

Numerical Simulation of the Mass Flow of Leachate in a Municipal Solid Waste Fill (Part 3) - Leaked Vertical Flow Systems

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Abstract: This study reports the simulation technique and the visualisation of the temporal vertical mass flow and leakages in waste layers and gravel bed of a municipal solid waste fill. Visual comparison of the cumulative mass leakage with optimal leachate mass flow in each waste layer enables the negative consequence of seepage of any highly toxic leachate to be mentally comprehended. The impact of the mass leakage appears to be influenced not necessarily by the location of the seepage pore but by its volume, and also distance from the source of the solute contamination. The simulation results necessitate the need for an effective leachate monitoring system within and in the vicinity of a waste landfill. The findings will be of utmost usefulness to the stakeholders of solid waste landfill in both developed and developing countries.

Key words: Environment, municipal waste, leachate solute, leakage, simulation, waste layers

INTRODUCTION

The primary function of an engineered waste landfill is to contain the emplaced waste in a manner in which there will be no consequential adverse impact to human health and the environment. Therefore, the location of a waste landfill is influenced by many socio-economic to technical factors including geology, climate, waste type, climate hydrogeology and impact on the local community. Undoubtedly, leakage of the leachate from the emplaced contaminated waste constituents is usually the main concern of dwellers in the immediate vicinity of any proposed or sited Municipal Solid Waste (MSW) landfills. Any unacceptable leak will have an adverse impact on the health and the property price of such individuals thus resulting in death or bankruptcy. Leakage, which ordinarily may mean any form of discharge, is an ambiguous term since seepage of highly toxic contaminant from a landfill into a shallow aquifer may have the same devastating environmental effect as any discharge of a significantly volumetric content.

In the past, waste landfills were usually sited in the voids created by extraction of economic mineral deposits such as sand. Fortunately, in many of these locations the basal layers were usually beds of clay thus limiting direct leakage of the leachate from such sites (Oni, 2000). The main problem with the use of clay as a liner are the cracks often formed owing to desiccation thus enhancing preferential flows through the ensuing macropores (Berger *et al.*, 1996; Yesiller *et al.*, 2000; Miller and Mishra, 2007). Over the years, however, the use of natural liners such as clay as sole liners has evolved to the use of composite liners in order to enhance the integrity of the landfills as safe earth storage. It is now common for

modern landfills to combine two different types of liners, which may act to complement each other. These can be a geomembrane (GM) over a Compacted Clay Liner (CCL), or a GM and a Geosynthetic Clay Liner (GCL) or a GM over a GCL over a CCL (Daniel, 1993; Barroso *et al.*, 2006). Even with these, there is no system of liners that guarantees lifetime 100% integrity. Composite liners at which extreme caution have been taken in manufacturing, transportation, handling, storage and placement at landfills have often been found to have some degree of defects (Peggs, 2001; Touze-Foltz *et al.*, 2002; Rollin *et al.*, 2002; Giroud and Touze-Foltz, 2003; Needham *et al.*, 2004; Peggs *et al.*, 2004). Accordingly, the most pragmatic approach is to limit any leakage to quantities that will have insignificant effect on the environment. Various countries of the developed world have varying but similar stringent regulations for the allowable release of liquids from waste disposal sites. The European Directive No 1999/31/EC stipulates a combined geological barrier with an artificial sealing layer (usually a GM) which has a hydraulic conductivity less than 10^{-9} m/s and be at least 0.5 m thick for the protection of soil and water in the immediate environment of a landfill site (EU, 2010). This condition is also similar to those stipulated by the United States Environmental Protection Agency (Last, 2010).

