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Migration of Tracer Contaminants from Landfills: Case Study for Chloride

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Abstract: Point sources, such as landfills, can release high concentrations of pollutant into the ground water because of migration of leachate from its bottom, which is generated primarily as a result of precipitation falling on an active landfill surface, leaching out the potential organic and inorganic contaminants from landfilled waste and discharging the same to ground water in underlying aquifer. Leachate contains a high level of dissolved solids content, high concentration of organic matter, and a trace amount of hazardous constituents. To protect the ground water from contamination by landfill leachate, it is quite essential to provide the bottom barrier of suitable thickness, and to minimize the amount of water that could enter the landfill to create leachate. The present study was undertaken to determine the rate of movement of potential contaminants from its bottom to the aquifer media, so as to evolve a rational method for the determination of thickness of bottom barrier. The study was undertaken for conservative contaminant chloride. The governing equation of contaminant transport was solved using finite difference method, and finite mass boundary condition, to ape the field conditions of landfill. The solution of the model was run in MatLab 7.0 for a range of Darcy velocities, and equivalent height of leachate. Design curves were drawn which can be used for determination of suitable barrier thickness on the basis of expected maximum concentration of contaminant in landfill leachate and maximum permissible concentration of the same in groundwater.

Key words: Landfill, leachate, groundwater, liner thickness, chlorides.

Background

In the broadest sense, solid waste includes all the discarded solid materials from commercial, municipal, industrial, and agricultural activities (Henry and Heinke, 1989). Landfilling is still the preferred method of municipal solid waste (MSW) disposal due to its favourable economics. A sanitary landfill is defined as a system in which municipal solid wastes are disposed off, compacted, and covered with layer of soil at the end of each day's operation (Tchobanoglous et al., 1997). However, poorly designed landfills can create notable contamination of groundwater due to the migration of leachate in surrounding soil (Kelley, 1976; Crooks and Quigley, 1984). Leachate is produced when moisture enters the refuse in a landfill, extracts contaminants into the liquid phase, and produces moisture content sufficiently high to initiate liquid flow. Leachate may contain dissolved or suspended material associated with wastes disposed off in the landfill, as well as many byproducts of chemical and biological reactions. During the course of stabilization of landfilled wastes, non-conservative constituents of leachate (primarily organic in nature) tend to decompose and stabilize with time, whereas conservative constituents will remain long after waste stabilization occurs. Conservative constituents include various heavy metals, chloride, and sulfide (Farquhar, 1989).

Landfill design requirements include provision of bottom liners, in suitable thickness to contain the migration of landfill leachate to the underlying aquifer. A typical municipal solid waste landfill is designed with

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a liner system composed of soils and geosynthetic materials that together form a barrier between the waste, the virgin soil, and ground water. Most commonly, soils that are used for barrier material include silty clay, sand, and gravel. However, clay liners must be typically 0.60–1.8 m (2–6 ft) thick, which takes a significant amount of space that can be used to contain waste (Swarbrick, 1994).

Modelling of Contaminant Transport Processes

The process of groundwater flow is generally assumed to be governed by the relations expressed in Darcy's law and the conservation of mass. Changes in the concentration of a contaminant occur within a dynamic groundwater system primarily due to (i) *advective transport*, which involves moving of the contaminants with flowing groundwater, (ii) *diffusive transport*, which involves the movement of contaminant due to concentration gradient, (iii) *dispersion*, which involves mixing of the contaminants at relatively high flows due to local variations in the flow velocity of ground water, or mixing and spreading of contaminants due to non-homogeneity of aquifer and (iv) reaction, absorption, or decay of the contaminants (Bear et al., 1997; Domenico and Schwartz, 1998; Reilly et al., 1987; Zheng and Bennett, 1995). For most practical applications, dispersion and diffusion processes are often lumped together as composite parameter, D_h, called the coefficient of hydrodynamic dispersion $D_h = D_e + D_{md}$, where D_e is the effective molecular diffusion coefficient for the contaminant species of interest, D_{md} is the coefficient of mechanical dispersion. At low velocities, diffusion controls the parameter D_h and dispersion is negligible, while at higher velocities opposite tends to be true. It is often convenient to model the dispersive process as linear function of velocity expressed as $D_{md} = \alpha v$, where α is dispersivity (Shakelford and Daniel, 1991). The governing equation for transport of contaminant due to advection, diffusion-dispersion, and absorption/decay can be expressed by the equation (1) which states that the increase in contaminant concentration within a small region is equal to the increase in mass due to advective-diffusive transport minus the decrease in mass due to sorption/decay processes represented by retardation factor $R_f = 1 + \rho K_d/n$, where K_d is determined through laboratory batch sorption tests and ρ is mass density.

