Numerical Simulation of the Mass Flow of Leachate in a Municipal Waste Fill
(Part 1) – Closed Recycling Flow Systems

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Abstract: This paper examines the use of numerical modelling in simulating the mass flux of leachate solute in an emplaced municipal waste subjected to a closed recycling flow. The simulation model comprises of a deterministic hydro-physical model, which effectively utilises the principle of conservation of matter to depict the average characteristics of the temporal mass of recycling leachate flow in an emplaced waste in a large-scale cell. Unlike in previous studies, the characteristic trend of the mass flux in various segments of the waste body is numerically and visually depicted. Although exact quantification of the temporal solute flux has not been achieved, the simulation results have been reasonable, and the 2-dimensional visualisation appears to enhance the understanding of the trend of solute mass transport within various layers of the waste fills.

Key words: Concentration, Flow, Simulation model, Solute, Waste

INTRODUCTION

The leachate produced from municipal waste landfills has the potential to contaminate and eventually pollute the surface water and the underlying aquifer where a waste disposal facility is located. No wonder there have been several investigations [3,5,28,30] into the characteristics of leachate following numerous cases of pollution owing to the seepage of landfill leachate [1,20,21,24,25]. The majority of these investigations have however been undertaken in the developed countries, where both the financial and intellectual resources abound.

Initial researches involved understanding the theoretical fundamentals of the formation, and chemical composition of leachate [15,16,22,23]. These were followed by the simulation of the volumetric quantity of leachate using the water balance method (WBM) and validating the results with leachate quantities measured from the basal drains of the landfill [6,8,18,19,31]. Owing to the complex nature of waste, the waste fill was treated as an entity as the modelling was undertaken on closed landfills. However, the disparity in the observed measurements and modelled data during these periods indicated that leachate cannot be reasonably predicted using the basic WBM equation.

Perhaps the most significant earlier effort to simulate the waste volume produced in landfills was the development of the HELP computer model, which is a quasi-two-dimensional hydrological model of water movement across, into, through and out of landfills. The model considers several factors that thus include the effects of surface storage, snowmelt, runoff, infiltration, evapotranspiration, vegetative growth, soil moisture storage, lateral subsurface drainage, leachate recirculation, unsaturated vertical drainage, and leakage through soil, geomembrane or composite liner systems. Whereas the HELP model was found to reasonably simulate the quantity of leachate generated from completed waste landfills, its inability to simulate the leachate generated during the active period of waste infilling was seen as a deficiency.

Further efforts involved using macro-modelling which comprises empirical waste models and traditional soil models in parallel with the Hydrologic Evaluation of Landfill Performance (HELP) computer model to model the volumetric water in an emplaced municipal solid waste fill during both operative and post-closure periods [28-30]. This model, though simple and effective could not replicate the exact leachate volume but reasonable average quantities. A lot of efforts have also been undertaken in the use of micro-modelling for simulating the characteristics of emplaced waste at landfill sites; however, there has not been any model that can universally and exactly predicted the site measurements [14]. The majority of the earlier modelling efforts have been based on the bulk volume and biochemical properties of the leachate. When the models used for estimating leachate quantity and quality in solid waste landfills were reviewed, it was found that; while some models for simulating leachate quantity have been relatively successful, there is yet a model that can reasonably simulate the leachate quality in waste fills [12,27].

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In addition to the above there has been numerical modelling of various elements of the landfill system. For instance reasonable results were obtained from numerical modelling of gas flow and heat in landfills [10,13]. Similarly, relatively fair results have been obtained from the numerical simulation of contaminant migration from the landfill and the flow in the interface of a composite basal liner [9,35].

As the main concern in the water leached (leachate) from waste landfills is not particularly the volume but the concentration of contaminant pollutants in the effluent stream from the basal region, researchers have currently been involved in studying the transport of solute in the configuration of the waste fill. These studies have been relatively successful in utilising characteristic soil equations to calculate the solute mass flux in the bulk waste fills under steady state conditions. The fundamental theories involved has evolved from using convection and dispersion concept, mobile-immobile concept, double porosity concept to a proposed multi-porosity, multi-modal, and dual/multi-mobile-immobile concept [2,33,34]. These models have been solved using deterministic and stochastic methods.