Perhaps one of the reasons why the liners usually have defects is the configuration of a solid waste landfill, as it is not entirely flat. The slope of the sides of the landfill makes it difficult for suitable placement of both the waste layers and the cover liner thus affecting the integrity of the containment of the system. Ordinarily, the main concern about leachate leaks is not for the modern landfills but for the old landfills operated prior to the



Fig. 1: Seepage of leachate (black) through a weak spot in the landfill cover (Freudenrich, 2010)

introduction of the stringent laws in the 1980s. Many of those operated were as “dilute and disperse”, basically depending on natural attenuation and dilution of the leachate leaked into the groundwater in the immediate environment. An example of a typical leak is shown in Fig. 1, where the leaked leachate is seen as the black liquid on the slope of the landfill. The toxicity of the leachate is demonstrated with the loss of vegetation where the leak occurs compared to its surrounding environment. It is well known that the catastrophic impact of the old techniques of solid waste landfilling, such as the popular pollution case of Love Canal near Niagara Falls, New York, initiated the promulgation of the edict requiring the compulsory engineering of refuse landfills in the western countries (Yeh, 1981).

The majority of researches on landfill have been commonly undertaken on bulk emplaced waste. However, landfilling is not instantaneous but involves emplacement of waste loads in layers in a cell. A cell is described as the volume of material placed during an operation period, which is usually one day. The typical height of a completed cell varies from 2 to 4 m. The exposed surface of the waste compacted in each cell is covered at the end of working period with a daily cover. This commonly comprises granular materials spread thinly over the working face of an active cell at the end of each day to minimise odour and rainwater infiltration, and to prevent rodents and insect infestation, without being harmful to human health and the environment (Oni, 2009). In addition to soil materials, compost and other eco-friendly materials are now used as daily covers. Often, it has been reported that the soil layers in waste fills get clogged thus reducing the vertical hydraulic conductivity within the fill (Fleming *et al.*, 1999; Hilger *et al.*, 2000; Oni, 2009). This may result in hydraulic isolation of cells and also enhance horizontal flow towards the sideliners, resulting in seeps as seen in Fig. 1, especially if the underlying soil layer has become relatively impermeable (Blight *et al.*, 1992).

Simulation of the waste characteristics in layers or lifts of a landfill is not common owing to the heterogeneity of waste materials in occurrence, nature, and emplacement at landfill sites. Although the initial efforts to model waste characteristics in layers or lifts have not yielded accurate quantification, reasonable behavioural trends of the pertinent waste properties have been depicted (Bleiker *et al.*, 1995; Oni, 2000; Oni and Richards, 2004).

Understanding the hydro-physical properties of waste layers will undoubtedly enhance the design and operation of a waste landfill toward a better environmental protection and early stabilisation needed for effective after-use. In the preceding part of this topic (in press), numerical simulation of the sealed vertical flow was comprehensively reported. In this study, a similar simulation technique is also applied, but with the inclusion of leakage from the sides (slope) of waste fills that is subjected to predominantly vertical flows.

METHODOLOGY

Simulation method: The simulation technique involves the application of the main principle of conservation of mass to the vertical water flow through an emplaced waste body (Freeze and Cherry, 1979; Massey and Ward-Smith, 2006). This involves the application of mass balance to the flow in and out of consecutive layers of a waste fill. The essential model is thus defined as:

$$M_i = (M_{i-1} + \Delta M_{in} - M_{ou} - L) \quad (1)$$

This is further expressed as:

$$M_i = \left((M_{i-1} + \Delta M_{in}) - \left(\left(\frac{M_{i-1} + \Delta M_{in}}{V + \Delta V} \right) \times \Delta V \right) - L \right) \quad (2)$$