$$\frac{\partial C}{\partial t} = \frac{D_h}{R_f}\frac{\partial^2 C}{\partial z^2} - \frac{v}{R_f}\frac{\partial C}{\partial z} \qquad (1)$$

Finite Mass of Contaminant

Solution to the equation (1) is subject to the initial and suitable boundary conditions. In the case of landfill, the mass of contaminant within a source is limited and will be reduced as the contaminant is transported into soil. The mass of the contaminant available for transport in the case of landfill can be represented in terms of equivalent height of leachate H_f, which corresponds to the portion of mass that is available for transport into hydrogeologic system. H_f may be defined for each contaminant species of interest and corresponds to the volume of fluid (per unit area of landfill) that, at a concentration c_0, would contain the total mass m_0 of that contaminant species which could be released for transport (Rowe et al., 1995; Rowe, 1988). Considering the conservation of mass within the source solution, concentration of the contaminant in source solution $c_T(t)$ at any time t can be expressed by Eq. (3), in which the terms on right hand side indicate the initial concentration of contaminant in source, and the total mass of the contaminant transported into the soil up to time t.

$$C_T = C_0 - \frac{1}{H_f}\int_0^t f_T(c,\tau)\,d\tau \qquad (2)$$

Materials and Methods

Governing equation of solute transport through porous media (Eq. 2) was solved in Matlab 7.0 using finite difference approach with upwind correction. Thus equation (2) in explicit finite difference form with upwind correction can be written as

$$\frac{C_i^{m+1} - C_i^m}{\Delta t} + \frac{1}{R_f} v_x \frac{C_i^m - C_{i-1}^m}{\Delta x} - \frac{1}{R_f} D_x \frac{C_{i+1}^m - 2C_i^m + C_{i-1}^m}{(\Delta x)^2} = 0 \qquad (3)$$

The above equation can be rearranged by keeping

$\kappa_1 = \frac{1}{R_f}\frac{v_x \Delta t}{2\Delta x}$ and $\kappa_2 = \frac{1}{R_f}\frac{D_x \Delta t}{(\Delta x)^2}$. Thus

$$C_i^{m+1} = C_i^m - (1 - 2\kappa_1 - 2\kappa_2)C_i^m + \kappa_2 C_{i+1}^m + (2\kappa_1 + \kappa_2)C_{i-1}^m = 0 \qquad (4)$$

Thus, the unknown concentration at next time step is found out by marching the solution forward at the interior nodes, bringing with it the effects of the initial condition and the boundary nodes. For the implementation of the above solution in MatLab, the domain of problem is discritized in suitable no. of nodes for time and space, in

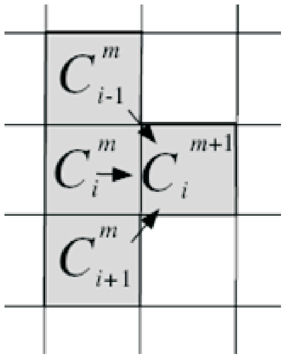

Figure 1: Schemetic of solution in finite difference method.

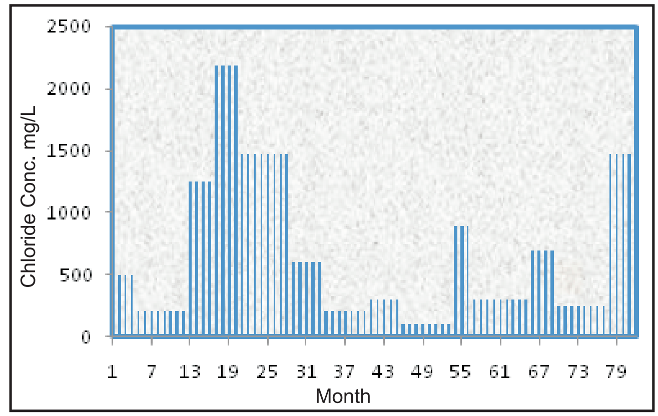

Figure 2: Chloride concentration Histogram.