Until now there has not been any effort to investigate the mass flow of contaminant within the various vertical layers or segments of a waste body (fill), which is subjected to a recycling flow pattern. As is observed in the review of researches on the leached water from landfills above, it is almost practically impossible to replicate waste characteristics exactly owing to the complex nature of waste. Therefore a “reasonable result” in the context of waste research can be defined as a situation when the quantitative result and the characteristic trend of the waste property are achieved within a reasonable degree of agreement with the actual measurements.

With the advent of computer technology, it is well known that simulation is often used to simplify and have a better understanding of complex systems in relation to time and space where analytical solutions may not be simply possible because of meta-stable or complex interrelating conditions of the system. Often, the most difficult aspect in numerial modelling is the formulation and calibration of the model [7,17]. Ordinarily, the most ideal technique is to use simple models devoid of ambiguity and complexity, yet able to reasonably simulate the reality using the real measured data as input. As recirculation of leachate is often used to accelerate the bio-chemical processes in landfill to achieve early stabilisation, numerical simulation has been undertaken on the mass flux of a recycling test for solute transport in large-scale test. This thus enabled real data to be used for validation and authenticity of the model.

In this study, the mass of the solute flux in different vertical layers (segments) of a waste fill subjected to a closed recycling flow of leachate is studied using a computer simulation.

**METHODOLOGY**

A computer model is used to simulate the transport of leachate solute in a closed recycling flow test previously undertaken by the author. The diagram of experimental set-up is shown in Figure 1. A closed recycling flow is a flow that is being circulated continuously without any external inflow of water - from rain on site or external water input in the laboratory.

The procedure of the test has been previously well described [29]. In order to specifically measure the transport of the leachate solute; Lithium, Bromide and Sodium Chloride, which are common solute tracers were mixed and input as surface pond in a previously established steady flow conditions in the large scale cell. Then a recirculation of flow of the tracer and inherent moisture in the waste fill continued until a period when concentrations of the surface pond and the basal outlet of the waste fill appeared to have reached equilibrium. The solute water in the pond was constantly mixed with a mechanical stirrer and measurements were taken from the surface pond and outflow from the waste. In this study, however, the mass flow of the Sodium Chloride, which appeared conservative and has excellent test data from the test data-loggers, is used for model testing and validity.

**Formulation of the Model:** In order to simplify the modelling process, the following are undertaken:

- The waste column is divided into finite constant volumes called segments
- The flow in the waste matrix is assumed to be predominantly vertical
- There is flow continuity through the waste and the basal gravel bed
- The basal gravel bed is not “discretised”
- For ease and a realistic simulation, a waste segment has a maximum constant pore volume that is equivalent to the pore volume of the basal gravel bed (3l)
- As the volume of the waste fill is approximately 36l, the possible lowest numbers of the waste segments is 12
- The overlying waste pond on the waste has a temporal constant volume
- The simulation is undertaken in 3 different section of the flow system, namely: (a) the surface pond; (b) the waste fill; and (c) the basal gravel bed.
As the objective of the study is to reasonably model the temporal mass of the leachate within the various segments of the waste fill, the model is conceptualised on the law of conservation of matter as it applies to a steady state flow condition. This is stated as [26]:

\[
\text{Mass flow into an elemental volume} = \text{Mass flow out of an elemental volume} \tag{1}
\]

In the majority of situations where the mass flux in waste fills is investigated, it commonly measured in terms of the concentration of the leachate solute, which is expressed as:

\[
\text{Concentration} = \frac{\text{mass}}{\text{volume}} \tag{2}
\]

Applying the law of conversation of mass as in [1], then a generalised simulation model is defined as:

\[
M_i = (M_{i-1} + \Delta M_{in} - M_{21u}) \tag{3}
\]

where:

\[
M_{21u} = \left(\frac{M_{i-1} + \Delta M_{in}}{V + \Delta V}\right) \times \Delta V \tag{4}
\]

\[
M_i = \text{Mass of the leachate solute in the constant volume at time } i
\]
\[
M_{i-1} = \text{the mass of the leachate solute in the constant volume at time } i-1
\]
\[
\Delta M_{in} = \text{inflow mass of the leachate solute added to the constant volume from time } i-1 \text{ to time } i
\]
\[
\Delta M_{ou} = \text{outflow mass of the leachate solute added to the constant volume from time } i-1 \text{ to time } i
\]
\[
\Delta V = \text{volume of the leachate solute added to the constant volume from time } i-1 \text{ to time } i
\]

