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Design Approach to Protect Water Resources from MSW Disposal

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Abstract: This innovative design provides the guideline for Engineers to locate a suitable site for MSW disposal. The design facilitates for a natural or compacted clay barrier with or without a leachate collection system.

The governing equation for one-dimensional contaminant transport model includes the effects of advection, dispersion, adsorption and decay of the contaminants in saturated soils. The model was solved by a hybrid numerical technique (Green Element Method) using Hermitian interpolation functions and validated for two case studies.

Subsequently, the analysis was conducted taking a finite mass of the contaminant as top boundary condition, while natural or flux condition was at the bottom.

The maximum relative concentration of the contaminant is determined as it percolates. Deducing from the results, design charts (Monographs) were developed to determine the minimum thickness of the barrier.

The principal design parameters are "Equivalent Leachate Heights" and "Darcy Velocities". The flow direction can be either downward or upward.

The Darcy velocity represents the hydro-geological condition while; the equivalent leachate height represents the density of the waste in a landfill and the prerequisite of leachate collection system.

Conservative contaminants are used for determining the minimum barrier thickness. However, the thickness is necessary to check for reactive contaminants.

Key words: Hermitian Green Element Method, Contaminant Transport Modelling, Municipal Solid Waste, Landfill, Leachate, Clay Barriers, Clay Liners.

1. Introduction

The streams at their birth have already been polluted due to Municipal Solid Waste (MSW) dumping in Urban Centres at high altitudes.

The MSW disposals do not conform to the modern practices of sanitary land filling and the waste is largely dumped at convenient locations. As a pioneering effort, the Nuwara-Eliya Municipal Council has commissioned a Sanitary Landfill thus preventing further pollution of "Bomburella" stream. (Upper Catchments of Uma Oya)

In the Western Province, disposal is carried out in low-lying areas prone to flooding and often susceptible to contamination of water. The Groundwater pollution, which has not been properly assessed is another threat posed by the dumping of wastes.

Therefore, the contamination of precious ground or surface water is unavoidable unless Sri Lanka too resorts to the modern practices of sanitary land filling, at least in urban centres, as an integrated approach to environmental protection.

The forecasts of the population distribution of Sri Lanka in year 2025 shows that the urban population will reach nearly 60% of the predicted overall population of 23 million. About 10 million of this urban population will crowd the urban centres in the Western Province, already inhabited by more than half of the urban population.

The residential per capita waste generation in Colombo is about 0.54 kg/day (Gamage & Costa, 2001). In India the amount ranges from about

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0.1 kg/day in small towns to 0.5 kg/day in large towns. (Pachauri & Sridharan, 1998). This figure varies from 1.0 to 2.2 kg/person/day in industrialised nations (Hanashima, 2000).

Therefore, the Municipal Engineers of Sri Lanka should be prepared to solve the problem of disposing about 7,450 Metric Tonnes per day in year 2025. Please note that at the moment, Colombo Municipal Council (C.M.C.) is handling approximately 500 Metric Tonnes per day. The need of a National Programme is highlighted here on infrastructure development of MSW disposal with minimum damage to the environment.

Waste disposal facility design must involve some form of a barrier that separates the waste from the groundwater system located below it. The barrier is intended to minimise the migration of contaminant from the waste facility. Natural clay deposits, decomposed rock formations, abandoned quarries and compacted clay liners can be used as landfill barriers, thus preventing pollution of water resources.

The leakage through the barrier system and its environmental impact on the ground water quality depends on the nature of the site, the climate, the type of waste, the local hydrogeology and the presence of dominant flow path. (Jayawardena & Mathur 2000a)

The design of a landfill barrier system is generally based on a prescriptive standard type. The regulatory organisations often specify some guidelines to determine the minimum thickness of the compacted clay liner for satisfactory performance. The bottom-lining system of the prescriptive standard for municipal waste landfills is varied from either one country to another or is practically non-existent.

There is however no consensus on what an appropriate minimum thickness ought to be due to difficulties encountered while analysing soil liners.

The disadvantage of the perspective standard is that it could lead to gross over design of barrier system where either the hydro-geologic environment is favourable or the landfill is small with low toxicity waste.

The present state of knowledge enables to promote the performance standard design for barrier system, ensuring the environment safety in an efficient manner. (Jayawardena & Mathur 2000b)

In this paper, design curves (monographs) developed in the study are presented to determine the minimum barrier thickness required in an "Engineering Landfill" or "Naturally Attenuated Landfill" with a view for protecting the environment. The above minimum thickness should be checked against other reactive contaminants such as heavy metals, dissolved organic compounds and biodegradable substances.

Moreover, this innovative design approach promotes performance standard design instead of transposing perspective standard practices of other countries, which is expensive for developing countries such as Sri Lanka.

2. Methodology:

2.1. Governing Equation:

In one dimension, the mass transport of a decaying solute through a porous medium can be expressed by following equation, which constitutes the governing equation. It is based on the theory discussed in Spitz and Moreno (1996). The retardation due to adsorption discussed by Kim et al., (2001) is incorporated in this equation to yield

$$\frac{D_h}{R_f}\frac{\partial^2 C(x,t)}{\partial x^2}-\frac{U_x}{R_f}\frac{\partial C(x,t)}{\partial x}-\frac{\partial C(x,t)}{\partial t}-\frac{K_d}{R_f}.C(x,t)=\frac{1}{R_f}f(x,t)$$

on $X_0 \leq X \leq X_L$ (Eq 1)

The retardation factor R_f can be expressed as

$$R_f = 1+\left[\frac{\rho_d K_P}{n}\right] \quad \text{(Eq .2)}$$

It is assumed that the sorption processes are linear and can be represented in terms of partition or distribution coefficient K_p. The above assumption is valid at relatively low concentrations found in MSW disposal sites. Both Langmuir's and Freundlich's isopleth reduces to linear representation at very low concentrations (Rowe et al., 1995).

where,

$C(x,t)$ = Aqueous concentration of a decaying solute (M/L^3);

x = Distance along the direction of mass transport (L);

t = Elapsed time. (T).

D_h= Hydrodynamic dispersion coefficient. (L^2/T);

R_f= Retardation factor.

U_x= Seepage velocity in the direction of x (L/T)

K_d= First order decaying degradation constant. (1/T)

f(x,t) = An external contaminant source, (M/L^3T); and $L = X_L - X_0$ is the length of the flow domain (L)

The above governing differential equation exhibits intriguing features of parabolic and hyperbolic characteristics depending on the relative values of the parameters included in the equation. When hydrodynamic dispersion is dominant, the equation behaves as a parabolic equation, and when advection is large it behaves as a hyperbolic equation. The relative importance of these two transport processes is indicated by the value of the dimensionless parameter known as the Peclet number (Taigbenu 1998a, 1998b, 1999a).

If numerical techniques are arbitrarily applied, it may cause numerical dispersion that could outweigh the actual physical dispersion and render the numerical solution meaningless.

The traditional Finite Difference Method (FDM) or Finite Element Method (FEM) performs quite well when dispersion dominates the transport, and the distribution of concentration is relatively smooth. However, in transport problems where advection dominates, the FDM / FEM solutions exhibit a combination of numerical dispersion and oscillation.

Numerical dispersion is an artificial, grid-dependent smearing of sharp solute concentration fronts, while numerical oscillation is manifested by overshoot and undershoot about the true solution. (Sharma et al., 2000)

Therefore scientists continually search for hybrid models by incorporating the "Method of Characteristics" and "Random Walk" in FEM & FDM to thwart these problems (Spitz and Moreno 1996).

2.2. Numerical Technique:

Similarly to impede the above problems, a new technique was proposed by Taigbenu. (Taigbenu 1999b) & the method employs a one-dimensional hybrid Boundary Element Method (BEM) named as Green Element Method (GEM).

The Green Element Model uses the free space Green's function of the 1-D Laplace operator in the derivation of the integral equation, and approximates the temporal derivative by a weighted difference that yields a time marching scheme. The second order accuracy is maintained by transforming the second order differential equation (Governing Equation) into first order by the Green Identity. The governing equation is converted to a set of discrete element equations by incorporating Hermitian interpolation functions for the approximation of unknown quantities. These element equations are later assembled to form the global matrix that is solved for each time interval by the Gauss Elimination Technique.

The formulation of the numerical scheme is beyond the scope of this paper. However, the theory & application techniques could be understood by referring to (Taigbenu 1999b & Jayawardena 2002).