such a way that $\frac{1}{R_f}\frac{D_x \Delta t}{(\Delta x)^2}+\frac{1}{R_f}\frac{v_x \Delta t}{2\Delta x}\leq\frac{1}{2}$. Initial condition of contaminant concentration was implemented by keeping C_i^m at the beginning of solution to be zero everywhere along the entire depth of domain. The boundary condition at the top of domain was considered to be one representing finite mass of the contaminant.

Model Validation

Model developed herein was validated against the observed field data chloride concentrations below a landfill at New Brunswick. The observed field profile of chloride below the landfill was compared with the results of numerical model developed in the study. In the field investigation conducted by Munro et al., 1997 the hydraulic gradients underlying the landfill waste was determined by using data from monitoring wells. It was concluded by them that the movement of contaminant was predominantly vertical, and mechanisms controlling the contaminant transport were predominantly advection and dispersion. Source concentration of chloride in their study was not uniform and temporal concentration of chloride was determined by adopting a process-based approach (Munro et al., 1997). The variation of chloride source concentration is shown as histogram in Figure 2.

Table 1: Model parameters for chloride (Munro et al., 1997)

Model parameter	*Unit*	*Value*
Depth	m	4.0
Effective molecular diffusion coefficient	m^2/yr	0.02
Porosity		0.28
Retardation factor (*R*)		1.0
Advective velocity	m/yr	0.7

Due to the possible uncertainties in the chloride source function, comparison of the field data and numerical results were considered to be good if the model simulation adequately fit the steeply declining concentrations in the top one metre of the profile (Munro et al., 1997). The field parameters obtained by Munro et al. (1997) from field monitoring are listed in Table 1 and the simulated and observed chloride concentration at various depths below landfill is depicted in Table 2.

Table 2: Simulated and observed chloride concentration profile at bore hole L1B

Depth	*Observed*	*Simulated*
0.18	1250	1055
0.38	814	744
0.54	680	506
0.6	500	453
1.2	500	403
1.38	435	397
1.5	355	390
2.1	460	490
2.7	600	707
3.06	636	773

Design Charts for Liner Thickness

The model representing advective dispersive transport, using finite difference approach was used for plotting of a design chart which can be used for the determination of minimum thickness of barrier with known values of the hydraulic and transport parameters, and using design period of 50 years, assuming 15 years for waste receiving period and remaining for post-closure. Such chart can be utilized for the determination of liner thickness if the maximum permissible relative concentration after a certain period of time is defined based on pollution prevention criteria in a region. The range of Darcy velocity for Municipal Landfill liner has been found to be in the range of 0.0003 m/yr to 0.03 m/yr for compacted liners (Quigley, et al., 1987; Rowe and Nadarajah, 1993).

Table 3: Common data for simulation (Chloride)

S.No.	*Parameter*	*Value*
1	Duration	50 years
2	Porosity	0.40
3	Effective molecular diffusion coefficient (m^2/yr)	0.02
4	Equivalent height of leachate (m)	10, 5, 1, 0.5, 0.1

Design charts were drawn from the results of model simulation for chloride transport below landfill for the selected range of Darcy velocities, equivalent height of leachate, and design life. The range of parameters selected for plotting of design charts is shown in Table 3. The initial concentration (background) was assumed to be zero for a fully flushed boundary. The maximum concentration attained at various depths as obtained from the results of model simulation was plotted for every equivalent leachate height and Darcy velocity considered.

