driven by the same infiltration pattern. The occurrence of of channeled flow in the heterogeneous soils and diffusion from non-flowing water towards flowing water leads to an emergence of non-equilibrium behavior in the macroscopic breakthrough curves. Results from laboratory experiments which were set-up in a similar way as the numerical experiments were resembling to the ones simulated giving confidence to our model. This research helps to understand modeling approach that needs to be used for analyzing data from full scale landfills in order to quantify leachate emissions and emission potential.

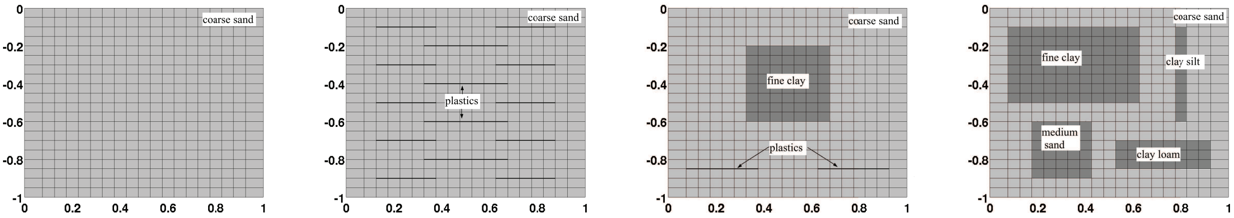
INTRODUCTION

Various mathematical models have been used for simulating leachate quantity and quality of landfills (El-Fadel et al. (1997)). Based on landfill hydrology, we can classify them in two major categories (1) Continuum based models and (2) Up-scaled models. The continuum based models use, laboratory determined properties of waste material for determining the spatial and the temporal characteristics of leachate (McDougall (2007); Powrie and Beaven (1999); Gholamifard et al. (2008)). The up-scaled type of mathematical models are generally based on an input-output approach such as a stochastic transfer function approach (Rosqvist and Destouni (2000); Rosqvist et al. (2005)Zacharof and Butler (2004b,a)) a dual porosity or dual permeability approach (Bendz et al. (1998); Fellner and Brunner (2010)) and stream tubes models (Matanga et al. (1996)). Understanding the underlying physics of landfill hydrology is thus important for deciding which approach is most appropriate for a given application. The application which we focus on for this paper is to determine the emission potential in the waste body, where emission potential can be defined as a remaining amount of quantities of pollutants present inside landfill (Bun et al. (2013)).

We explore the origin of preferential flow and the impact it has on solute transport in a two dimensional (2D) numerical model. Our deterministic model is based on Richards" equation (RE) and the Advection Dispersion Equation (ADE), allowing us to simulate coupled water flow and solute transport. In order to show how physical heterogeneity leads to the emergence of non-equilibrium flow we simulate three different spatially heterogeneous domains and compare the results from these scenarios with those obtained from a homogeneous domain. Because waste materials are highly variable we chose to simplify our approach by creating the heterogeneous domains by considering a limited number of materials with known unsaturated parameters (van Genuchten (1980)) with large differences. The heterogeneity is located in a systematic fashion in a $1.0\,\mathrm{m}\times1.0\,\mathrm{m}$ square domain. The considered soil profiles are unsaturated and are infiltrated with water in a continuous and a square wave pattern.

Both outflow rates and electrical conductivity in drained water were measured as a function of time. Comparison of these measured break through curves (BTCs) indicated non-equilibrium effects for the heterogeneous domains which can clearly be related to increased path lengths and funneling of water in to increasingly smaller domain with depth in the profile. Comparing the results from the BTCs of the different scenarios plotted as a function of number of flushed pore volumes clearly shows the emergence of non-equilibrium effects due to local diffusion in the heterogeneous domains.

Laboratory scale experiments conducted in a set-up which is similar to the one used for the numerical scenarios lead to results that validate our modelling approach. Material heterogeneity in combination with variations in infiltration rates are responsible for emergent non-equilibrium effects in BTCs measured.



(a) (b) (c) (d)

Figure 1: Different spatial scenarios, namely H(a); SP (b); SCP (c) and FM (d).