2.3. Boundary & Initial Conditions:

The top boundary is the point of contact with the contaminant source. It can be finite mass, time variable histogram or constant concentration of the contaminant. Similarly the bottom boundary condition is an aquifer (fixed outflow), a bedrock (zero flux) or constant concentration.

In developing the Monographs, a finite mass boundary condition was assumed at the top. Similarly, natural or flux boundary conditions was assumed at the bottom. The above bottom boundary condition is more conservative than aquifer (fixed outflow) boundary condition, thus contaminants were not being transported by horizontal outflows. As the initial condition, concentration of the contaminants is assumed a constant value through out the domain.

The detailed descriptions of the special boundary conditions used in this study are described below, since the reader should understand the assumptions made in developing the monographs and its limitations in applying it to the complex situation.

2.3.1. Finite Mass Boundary Condition

The finite mass boundary condition may be used to represent contaminant sources in landfills. When the mass of contaminant is finite, the concentration of contaminant at the source will decline as contaminant mass is transported into the layers below or is removed by a leachate collection system. The boundary condition is defined by

$$C_T(t) = C_0 - \frac{1}{H_f}\int_0^t f_T(c,\tau)d\tau \qquad \text{(Eq 3)}$$

where H_f is the equivalent height of the leachate defined as

$$H_f = \frac{m_{TC}}{C_0 A_0}\frac{q_a}{q_0} \qquad \text{(Eq 4)}$$

m_{TC}= The total weight of the particular solute in a landfill for entire life span of the project.

C_0= The maximum concentration of the solute at the landfill waste.

q_a= The rate of leachate available for migration at the top of the barrier.

9_0=The rate of leachate generated due to infiltration from the cover, and f_T (c,τ) , is the surface flux (mass per unit area per unit time) entering the soil.

For the case of advective-diffusive transport the mass flux f, is given by,

$$f = nV_x C - nD\frac{\partial C}{\partial x} \quad \text{(Rowe et al., 1995).}$$

Thus

$$f_T(c,\tau) = n_L U_x C_T(0,t) - n_L D_h \frac{\partial C_T(0,t)}{\partial x} = n_L\{U_x C_T(0,t) - D_h \Phi(0,t)\}$$

Also,

$$\int_0^\tau f_T(c,\tau)d\tau = n_L\left[U_x \sum_{t=0}^{t} C_T(0,t)\Delta t - D_h \sum_{t=0}^{t}\Phi(0,t)\Delta t\right]$$

$$\frac{1}{H_f}\int_0^\tau f_T(c,\tau)d\tau = \frac{n_L}{H_f}\left[U_x \sum_{t=0}^{t} C_T(0,t)\Delta t - D_h \sum_{t=0}^{t}\Phi(0,t)\Delta t\right]$$

Hence the numerical scheme the finite mass boundary condition can be defined as

$$C_T(0,t) = C_0 - \frac{n_L}{H_f}\left[U_x \sum_{t=0}^{t} C_T(0,t)\Delta t - D_h \sum_{t=0}^{t}\Phi(0,t)\Delta t\right] \qquad \text{(Eq 5)}$$

If the landfill contaminant source is assumed as finite mass; the waste density, infiltration through the cover, and percentage of mass are to be specified for the contaminant.

2.3.2. Natural or Flux Boundary Condition

The second type of boundary condition is referred to as the Neumann (Natural or flux condition), and it specifies the flux (fluid flux) across an area. This condition is expressed as and

$$-K\frac{dC}{dx}\bigg|_{x=0} = q_s$$
$$-K\frac{dC}{dx}\bigg|_{x=x_L} = q_L \qquad \text{(Eq 6)}$$

In the solute transport equation this boundary condition is used when there is an impermeable layer at the bottom of the domain. Similarly in most of the analytical models the boundary condition at end of the infinite domain is also modelled by taking. $\frac{\partial C}{\partial x} = 0$ The same condition preavails when the contaminant moves out of soil with moving soil-water. However dispersion and diffusion do not contribute to this movement. (Mass flow without hydrodynamic dispersion).

2.4. Model Validation:

The numerical model was simplified sufficiently so that it could be compared with the analytical solution to conduct a sensitivity analysis and discuss the importance of the Courant and Peclet numbers that result into oscillations and numerical dispersion in the numerical solution. (Jayawardena 2002).

Rowe & Booker (1985) introduced the concept of equivalent height of leachate H_f defined in equation (Eq 4) and found that in the absence of a first order decay in a landfill, the one dimensional (vertical) spatial and temporal variation of solute concentration below the landfill is given by following simplified expressions

$$C(x,t) = C_0 e^{(ab-b^2 t)}\left[\frac{bf(b,t) - df(d,t)}{(b-d)}\right] \qquad \text{(Eq. 7)}$$

where $f(b,t) = e^{(ab+b^2)} erfc\left[\frac{a}{2t^{1/2}} + bt^{1/2}\right]$ (Eq. 8)

$$f(d,t) = e^{(ad+d^2)} erfc\left[\frac{a}{2t^{1/2}} + dt^{1/2}\right] \qquad \text{(Eq. 9)}$$

$$a = x\left[\frac{(n + pK_d)}{nD_h}\right]^{[\frac{1}{2}]} \quad \text{(Eq. 10)}$$

$$b = U_z\left[\frac{n}{4D_h(n + \rho K_d)}\right]^{[\frac{1}{2}]} \quad \text{(Eq. 11)}$$

$$d = \frac{nD_h}{H_f}\left[\frac{n + \rho K_d}{nD_h}\right]^{[\frac{1}{2}]} - b \quad \text{(Eq. 12)}$$

The notations were defined similar to the governing equation (Eq 1).

As discussed above, the stability characteristics for each model depend upon the dimensionless parameters; namely, the Courant number (Cr), and the Peclet number.

This model facilitates a conditional solution, which was tested extensively by Taigbenu (1998b) for an Advection-Dispersive Equation, and the values of the dimensionless constants suggested for a stable solution should satisfy the following conditions.

(a.) $P_e \leq 50.0$ & $Cr \leq 0.2$

(b.) $P_e \leq 1.0$ & $Cr \leq 1.0$

It is found that the analytical solution & numerical solution matches absolutely, (Figure 1) if the same stable conditions are assumed in this model while deciding on the time step during the computations.

After the model was compared with the analytical solution, the model developed was validated for two cases of field data. (Mathur & Jayawardena 2005).

In the first case, field data of Munro et al. (1997) for a landfill at New Brunswick was used to validate the numerical model. The field profile for chlorides in the media was compared with the numerical model developed in this study. The mechanisms controlling the solute transport in the shallow till deposit at the landfill site were predominantly advection and diffusion-dispersion for the conservative (non reactive) chloride solute. The comparison of field data & the simulation by the author is given in the Figure 2.

Similarly, for the second case, field data of organic dissolved carbon at the same location was compared with the simulated model data. The solute was non-conservative (unlike the previous case of chlorides) and the model took into account advection, dispersion-diffusion, decay or retardation of the solute as it moved vertically down below the landfill. In this case too, advection and mechanical dispersion are more important than molecular diffusion for shallow depths of the till.

The simulation was done for two cases, one with a retardation factor of 1.5, and the other assuming a decay factor also. The half-life of DOC found in landfills has been reported to be around 6 years (Rowe et al., 1995).

The porous medium simulation developed for this case is compared with the observed field data and the comparison is shown in the Figure 3.

The above validation for chlorides and dissolved organic carbon at an actual landfill site shows the strength of the model.

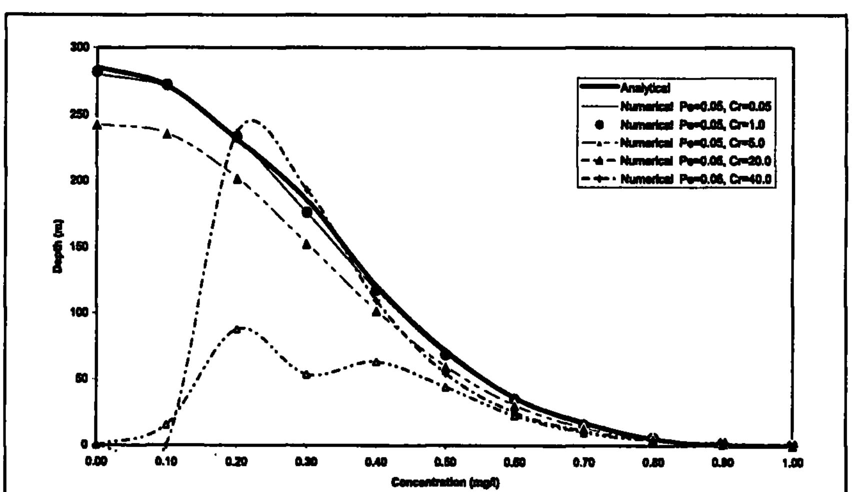

Figure 1 : Stability Analysis of the Solution for Peclet and Courant Criterion. Concentration Profile after 160 yrs.