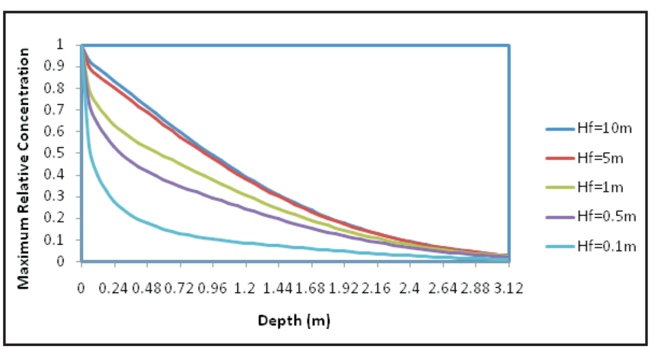

Figure 3: Variation of maximum relative concentration Darcy velocity = 0.03 cm/yr (time 50 years) chloride

Results and Discussions

The results of model validation with field data, as shown in Tables 1 and 2, indicate satisfactory performance of model. Design charts plotted in the present study can be used for the determination of minimum thickness of barrier for a given permissible concentration of chloride below the landfill, and equivalent height of leachate. The permissible value of chloride concentration divided by the typical maximum concentration of chloride in landfill leachate, gives the design maximum relative concentration. Minimum thickness of barrier required can be then found by referring appropriate chart based on designated equivalent height of leachate. On comparing charts, one observes that there is hardly any variation in the respective design charts for the velocities 0.0003 m/yr and 0.003 m/yr respectively. This implies that the advection is not the primary transport mechanism at such low velocities and that the contaminant transport takes place on account of diffusion only.

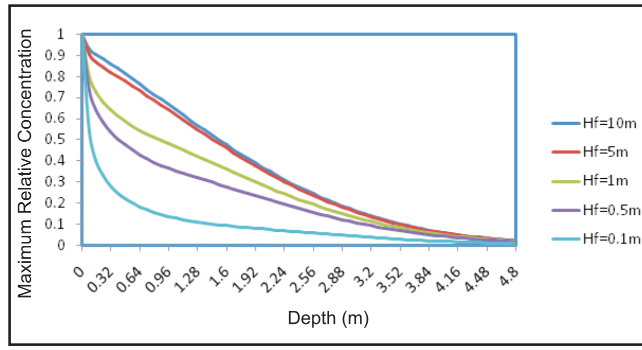

Figure 4: Variation of maximum relative concentration (time = 50 years) Darcy velocity = 0.3 cm/yr. Conservative solute

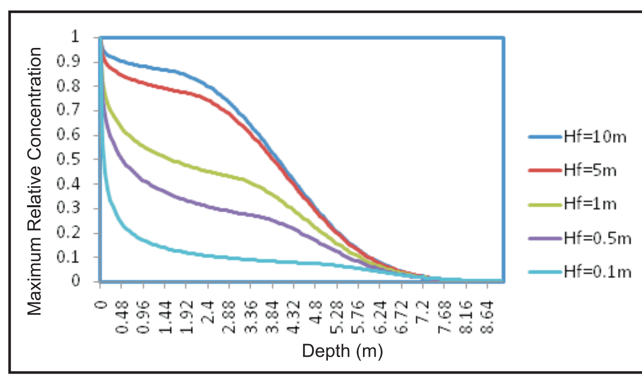

Figure 5: Variation of maximum relative concentration darcy velocity - 3 cm/yr. (time = 50 years) [chloride]

As the Darcy velocity increased to ten fold, the minimum barrier thickness required also increases. Since advection becomes an important transport mechanism at high Darcy velocities, a small increase in the velocity has predominant effect on barrier thickness required. However when a leachate collection system is provided at a landfill site, the value of equivalent height of leachate is reduced. For the case when leachate height is equal to 1 m (implying that the 90% of the leachate is collected in the leachate collection system located at the bottom of landfill), the amount of leachate that infiltrates the barrier is about 10% only.

Conclusions

Mass transport of chloride from landfill leachate was modelled taking into account the mechanisms of contaminant transport advection and diffusion-dispersion, and using the finite difference method with upwind correction. The model was solved in MatLab 7.0 and validated with filed data of solute transport (Munro et al., 1997). Simulation of validated model were run for a range of parameters commonly observed in municipal solid waste disposal sites for a duration of 50 years. Design charts were drawn from the results of such simulation showing maximum relative concentration with depth at the end of simulation period over the domain of interest. Transport of chloride was subjected to finite mass of contaminant boundary condition to ape the field conditions of landfill. Design charts prepared can be used for determining the minimum thickness of barriers required at the bottom of landfill so as to meet the regulatory requirements of controlling the chloride concentration in aquifer.

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