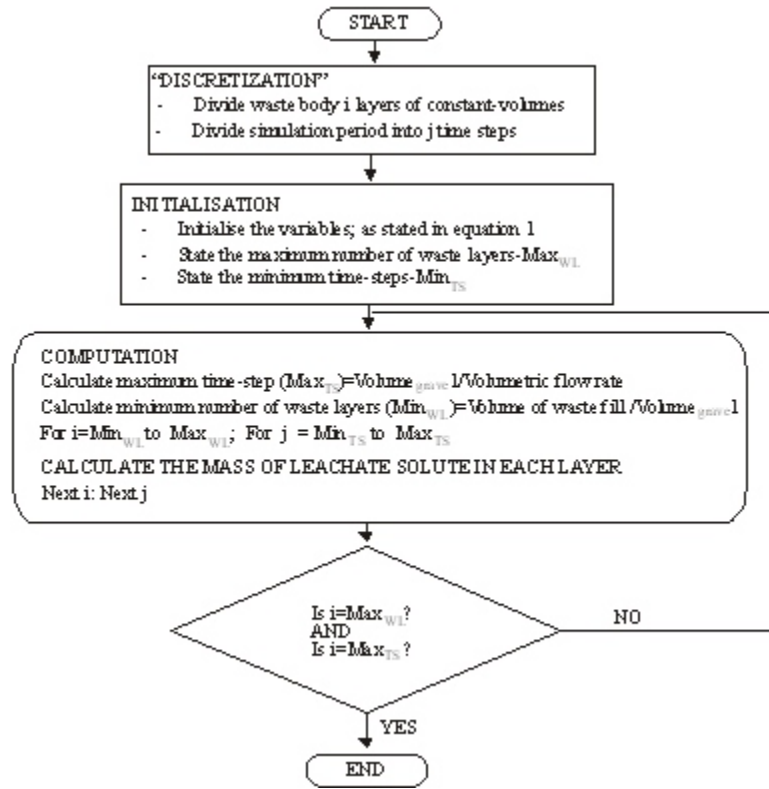


Fig. 2: Flowchart of depicting the simulation processes

Table 1: Composition of the waste fill

Waste component	Paper	Plastic	Textile	Wood	Glass	Metal	Other
Percent (dry mass)	9.6	16.67	3.86	3.78	3.65	1.78	60.66

where;

- M_i = Mass of the leachate solute in the constant volume at time i
- M_{i-1} = The mass of the leachate solute in the constant volume at time $i-1$
- ΔM_{in} = Inflow mass of the leachate solute added to the constant volume from time $i-1$ to time i
- ΔM_{ou} = Outflow mass of the leachate solute added to the constant volume from time $i-1$ to time i
- ΔV = Volume of the leachate solute added to the constant volume from time $i-1$ to time i
- V = Constant volume
- L = Leakage mass of the leachate solute from the constant volume from time $i-1$ to time i

The simulation processes are summarised in the flow chart in Fig. 2. It involves the segmentation of the waste fill into appropriate number of layers with constant volumes and the division of the flow period into time-steps. These are bound by conditions such as the minimum numbers of layers and the maximum time-steps, which are derived in a way to enhance the workability and

realism of the simulation results. The leachate solute mass is then calculated for the various time-steps and layer numbers until the chosen iteration condition is reached. The various characteristic trends obtained for various iterations are then compared with that for the measured data to obtain the optimal simulation conditions.

Application: The simulation technique described above has been successfully used in the preceding part of this topic to model the mass of leachate solute in vertical layers of an experimental saturated waste-fill with an overlying water pond subjected to solute input for 48 h followed by a washout till the end of flow at 300 h, which was undertaken by the author at the Waste Research Laboratory, University of Southampton, UK in 2006. The composition of the waste fill is summarized in Table 1. The dry mass and the dry density of the waste fill in the large-scale cell are approximately 56 Kg and 722 Kg/m³ respectively. The waste fill has an effective porosity of 7.5%, the average linear velocity of the gravitational flow is 3.40 x 10⁻⁶ m/s, and the Darcian flux is 1.54x10⁻⁶ m/s. Sodium Chloride (5 g/L) was the conservative tracer used