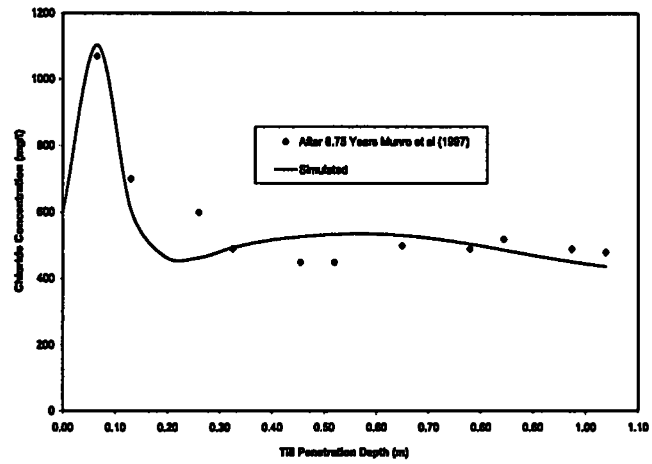

Figure 2 : Simulated and Observed Choloride Profile at Bore Hole L1B

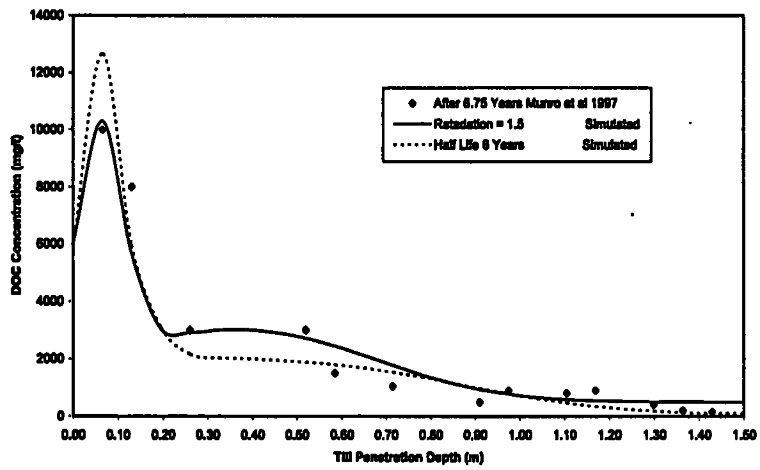

Figure 3 : Simulated and Observed Dissolved Organic carbon Profile at Bore Hole L1B

2.5. Development of the Design Charts

The simulation was done for a finite mass concentration of the solute as the upper boundary defined by equation (5) where is assumed to be 1000 mg/l and the porosity of clay assumed as 0.4. The model gives the spatial and temporal variation of concentration along the thickness of the barrier and the maximum concentration recorded in each depth for the entire time domain (200 yr).

The equivalent leachate height representing the density of the waste in a landfill has been defined earlier by equation (4). If the percentage of solute that is present in the waste in known through chemical analysis or through typical landfill data charts (Rowe et al 1995), and the total design weight in metric tons is available, then the total mass of the solute can be computed in tons. The maximum concentration of the solute in the waste needs to be known from the typical municipal landfill data (Refer Appendix A) for the information.

Knowing the quantity of the leachate that infiltrates through the bottom of the waste into the barrier and the aerial extent of the landfill, the equivalent leachate height of the landfill can be determined (Rowe et al., 1995) from the available data. Various values of the equivalent leachate height ranging from 0.1m to 10m are considered in the study to develop the design charts.

The simulation was run for a time domain of 200 years, and the time step was determined after satisfying the Peclet and Courant number criteria

APPENDIX A - Composition of MSW Landfill Leachate

Parameter	Name of the Landfill				Maximum Acceptable Concentration in Ground Water
	California (USA)1*	Ontario (Canada) 2*	Masalvck (Sweden)3*	Ampang Jajar (Malaysia)4*	
Conventional Parameters					
Biological Oxygen Demand (BOD) [mg/l]	1083	3500	1900	405	
Chemical Oxygen Demand (BOD) [mg/l]	2081	4700	9400	2160	
Suspended Solids [mg/l]	105				
Oil & Grease [mg/l]	13.5				5
Alkalinity (CO3) [mg/l]	1430	2600			300
Ammonia (NH3) [mg/l]	93		540		
Sulphate (SO4) [mg/l]		103		1300	200
Chloride [mg/l]	632	1915	600		250
pH	7.08	6.6	7.3	7.6	7.0-8.5
Manganese (Mn) [mg/l]	9.38	240	9.9		0.3
Zinc (Zn) [mg/l]		2.4	10	1.68	5.0
Iron (Fe) [mg/l]		80	350	14.9	0.3
Other Constituents					
Cadmium [mg/l]	0.007		0.024	0.13	0.001
Phenol [mg/l]	3.9				0.002

1* Francis X Taylor (1991) Wastage Magazine.

2* Rowe, R.K., Quigley, R.M. and Booker, J.R. (1995). "Clayey Barrier Systems for Waste Disposal Facilities," E & FN Spon (Chapman & Hall), London

3*William Hogland, Marcia Marques and Sven Nimmermark -Proceedings of the Asia Pacific Landfill Symposium Fukuoka 2000

4*Matsufuji Y., Tachifuji, A & Hanashima M, Proceedings of the Asia Pacific Landfill Symposium Fukuoka 2000

so that $P_e<1$ and $C_r<1$. The time step was thus found to be in the range from 0.8 years to 1 year for element sizes ranging from 5cm to 22cm. All combinations of the simulation and other important parameters are listed in Table 1.

The initial concentration (background) was assumed to be zero and at the bottom of the barrier the concentration was again assumed to be zero for a fully flushed boundary. The conservative solute front in all the cases could not reach the bottom boundary for the cases of both, small and large Darcy velocities (domain depths 5m, 10m, 20m and 30m). The maximum concentration attained at various depths for a number of leachate heights was determined next. This procedure was followed for every equivalent leachate height and the Darcy velocity considered.

The molecular diffusion coefficient for the conservative solute has a very small range for any given solute and is generally taken as $0.02 m^2/yr$ Rowe (1988). Similarly, the dispersivity for clay ranges from 0.01m to 0.14m depending upon the texture of the clayey soil (Munro et al., 1997) and this range has been considered in the model developed in the study.

The development of a monograph is also explained graphically in Figure 4 to Figure 6.

Figure (4) shows the temporal variation on concentration of conservative solute for various depths up to 300mm (50mm intervals) for Darcy velocity of 0.003m/yr and leachate height of 1.0m. The solid points represent the maximum concentration attained at a particular depth. The values plotted up to a period of 30 yrs were shown for clarity although the simulation was done for the period of 200 years.

In Figure (5) the maximum concentration recorded at various depths were plotted against the respective depth for the entire time period of 200 years. Once the maximum concentration is divided by C_0, the dimensionless relative concentration can be obtained.

The Monographs were developed by connecting the maximum relative concentration for the respective depth. Figure 6 shows the extension of the trend given in the figure 4 for the entire time domain (200 years) against the relative concentration. The maximum relative concentration and the time it occurs can be determined from this figure for various depths below the waste.