For the specific different sections of the flow system, the temporal concentration is calculated as:

\[
C_{sp} = \left(\frac{1}{11.76}\right) \times \left(\frac{M_{i-1} + \Delta M_{in}}{M_{i-1} + \Delta M_{in} - \Delta M_{ou}}\right) \times \Delta V \tag{5}
\]

\[
C_w = \left(\frac{1}{V_e}\right) \times \left(\frac{M_{i-1} + \Delta M_{in}}{V_e + \Delta V}\right) \times \Delta V \tag{6}
\]

\[
C_{gb} = \left(\frac{1}{3}\right) \times \left(\frac{M_{i-1} + \Delta M_{in}}{3 + \Delta V}\right) \times \Delta V \tag{7}
\]

where:

\[
V_s = \text{constant pore volume of the waste segment chosen.}
\]
\[
C_{sp} = \text{concentration of the leachate solute in the surface pond at time } i
\]
\[
C_w = \text{concentration of the leachate solute in the waste at time } i
\]
\[
C_{gb} = \text{concentration of the leachate solute in the gravel bed at time } i
\]

Simulation Technique: The sequence of the simulation is simply depicted in a flowchart shown in Figure 2. At the first time-step, the simulation technique involves calculating the mass of the leachate solute starting from the surface pond and downward through each vertical segment to the basal gravel bed using the initial conditions at time \( t = 0 \). At the next time-step, the solute mass inflow (\( \Delta M_{in} \)) into the waste pond is taken as the solute mass outflow from gravel bed (\( \Delta M_{ou} \)) and the same process in the previous time period is repeated again for the waste segments and the basal...
Input initial conditions – mass of leachate solute in each segment/volume

Calculate the mass of leachate solute in each segment/constant volume in a time-step (in a close loop –sequence is shown as below) for 300h

Surface pond waste segment 1… waste segment n gravel bed

Calculate maximum time-step (TS) = Volume of gravel / Volumetric flow rate

Is time-step = TS?

YES

END

NO

Fig. 2: Flowchart of the simulation

Fig. 2: Flowchart of the simulation

The iteration is repeated until the maximum time-step is obtained. The same process depicted in Figure 2 is also repeated for various segment volumes. Thereafter, each of the iteration’s simulation result is compared to the measured (real) data, and the solution with the best fit is chosen and proposed.

RESULTS AND DISCUSSION

The essential properties of the waste fill used in the recycling test are recorded in Table 1. These hydro-physical characteristics are typical of municipal solid refuse. The discharge rate was maintained during the experiments with two peristaltic pumps that have been previously calibrated for a constant recycling flow of 1l/h.

The temporal concentration of Sodium Chloride, being the tracer used to monitor the transport of leachate solute has been simulated for various numbers of segments and time-steps. Owing to the complex nature of waste, and in order to minimise the error that may result in estimating the solute mass in a segment owing to difficulty in calculating preferential and non-preferential flows, the majority of the simulations have been done with the concept that the mass flux into a segment is the same as the mass flux out of the segment.

Table 1: Fundamental properties of the waste fill

<table>
<thead>
<tr>
<th>Waste properties</th>
<th>Dry density of waste (kg/m³)</th>
<th>Bed volume of surface pond (l)</th>
<th>Effective Bed volume of waste (l)</th>
<th>Effective Bed volume of gravel (l)</th>
<th>Drainable porosity (%)</th>
<th>Effective field capacity (%)</th>
<th>Discharge rate (l/h)</th>
<th>Saturated hydraulic conductivity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured values</td>
<td>722</td>
<td>11.76</td>
<td>35.17</td>
<td>3.0</td>
<td>7.5</td>
<td>37.7</td>
<td>1.0</td>
<td>1.65 x 10⁻⁷</td>
</tr>
</tbody>
</table>
The simulated temporal concentration of Sodium Chloride at the time-steps of 1h, 1.5h, and 3h and the corresponding segments of constant volumes 1l, 1.5l, and 3l respectively are shown in Figures 3-5. As expected, the concentration of Sodium Chloride in the waste pond decreases gradually with time to a constant value, which is the equilibrium concentration in the waste fill. In general, it is observed that the Sodium
Chloride in the waste segments quickly peaks in concentration from the initial zero concentration following the start of recirculation of solute water initially in the surface pond. The rate of the peak in concentration of each segment appears to increase with the closeness to the surface pond and the maximum concentration attained in each segment appears to decrease with an increase in the vertical distance of each segment from the surface pond. The maximum concentration attained in each segment and the gravel bed is distinctly less than the maximum concentration in the surface pond;