Table 1: Material parameters for different soil profiles.

Material parameters	coarse sand	fine clay	medium sand	clay silt	clay loam
α [m^{-1}]	2	1	1	1	1
n	1.5	2.5	1.378	1.242	1.6
θ_r [m^3 m^{-3}]	0.04	0.08	0.041	0.075	0.02
θ_s [m^3 m^{-3}]	0.4	0.45	0.41	0.39	0.41
$\mathbf{K_{sat}}$ [m s^{-1}] in $\mathbf{xx}$ and $\mathbf{zz}$ direction	5 $\times 10^{-2}$	5 $\times 10^{-5}$	4.2$\times 10^{-5}$	2 $\times 10^{-5}$	2.3 $\times 10^{-5}$

Full-scale sanitary landfills in the Netherlands are unsaturated heterogeneous porous media driven by a heterogeneous infiltration pattern. It is very likely that the produced leachate will show similar behavior as we encountered in this research. These insights are important for developing approaches for interpreting leachate dynamics and estimating emission potential at full-scale waste bodies and landfills.

MATERIALS and METHODOLOGY

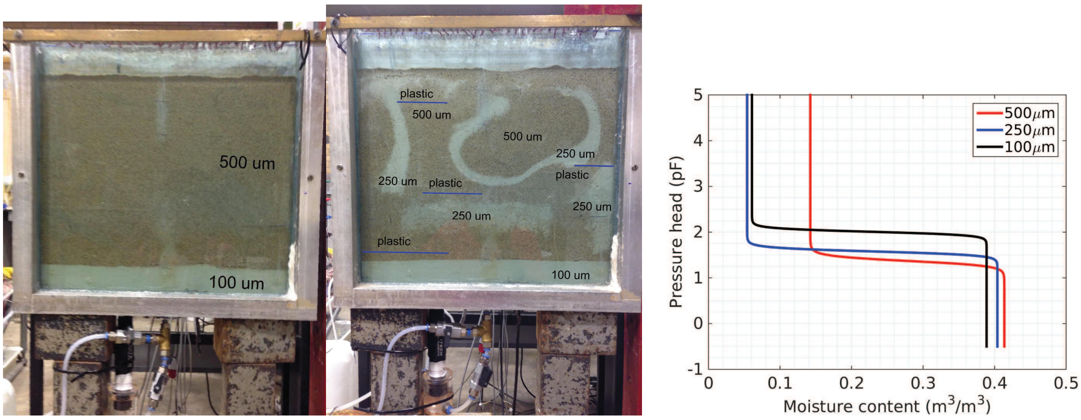
Numerical Model

We discretized the mixed-form of Richards' equation (Celia et al. (1990)) using a fully implicit finite difference method. The ADE was solved on the same finite difference grid with a method based on the Lagrangian marker-in-cell scheme (Gerya (2010)). This implementation was developed in order to minimize numerical dispersion. The code was developed as a MATLAB toolbox called as VarSatFT (**Var**iably **Sat**urated **F**low and **T**ransport). (See the presentation, by Shirishkumar Baviskar on 15/04/2015, 0900 hrs).

To determine the effect of heterogeneities in porous media on flow and transport, we consider different spatial scenarios. We identify these scenarios as Five Materials (FM); Sand, Clay and Plastic (SCP) , Sand and Plastic (SP) which are compared to a Homogeneous (H) scenario. Detailed diagrams of these scenarios are given in figure.1 and the material parameters considered shown in table1. The model was driven by an infiltration rate of 9×10^{-4} and 7×10^{-3} m s^{-1} in a continuous and square wave pattern for a duration of 1 hour.