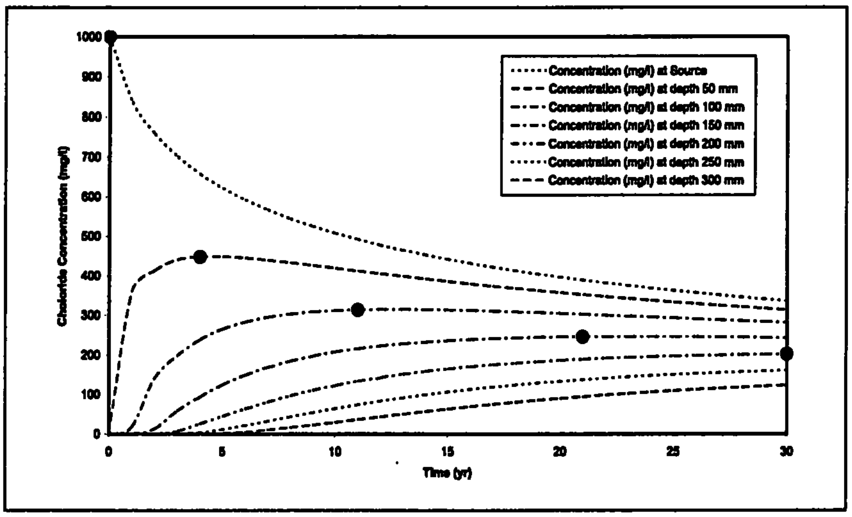

Figure 4 : Temporal Variation of Concentration of Conservative Solute Darcy Velocity 0.003 m/yr, Equivalent Leachate Heigth 1.0 m

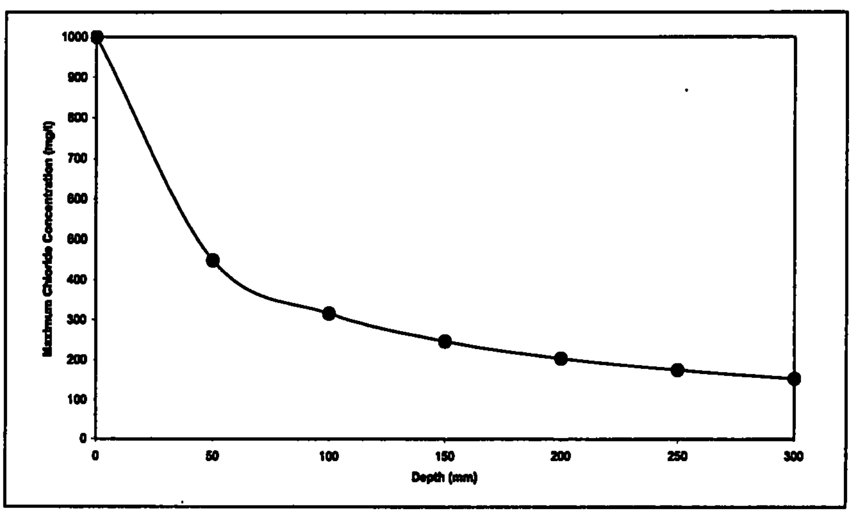

Figure 5 : Maximum Concentration Recorded for 200 yr Time Domain (From the Top of the Barrier upto 300 mm Depth Only)

The relative maximum concentration is the ratio of the maximum concentration at a particular depth and the initial source concentration defined at the top boundary.

The maximum relative concentration attained for a time period of 200 years and the depth from the contaminant source were plotted for various Darcy Velocities, leachate heights & type of contaminants.

These results are also presented graphically in Figures (7) to (20). From the figures, one can determine the minimum design thickness of the barrier knowing the permissible (allowable) concentration of that particular solute. The permissible value (Appendix A) when divided by the typical maximum concentration value of that solute in the landfill waste gives the design, maximum relative concentration, and the appropriate minimum thickness of the barrier for that designed leachate height from the design figures.

As an example, the maximum relative concentration is determined by computing the ratio of the permissible chloride concentration (250 mg/l) to the maximum chloride concentration in the landfill (2000 mg/l).

The illustration was made in the Appendix (B) in determining the minimum thickness for a barrier using above design charts (Monographs) for a fantasy landfill for several Municipal/Urban Councils.

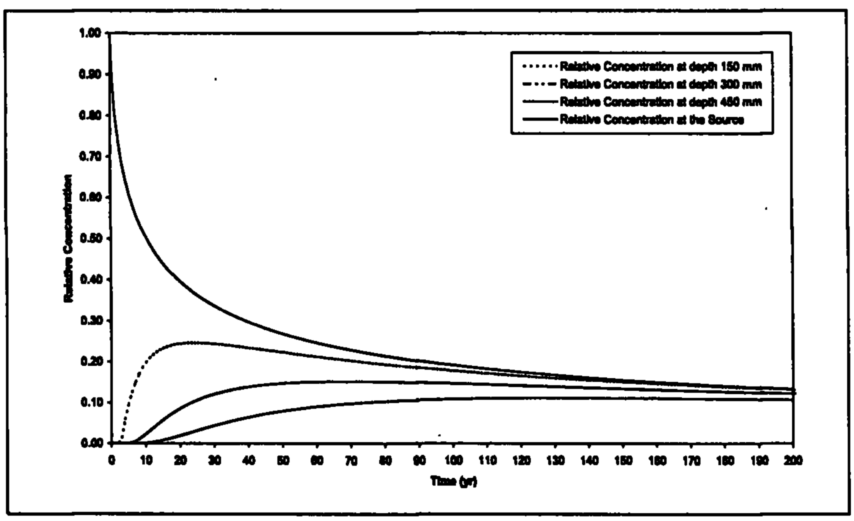

Figure 6 : Temporal Variation of Relative Concentration of Conservative Solute at Various Depths

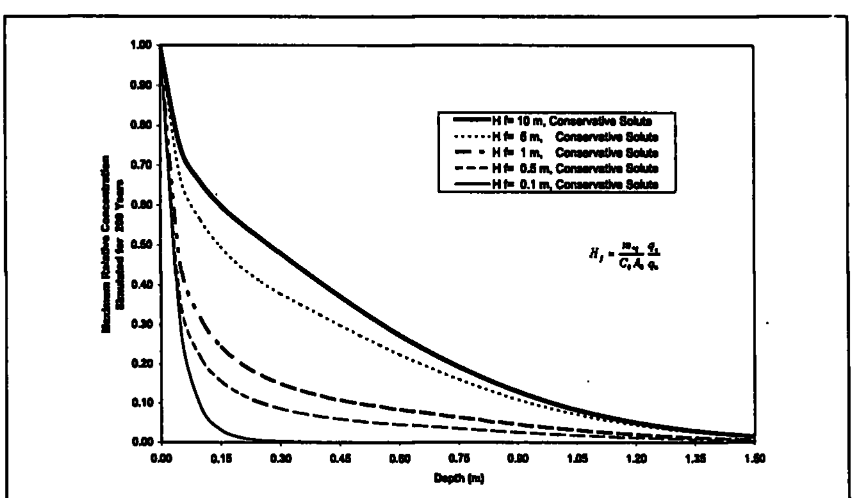

Figure 7 : Variation of Maximum Relative Concentration with Depth Darcy Velocity = 0.0003 m/yr (Conservative Solute)

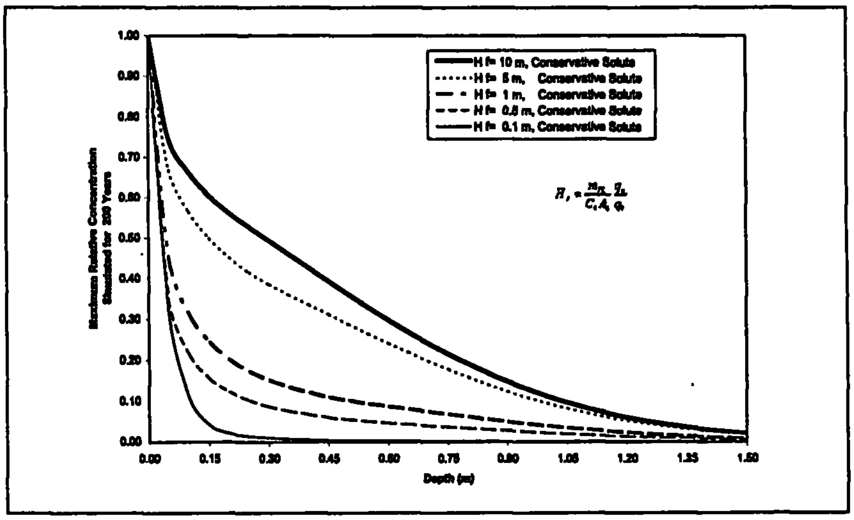

Figure 8 : Variation of Maximum Relative Concentration with Depth
Darcy Velocity = 0.0003 m/yr (Conservative Solute)