The decrease in the maximum Sodium Chloride concentration attained in each segment with increase from the origin of solute mass inflow (surface pond) appears reasonable as dilution of the solute with some water inherent in waste pore is expected, and its effect will increase along the direction of flow. Accordingly, the gravel bed has the lowest peak concentration and the first waste layer has the highest peak concentration within the waste. For the validity of the model, the temporal concentration of the surface pond and outflow from the waste via the gravel bed for various simulation conditions are compared with the measured values. The characteristic curve for temporal concentration has been made distinct in Figures 3-6 to be able to visually observe the accuracy of each simulation. Owing to a pre-knowledge of the actual trend from the measured data, the degree of accuracy of the simulated concentration curves are determined via the degree of resonance (smoothness) of the curve prior to the attainment of equilibrium concentration. In order to observe the effect of time-step on the simulation results, modelling was undertaken with a segment of 3l and time-step of 1h (Figure 6) in addition to the time-step of 3h. It could be seen that the resultant solute mass profile of Sodium Chloride for a time-step of 1h appears less accurate than that using a segment of 3l and a time-step of 3h thus indicating that the simulation is improved with an increase in
time-step although there is maximum time-step (TS) that can be used, as given in the flowchart (Figure 2). As the principle underlying the simulation technique used is based on average values of the leachate solute mass, a higher time-step will result in a higher volume/mass of solute in each segment for averaging, which in turn will result in a better approximation of the mass flow. In the same vein, if the inflow volume of the solute flux is smaller than the volume of the segment, it is very difficult to calculate the accurate corresponding mass of the outflow solute as the mixture of the solute in waste pores may not be uniform and therefore induce error in averaging the mass flow of the segment for the time-step.

The simulated and measured values of the solute concentration for Sodium Chloride depicted in Figure 7 shows a reasonable fit of the trend of mass flow. It can be observed that the curve of temporal concentrations for both cases appear similar. It appears that simulated and measured values for the surface pond appear a bit more similar than the simulated and measured values of outflows from the waste via the gravel bed. This is not surprising as the simulated concentrations are calculated for average values, which is more typical of the concentration in the surface pond, as it is constantly uniformly mixed with a stirrer. The quick initial peak in concentration of the measured Sodium Chloride in the outflow compared to the simulated values (Figure 7) is an evidence of fast advective solute flux, and uneven mechanical mixing of the solute in the matrix pores of the waste fill.

With the reasonable validity, it can be stated that the concentration of leachate solute in waste layers increases gradually to a maximum and then stabilises at an equilibrium level. The rate of attainment of both the peak and the equilibrium solute concentrations in the waste layer is higher in the uppermost layers close to the original source of the leachate solute, in a recycling leachate flow system as described in this study.

Considering the complex nature of waste, the seemingly simple but smart simulation technique used in this study appears to reasonably depict the mass flux of leachate solute in a waste fill. More importantly, the ability to reasonably depict visually the characteristic trend of the mass leachate flow in layers of a waste fill; a process which will otherwise be very difficult and expensive to undertake physically is commendable. Through this, a better understanding of the mass flow of a recycling of leachate is achieved.

**CONCLUSION**

This study has shown that numerical modelling is useful in understanding the hydro-physical processes that takes place within a waste fill. The reasonable fitting of the measured temporal concentration of the recycling leachate using a simulation model suggests that the simulation technique is appropriate for depicting the characteristic mass flux within the various segments of a waste body and may also be used to study other hydro-physical mechanisms of various leachate systems of municipal solid refuse fills.

In general, it has been shown that non-complex numerical simulation is cost effective and equally important in understanding the average patterns of various mass flow in solid refuse landfills.

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**REFERENCES**