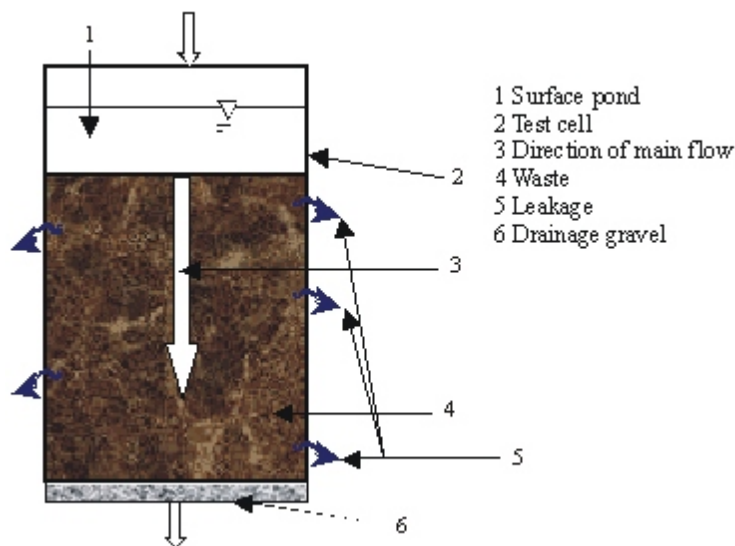


Fig. 3: The flow system of the waste fill

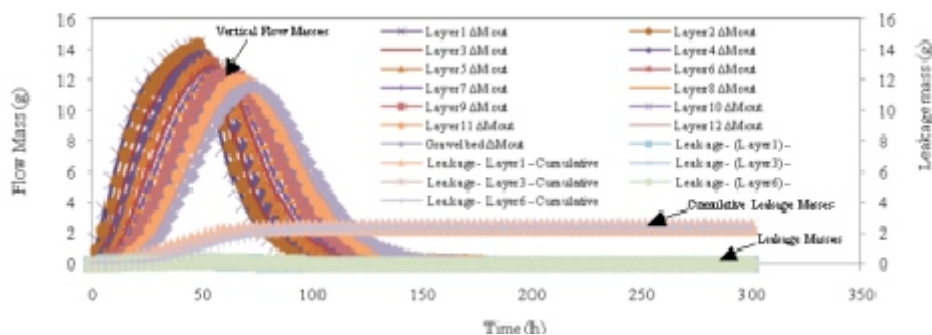


Fig. 4: The temporal mass of solute in main vertical flow and leakage from top waste layers and gravel bed in the waste fill (Leakage - 1%)

to trace the transport of the leachate solute and thus enabling the measured data to be compared with the simulated data for validation. Successive iteration shows that the results are optimized when time-step is 3h and the waste body is “dcretized” into 12 waste layers of a constant volume of 3 L. As there is no test data to validate the present study that involves leakage in the vertical flow, the optimal simulation condition obtained in the closed vertical flow is thus justly utilized. The schematic of the waste flow system with the assumed leakages is shown in Fig. 3.

RESULTS AND DISCUSSION

The simulation of temporal leachate mass in vertical flow and leakages in waste layers and basal gravel bed for various degree of leakage is shown in Fig. 4-7. The cumulative leakage mass is also depicted for comparison and visualisation of potential environmental risk that may otherwise appear benign in mere imagination. There are

12 waste layers and the basal gravel bed, each with a constant volume of 3 L. The waste layers are not of equal thickness owing to the heterogeneity of the waste body. The specific thickness can be obtained by sequential filling of the waste fill with incremental volume of 3 L and measuring and marking the corresponding potential in the manometers or the rise along outer wall of the test cell, as being undertaken during the determination of the effective (drainable porosity). As the time-step used for each simulation’s iteration is 3 h, it therefore suggests equal volume of mass flow into and out of each waste layer and the gravel bed for each elemental time period.