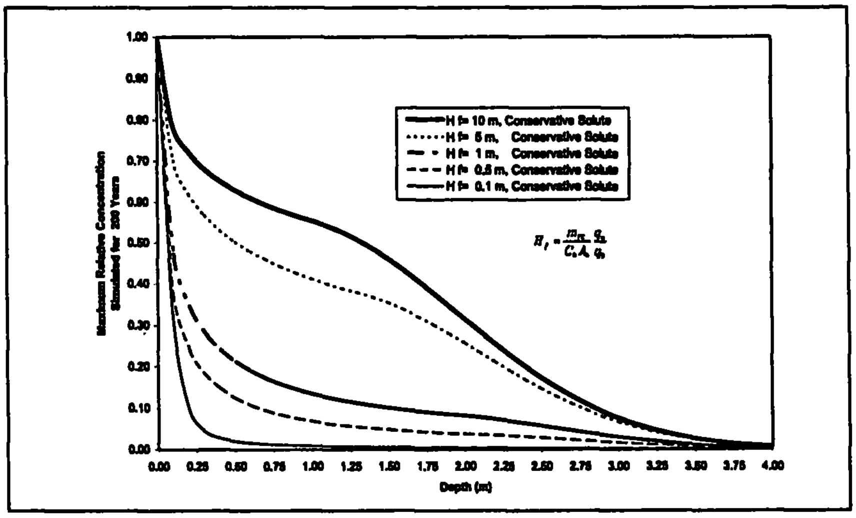

Figure 9 : Variation of Maximum Relative Concentration with Depth
Darcy Velocity = 0.03 m/yr (Conservative Solute)

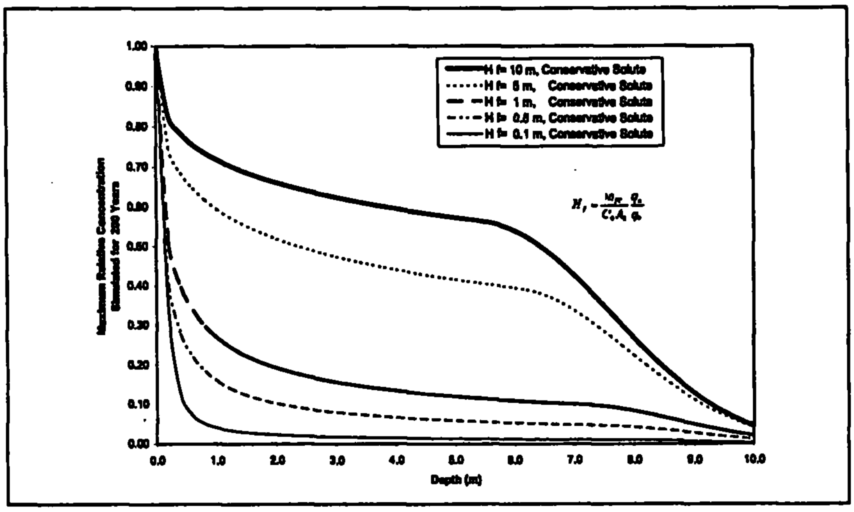

Figure 10 : Variation of Maximum Relative Concentration with Depth
Darcy Velocity = 0.07 m/yr (Conservative Solute)

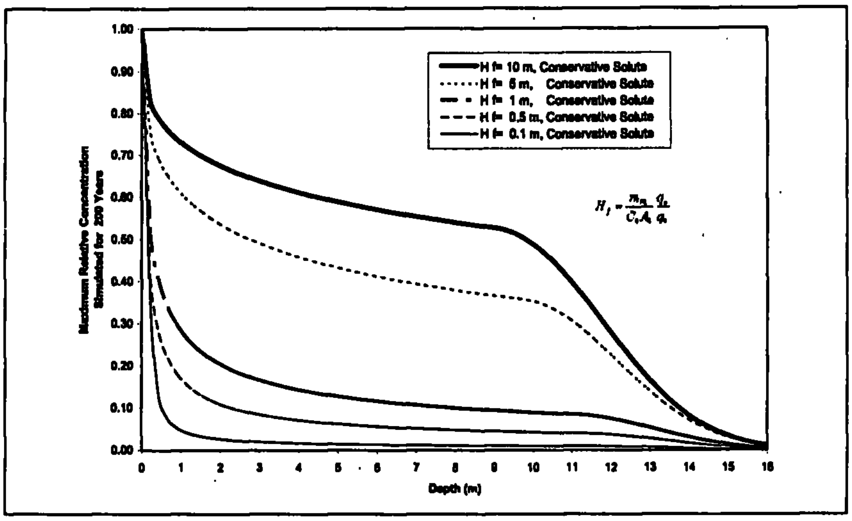

Figure 11 : Variation of Maximum Relative Concentration with Depth Darcy Velocity = 0.1 m/yr (Conservative Solute)

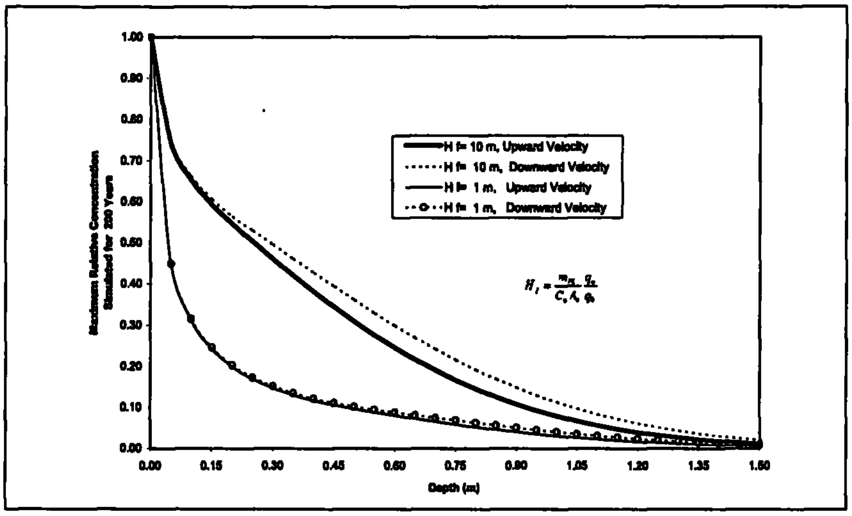

Figure 12 : Variation of Maximum Relative Concentration with Depth (For a Hydraulic Trap - More Pumping & Leachate Treatment) Upward Darcy Velocity = 0.003 m/yr (Conservative Solute)

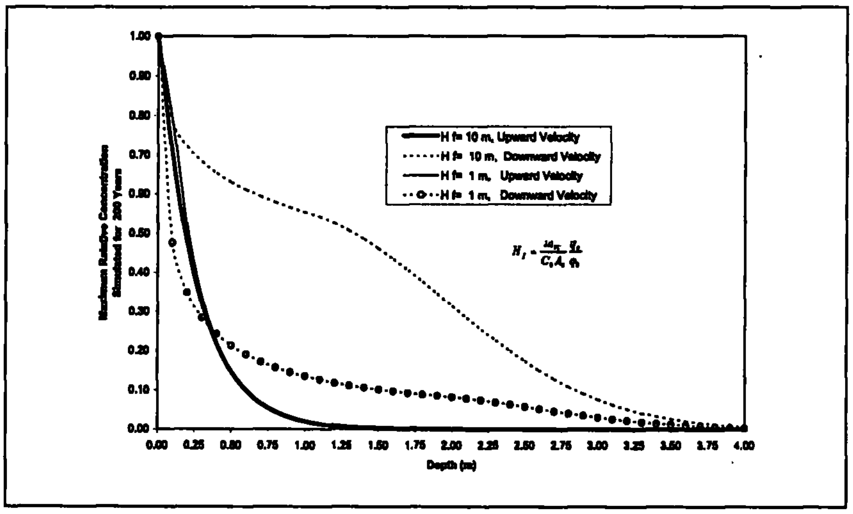

Figure 13 : Variation of Maximum Relative Concentration with Depth (For a Hydraulic Trap) Upward Darcy Velocity = 0.03 m/yr (Conservative Solute)

APPENDIX B - Application of Monographs in Determining the Barrier Thickness. (Conservative Contaminant)

(Sample Calculation)

Combine Population of Dehiwala-Mt Lavinia, Moratuwa & Panadura Municipal Councils)	=	500,000.
Per capita Waste Production (Gamage & Costa 2000, Pachauri & Sridharan, 1998)	=	0.5 kg/d/capita
The Design Period of Landfill (Assumed)	=	**30 Yr.**
The Total Mass of Solid Waste Produced	=	2737,500,000 kg
	=	2,737.5 Mega Ton
Areal Extend of the Landfill (500 m X 500 m)	=	**25 ha**

(Assumed that the proposed Land is away from the Ratmalana Airport, Main Highways, Streams, & Residential Areas - The Authorities intend to develop this land as golf course and a park after 30 years operation.)