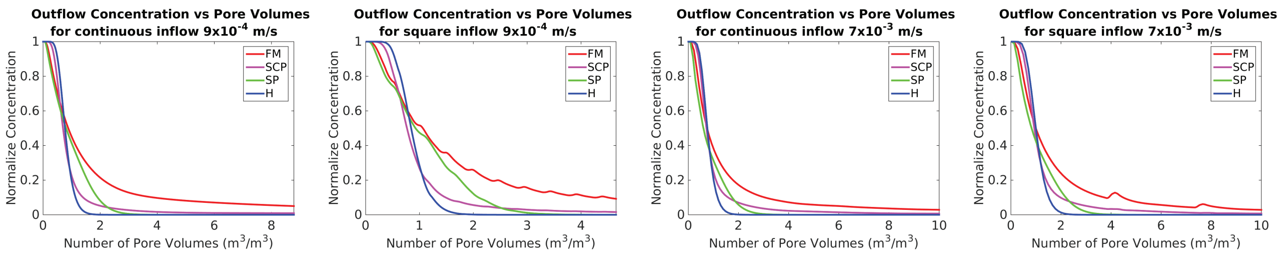
Lab scale

For the laboratory scale experiments we considered three types of sands distributed in 2D frame. figure 2 (a) and (b) shows photographs of the laboratory setup for theheterogeneous (Het) and homogeneous (Hom) experimental scenarios. The water retention properties of the sands used for this experiment are shown figure 2(c). The sand frame was pre-saturated from the bottom outlet with a $0.50\,\mathrm{kg\,m^{-3}}$ of $NaCl$ salt solution. After an equilibration time of 3.0 hours, water from the saturated 2D sand frame was allowed to drain overnight, leading to a hydrostatic unsaturated condition. The salt was then flushed by applying fresh water using different infiltration patterns at the top. Discharge rates and electrical conductivity of the draining water were measured during the experiment until the electrical conductivity indicated no salt present in the draining water. The maximum flow rate was set at at a pump flow rate of $0.098\,\mathrm{l\,min^{-1}}$.



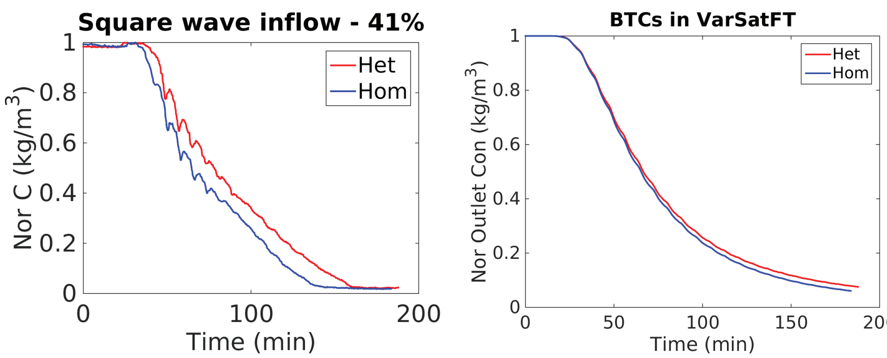
(a) (b) (c)

Figure 2: Laboratory scenarios for Homogeneous (a) and Heterogeneous (b) domains. Water retention curves optimized using $\mathrm{DREAM_{ZS}}$ for sands of size 100 µm, 250 µm and 500 µm (c).



(a) (b) (c) (d)

Figure 3: Measured outlet concentrations plotted against estimated number of flushed pore volumes for continuous and intermittent square wave inflow infiltration for different infiltration magnitudes.



(a) (b)

Figure 4: Normalized concentration against time duration for square wave intermittent infiltration in 41% of maximum pump flow rate on lab scale (a). VarSatFT validation for lab results (b).