In general, it is observed that the temporal mass of the leachate solute transported through each waste layer decreases along the direction of vertical flow; with the gravel bed having the least mass flow. As the concentration of the solute tracer used is 5 g/L, the maximum mass of the solute expected to be transported through a waste layer is thus 15 g. It is observed that quantities close to this value are transported only through

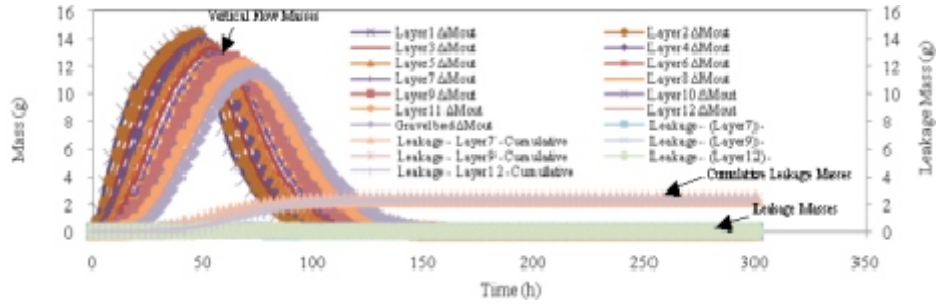


Fig. 5: The temporal mass of solute in main vertical flow and leakage from bottom waste layers and gravel bed in the waste fill (Leakage - 1%)

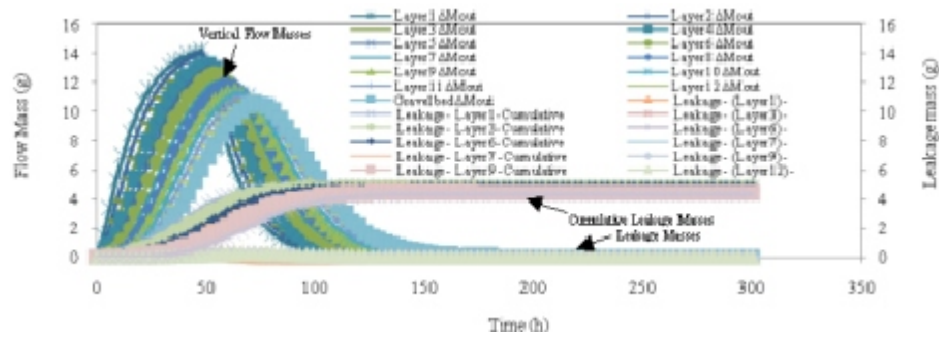


Fig. 6: The temporal mass of solute in main vertical flow and leakage from both top and bottom waste layers and gravel bed in the waste fill (Leakage - 2%)

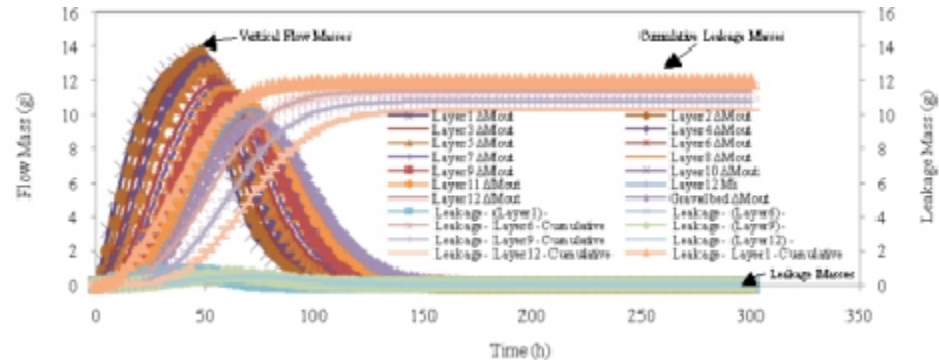


Fig. 7: The temporal mass of solute in main vertical flow and leakage from both top and bottom waste layers and gravel bed in the waste fill (Leakage - 5%)

the upper waste layers close to the surface pond - but not in the lower layers. This is owing to the dilution of the leachate solute in pores along the flow path. The hydrodynamic dispersion of the leachate solute in advection in flow paths effects mixing with the inherent water in the pores thereby reducing the concentration of the leachate in waste layers as the distance from original source of solute input (contamination) increases.