Percentage Chloride (Rowe et al 1995)	=	0.2 %
Total wt of Chloride	=	0.002X2737.5 Mega Ton
Total wt of Chloride	=	5.475 Mega Ton
	=	5475 Metric ton
Typical Maximum Concentration of Chloride in a landfill	=	2000 mg/l

Chloride Concentration in Typical Landfill Leachate 1500 - 2500 mg/l (Appendix A & Rowe et al 1995)

Equivalent Leachate height $= \dfrac{5475 \times 1000{,}000}{2000 \times 25 \times 10000}$ m

(Equation 4) = **10.95 m (Say 10.0 m)**

Permissible Concentration of Chloride (Appendix A)	=	250 mg/l
Possible maximum concentration of Chloride (Appendix A & Rowe et al 1995)	=	2000 mg/l

The Design Maximum Relative Concentration of Chloride (Conservative Solute) $= \dfrac{250}{2000}$

= **0.125**

Assuming that dominant flow path exists and no favourable hydro-geological condition.
Engineering Landfill is proposed with a compacted Clay liner.

In this case assumed Darcy Velocity = **0.003 m/year.**

The Liner Thickness Required = **1050 mm**

(From the Monograph given in the Figure 8 & assumed No Leachate Collection System Provided)
Therefore, it is worth wile to have a primary leachate collection system,
In general, 90 % leachate generated is collected & treated by the system. (Rowe et al 1995

The Equivalent Leachate height $= \dfrac{10.95 \times 10}{100}$ (Say 1.0 m)

The Liner thickness with Leachate Collection System = **450 mm.**

The above illustration was extended to the range of Darcy velocities from 0.0003 m/yr to 0.1 m/yr covering compacted clay liners to natural aquitards & the Hydraulic Trap (in the case of Vertical flow.). Moreover, The comparison was made with or without a leachate system.

Darcy Velocity m/yr	Reference Figure (Monograph)	Minimum Liner /Aquitard Thickness (mm)	
		Primary Leachate System	Natural Attenuation
Downward			
0.0003	Figure 7	450	1050
0.003	Figure 8	450	1050
0.03	Figure 9	1300	3000
0.07	Figure 10	4500	9000
0.1	Figure 11	6000	13500
Upward (Hydraulic trap)			
0.003	Figure 12	450	1050
0.03	Figure 13	450	1050
0.1	Figure 14	450	1050

CHECK FOR REACTIVE CONTAMINANTS

Once the minimum thickness was computed, it is necessary to check for reactive contaminants.

Permissible Concentration of Zinc = 5 mg/l
(Appendix A)

Possible maximum concentration of Zinc = 67 mg/l
(Appendix A & Rowe et al 1995)

For Zinc, the maximum relative concentration = 0.075
The respective retardation factor for Zinc = 3.5

Darcy Velocity m/yr	Reference Figure (Monograph)	The Depth that Zinc Attenuated to the Permissible Level (mm)	
		Primary Leachate System	Natural Attenuation
Downward			
0.003	Figure 15		400 (<1050)
	Figure 17	320 (<450)	

In both cases the Zn attenuation to the permissible level reaches with in the minimum thickness of the liner / Barrier provided. Therefore, the design minimum barrier thickness is sufficient for the attenuation of heavy metals.

APPENDIX C - Tables & Design Charts (Monographs)

Table 1

Simulation Schedule for Development of the Monographs

Duration Concerned = 200(Years)
(Landfill is active even after the closure of the operation)

Porosity = 0.40

Diffusion Coefficient = 0.02(m2/yr.)

Darcy Velocity (m/yr.)	Dispersivity (m)	Hydro Dynamic Dispersion (m^2/yr.)	Domain Length (m)	Length of the Element (m)	Duration of the Time Step (Yr.)
Downward					
0.0003	0.01	0.02001	5.00	0.05	1.00
0.003	0.03	0.02023	5.00	0.05	1.00
0.03	0.05	0.02375	10.00	0.10	1.00
0.07	0.10	0.03750	20.00	0.20	1.00
0.1	0.14	0.05500	30.00	0.22	0.80
Upward					
-0.003	-	0.02000	5.00	0.05	1.00
-0.03	-	0.40000	10.00	0.10	1.00
-0.01	-	0.02000	30.00	0.10	1.00

Conservative Solute Combinations for all downward Velocities

Equivalent Leachate Height (m)	10 m	5 m	1m	0.5m	0.1m

Non Conservative Solute -Combinations for Velocities 0.003m/yr. & 0.1 m/yr. & Equivalent Leachate Heights 10m & 1m

Retardation (Density*Partition Coefficient)	Retardation (Retardation Factor)	Decay Half Life (Yr.)
0	1.00	1
1	3.50	5
5	13.50	10
10	26.00	50
50	126.00	Infinity

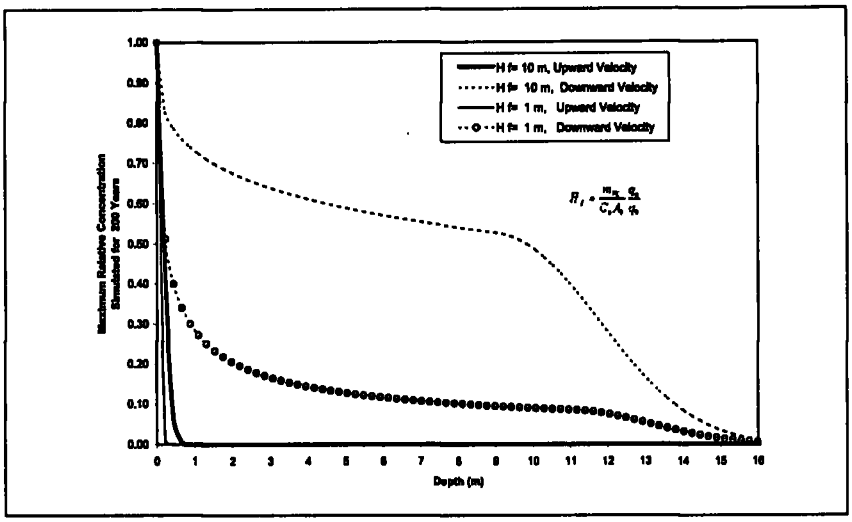

Figure 14 : Variation of Maximum Relative Concentration with Depth (For a Hydraulic Trap) Upward Darcy Velocity = 0.1 m/yr (Conservative Solute)

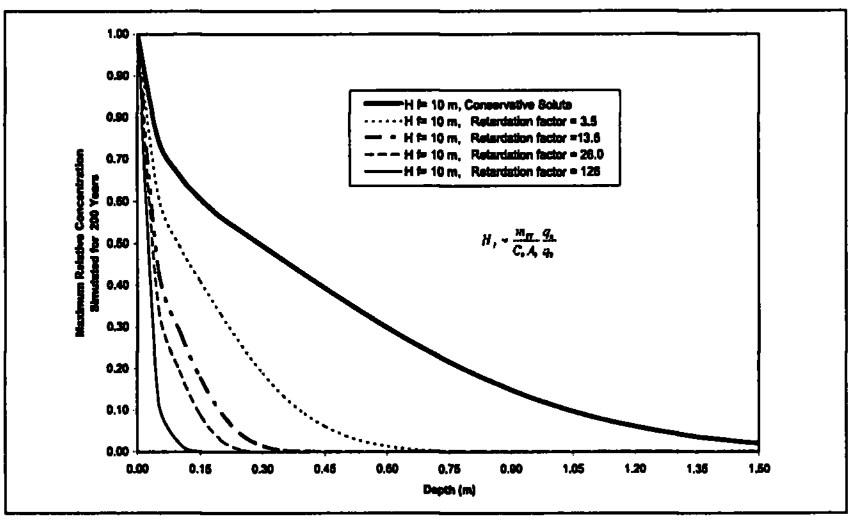

Figure 15 : Variation of Maximum Relative Concentration with Depth Darcy Velocity = 0.003 m/yr (Attenuation by Adsorption)