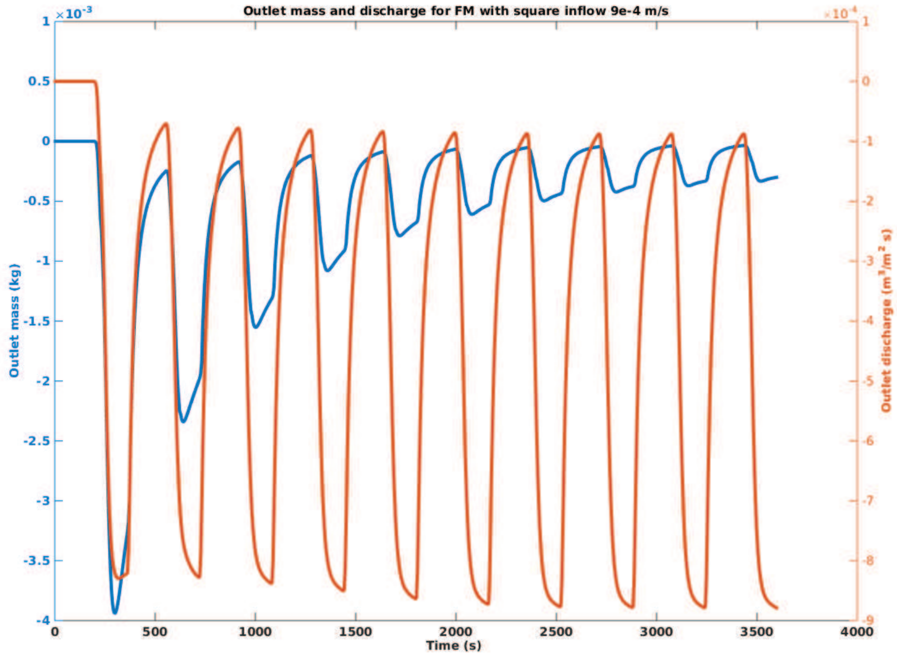


Figure 5: Outlet mass with outlet discharge rate obtained for FM

DISCUSSION and CONCLUSIONS

In the homogeneous scenario flow will only be vertical because no horizontal pressure head gradients can develop. In the heterogeneous scenarios horizontal gradients develops due to local variation in vertical hydraulic conductivity. As a result, the streamlines tend to diverge from the vertical and as a result the path length along a streamline increases. In addition, flow is still dominated by gravity, as a result water tends to get restricted to a smaller and smaller domains as water progresses deeper in to the soil (funneling). Consequently, gradients in water content and salt content develops as a result diffusion will occur from zones with high concentration to zones with lower concentrations.

Figure 3 show the simulated BTCs as a function of flushed pore volumes. If all flow processes are at equilibrium, all curves would be the same, as non-equilibrium processes become more and more important, the curves will increasingly differ from the one predicted for the homogeneous scenario. For these scenarios, non-equilibrium arises from an increase in path length, decreasing flushed volume and the subsequent diffusion which is caused by the presence of concentration gradients within the domain. Diffusion is a slow process and highly time dependent. The results indicate that the rate of flushing has a very limited effect on the measured results. However, a significant effect is found when we compare the intermittent square wave with the constant flush scenario. If a flow scenario allows for sufficient long periods of low flow rates, diffusion reduces the concentration gradients present in the profile. When flow starts-up again, increased concentrations will be measured in the draining water.

We observed similar results during our laboratory experiments with the sand frame. The BTCs show a lag for the heterogeneous scenario compared to the homogeneous one for the intermittent square wave infiltration. However the BTC for homogeneous scenario shows increase in concentration. This is probably due to the fact that flushing was not completely homogeneous as some pockets of high concentration still exists. These results were validated using our MATLAB toolbox VarSatFT where we try to simulate the lab experiment as closely as possible (See figure.4). The numerical model was not able to produce the increases in concentrations found in the measurements and in the simulations shown in figure 4. This is probably due to the fact that true packing of the sample and the true flow conditions were difficult to replicate exactly with our numerical model.

Extrapolating these results to full-scale landfills should be done with the necessary care, however we believe that these experiments can be used to provide understanding for why leachate concentrations are highly variable with time(Bun et al. (2013)). During dry periods, diffusion increase concentrations of conservative ions in the mobile leachate. When a drainage increases as a result of a rainfall event, this increased concentration will be measured in the leachate. As rainfall continues, the mobile zone of a landfill gets flushed and concentrations in the leachate decrease quickly.

Results from Abbaspour et al. (2004) and Fellner and Brunner (2010) indicate the presence of preferential flow in the full scale landfill leading to a strong correlation between electrical conductivity measurements and discharge rate of of leachate. Figure5 shows similar results for the Five Materials intermittent flushing scenario witha maximum flow rate of $-9 \times 10^{-4}\ \mathrm{m\,s^{-1}}$. The rise in outlet mass corresponds closely with the rise in discharge rate.

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