In order to know the impact of the vertical position of the leakage on the mass flow in the waste layers, the temporal mass flow in the waste fill with similar leakages in top waste layers only, and bottom waste layers only is simulated and depicted in Fig. 4 and 5, respectively. As

field leakages are normally small compared to the overall flow in waste landfills, a leakage of 1% of the vertical flow is simulated for the various locations of seepages. It is seen that the location of the leakage does not have any effect on the mass leakage from the layers. Although the mass leakage in individual waste layers appears insignificant, it is observed that the cumulative mass leakage from the layers into the immediate environment seems significant when compared to the maximum leachate mass flow through each waste layer. This probably explains the extent of environmental damage that seepages that may otherwise appear insignificant can cause in the shallow aquifer in vicinity of the location of

leaked municipal landfill sites, especially if the degree of toxicity of the leachate leakage is significant and the level of purity demanded for the economic use of the aquifer is high.

The mass leakages and vertical flows in the waste layers located in both the top and bottom section of the waste at different degrees of leakage are depicted in Fig. 6 and 7. As expected, the cumulative mass leakage from the waste layers increases with the degree of volumetric leakage. In addition, the leachate mass flow in the main vertical flow decreases with increasing mass leakage from the waste layers. The cumulative mass leakage compared to vertical mass flow in the waste layers becomes more significant with the percentage of leakage. In the case of the 5% leakage, the cumulative mass leakage is up to 75% of the maximum mass flow of leachate through the layers. It is also clearly observed that the mass leakage of leachate from the layers increases with the mass flow in each layer, thus making the mass leakage in a top layer higher than a subsequent underlying layer.

The waste flow conditions simulated in this study may exist especially in the region of a MSW old landfill, whose outer surface (probably on the lower gentle slope) has water pond in the cavity created by the biodegradation effects of the underlying waste layers. In reality, the solute input will be a contaminant source leached from the waste constituents in the fill by flowing water. The visualisation of the various degrees of leakage at various locations has enabled a better understanding of the potential negative consequence of seepage to both the gravitational mass flow within the waste fill and the immediate surface and subsurface water, especially if an economic aquifer exists in the vicinity of the location of such MSW landfill.

Initial method of monitoring the leakage from landfill using wells located in the vicinity of the site has often unable to easily and accurately determine the leachate plume formed from any seepage from the waste body. Current methods involve installing electrical detection system around the outer liners and in the immediate groundwater (White and Barker, 2007). There is no doubt that innovative cost-effective monitoring systems are required to enhance environment protection of areas of active and inactive waste landfilling owing the probable consequential effects of benign leakages, as is observed in this study.

In general, this study has shown that the numerical simulation of mass leakages in a waste fill enhances the mental visualisation of its adverse consequences on the immediate environment and may be useful when reporting to non-technical policy makers or stakeholders on the need to adequately finance the installation, operation and maintenance of a proposed or existing MSW landfill site. It provides a better understanding of the mass flow of

leachate in waste layers located at various locations and with varying leakage intensities. This is significant as the investigations of mass flow in landfill are usually undertaken by measuring the outflow from the waste fill and thus no information on waste layers is obtained and therefore being able to be interpreted. Moreover, it may be practically difficult and economically expensive to install a comprehensive monitoring data system in all waste layers of the MSW landfill in order to obtain the characteristic trend of hydro-physical properties of the waste fill.

CONCLUSION

This study has shown that numerical simulation is apt for determining the mass flow of seepages from a waste fill. It enables the mass flow of the leachate in both the main gravitational vertical flow and the leakage in various waste layers and the basal gravel bed to be easily visualised, a feat almost impossible using physical models and unnecessarily difficult with analytical methods.

Although, it is observed that mass leakage is relatively similar in all the layers regardless of the location if the leachate flux is small throughout the waste fill, however, the cumulative leakage mass may be significant if compared to the maximum mass flow in each layer. As the volume of leakage increases, so does the mass leakage - with highest in layers close to the source of the contamination solute. This study is significant to the environmental protection of leachate produced from the landfill of municipal solid refuse.

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