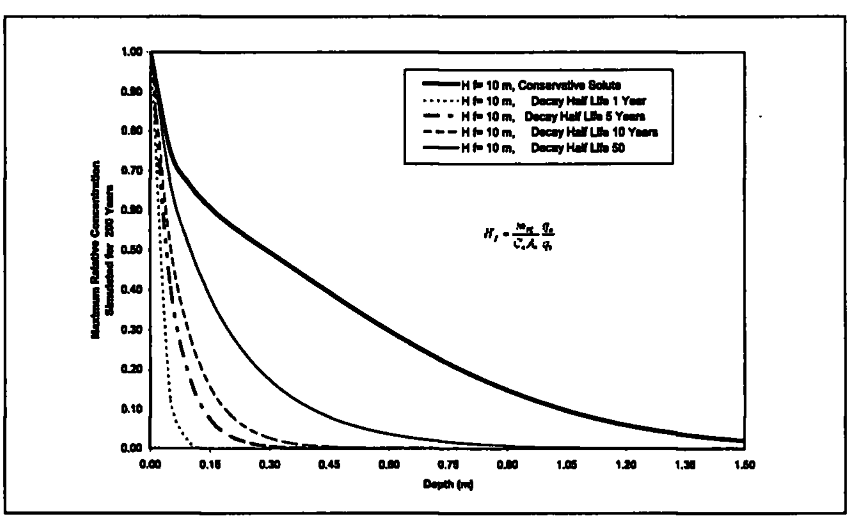

Figure 16 : Variation of Maximum Relative Concentration with Depth Darcy Velocity = 0.003 m/yr (Attenuation by Decay)

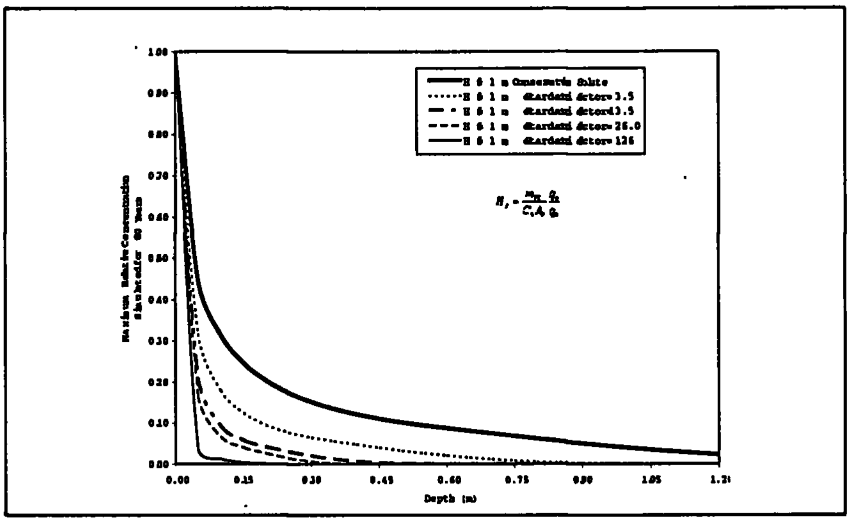

Figure 17 : Variation of Maximum Relative Concentration with Depth Darcy Velocity = 0.003 m/yr (Attenuation by Adsorption)

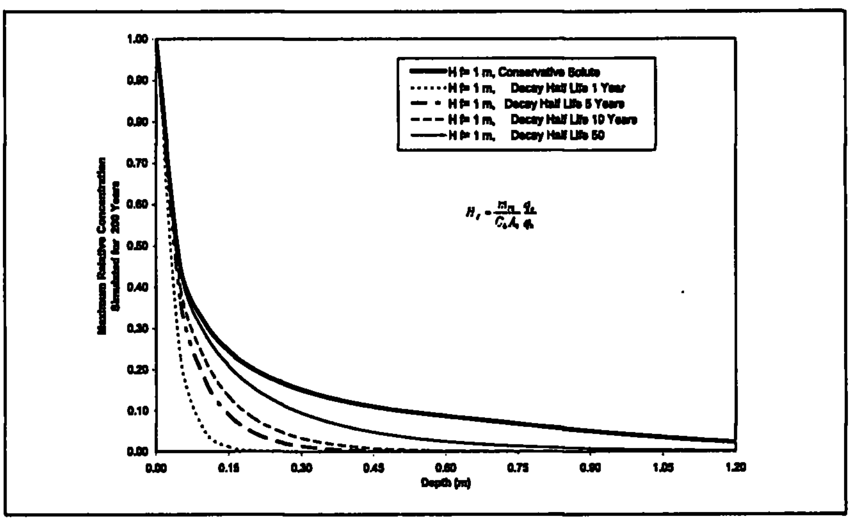

Figure 18 : Variation of Maximum Relative Concentration with Depth Darcy Velocity = 0.003 m/yr (Attenuation by Decay)

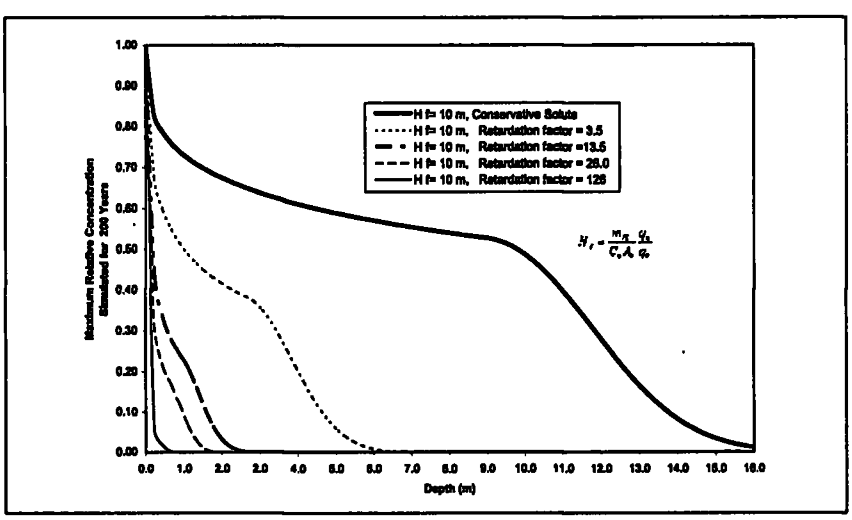

Figure 19 : Variation of Maximum Relative Concentration with Depth Darcy Velocity = 0.1 m/yr (Attenuation by Adsorption)

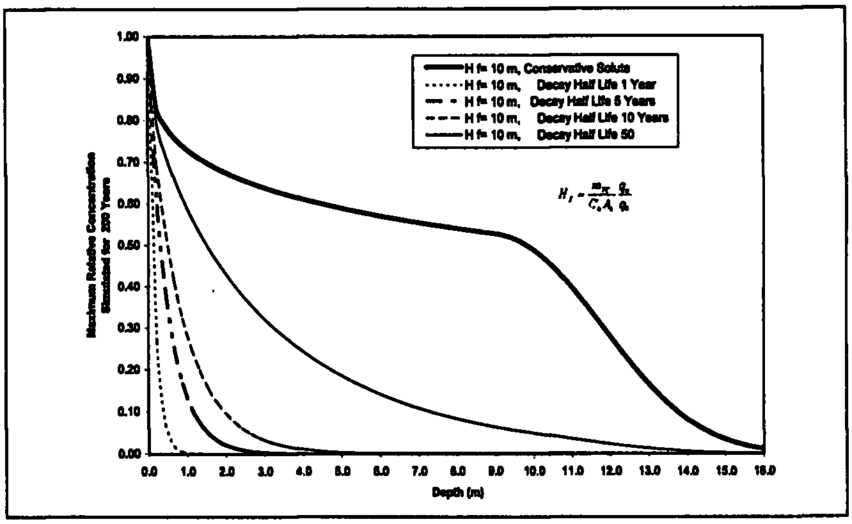

Figure 20 : Variation of Maximum Relative Concentration with Depth Darcy Velocity = 0.1 m/yr (Attenuation by Decay)

3. Results & Discussion:

3.1 Minimum Liner /Aquitard Thickness (Using Conservative Solute)

The range of Darcy velocity in municipal landfill has been found to be in the range of 0.003 to 0.03m/yr for compacted liners (Jayawardena & Mathur, 2000b). Similarly, in natural aquitard, the Darcy velocity is in the range of 0.03 to about 0.1m/yr (Munro et al., 1997).

On comparing Figures (7) and (8), one observes that there is hardly any variation in the respective design curves for velocities of 0.0003 and 0.003m/yr respectively. This implies that advection is not the primary transport mechanism at such low velocities and that solute transport takes place only on account of diffusion. This has also been observed by other researchers (Rowe and Booker, 1985, 1995) in the past.

The illustration in the Appendix (B) was extended to the range of Darcy velocities from 0.0003 to 0.1m/yr covering compacted clay liners to natural aquitards.

If the designer is intended to provide a primary leachate collection system, the following advantages exist. (Jayawardena & Mathur 2000b)

(a) Lowering the height of leachate mounding reduces seeps and consequently minimising the contamination of surface water.

(b) By reducing the leachate head acting on the base, the hydraulic gradient is reduced thereby reducing the seepage velocity of the water from the landfill.

(c) By removing the leachate from the landfill for treatment and disposal, the mass of contaminant available for transport into the hydro-geological system will be reduced.

(d) Avoid damage to the liner system.

Therefore, the introduction of leachate collection system reduces "Effective Leachate Height" by one tenth, since 90% of the leachate generated is taken out by the leachate collection system. For natural attenuation (without a leachate system) the designer should assume that entire leachate generated due to infiltration is available for migration. (Bagchi, 1994).

However, when a leachate collection system is provided at a landfill site, the value of the equivalent leachate height is small. For a case when the leachate height is equal to 1m (implying that 90% of the leachate is collected in the leachate collection system located at the bottom of the landfill), the amount of leachate that infiltrates the barrier is about 10% only.

In the illustration in the Appendix B, when equivalent leachate height is 1m and 10m respectively, which corresponds to the situation whether or not a primary leachate collection system is provided at the landfill site, the minimum (safe) barrier thickness required can be compared. The comparison is given in the Appendix B.

It has been reported that contamination migration can be reduced if the landfill is located in the discharging zone (Rowe, 1988). In such a case, the advective transport is through the barrier and into the landfill (flow in upward direction), and this in turn tends to reduce the downward movement of the contaminants on account of the concentration gradient. Such a system is also called a hydraulic trap where the flow is from the subsurface zone to the landfill through the barrier (inward flow). This situation is desired at times since it prevents any significant migration of the contaminant out of the barrier, however it does not necessarily imply that the migration stops completely when the flow direction is reversed.

A study was also conducted for a conservative substance to determine the effect of the advective transport in the upward direction.

It can be seen from the Monographs that as the velocity of flow in the upward direction increases, diffusion becomes a more predominant transport mechanism. However, when the flow is in the downward direction at such high velocities, dispersion is more important.

Also, at an upward flow velocity of 0.003m/yr (Figure 12) and a leachate height of 1m, there was hardly any variation in the two cases of upward and downward flow and there was a very marginal change when the leachate height was 10m. This is because since the Darcy velocity is very small, the effect of the dispersion is less compared to diffusion in the expression for hydrodynamic dispersion. Whether the flow is in the upward or downward direction the values of the maximum relative concentration at various depths for the two leachate heights is more or less the same implying that diffusion is the likely predominant transport mechanism.

Thus, when the advective flow is reversed (upward direction), the minimum barrier thickness can reduce drastically, but one has to resort to pumping out the groundwater that needs to flow in the upward direction through the barrier.

When the upward velocity is increased to a very high value (0.1 m/yr), the advection in the upward direction is so high that the impact of diffusion in the downward direction is negligible. Therefore the barrier thickness required is very small, however, this is not a practical situation since a large volume of water at a very high rate would have to be pumped out of the system. Moreover, in cases of engineered hydraulic traps, the base contours are sufficiently lowered thereby reducing the thickness of the natural barrier that separates the underlying aquifer and the waste.

3.2 Checking for Reactive Contaminants & Minimum Barrier Thickness.

The attenuation of a non- conservative solute is discussed in this section of the study for two cases of Darcy velocity and a leachate height of 10m.

At a low Darcy velocity (0.003m/yr) and for a product of partition coefficient and dry density ranging from 0 to 50 for most of the solutes found in municipal landfills (Rowe et al., 1995), the computed retardation factor assumes a value ranging between 1.0 and 126.0.

It is found that corresponding barrier thickness obtained from conservative solutes are safe for the entire range of retardation factors for a metal like zinc, where the maximum relative concentration is about 0.075 (assuming maximum zinc concentration in a typical landfill is 67 mg/l and the permissible value of zinc is 5 mg/l (Rowe et al.,1995).

One can determine the depth when the solute attained the required permissible concentration in the barrier and the respective depth is illustrated in the Appendix B.

An exercise was also conducted for a leachate height of 1m to study the impact of attenuation by decay and attenuation by adsorption for Darcy velocity of 0.003m/yr. Figures (17) and (18) illustrates the minimum thickness of the barrier for the non-conservative solute.

Similarly, first order decay of a non-conservative substance is considered at an equivalent leachate height of 10.0m for various values of half life ranging from 1 year to 50 years for two values of Darcy velocity (Figures 19 and 20). From these design curves the relevant depth of attenuation of a non-conservative solute can be determined.

From these figures it appears that there is very little change in the curves for cases where the half-life is 1, 5 and 10 yrs when the velocity of flow is 0.003m/yr and 0.1m/yr (low and large velocities respectively). However, as the half-life increases to about 50 yrs, the difference in the relevant depths of attenuation becomes quite obvious.

The lower boundary condition was taken as the zero concentration. The effects of the lower boundary conditions on design charts were investigated subsequently by changing the domain length and a thin aquifer boundary was introduced at various depths such as 10m, 5m and 3 m.

The parameters of the thin aquifer were taken as porosity 0.30; the Darcy velocity of the thin aquifer 1m/yr and the thickness is 2m. The length of the Landfill along the aquifer flow direction was taken as 200m.

Figure 21 shows that the variation of maximum relative concentration with depth has no effect with the thin aquifer boundary conditions located at various depths and the zero concentration boundary condition at a depth of 30.0m. Therefore introducing zero concentration at deeper depth and the thin aquifer boundary at lesser depths has no effect on the end results of the design charts.

4. Conclusions:

The main design parameters of the approach are Equivalent Leachate Height & the Darcy Velocity.

The Equivalent Leachate Height basically depends on the Population, the operational period of the landfill and the areal extent of the landfill. The monographs provide the wide range of leachate heights namely 0.1m, 0.5m, 1.0m 5.0m and 10.0m covering all possible cases such as small towns to metros and naturally attenuated landfill to engineering landfills.

By introducing a Primary Leachate collection system, the Design Equivalent Leachate Height can be reduced by one tenth.

The Darcy velocity of a natural aquitard or the liner can be obtained from the hydro geological investigations. However, for preliminary design purposes the typical higher values mentioned in this paper can be considered.

A hydraulic trap can be proposed by making upward ground water passage to minimise the barrier thickness. Although the costs of pumping and leachate treatment are considerably high; the active life span of the landfill will be reduced even after the closure of the operation.

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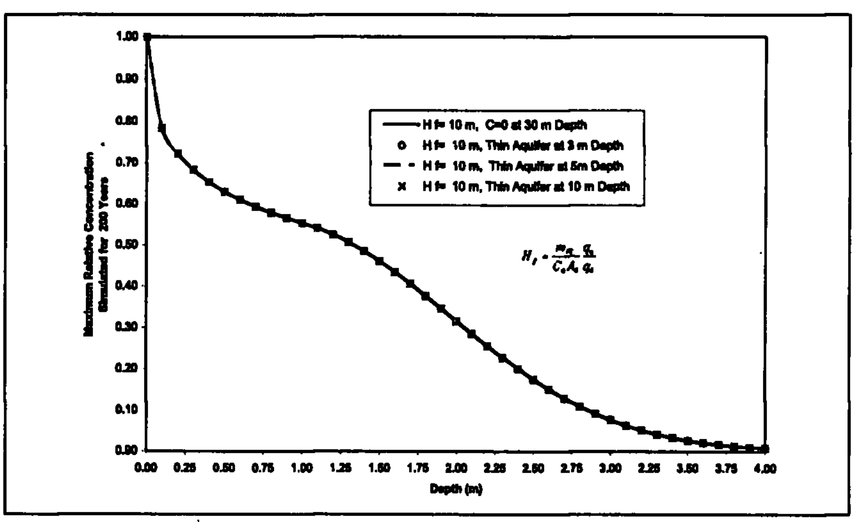

Figure 21 : Effect of the Bottom Boundary Condition on Variation of Maximum relative Concentration (Darcy Velocity = 0.03 m/yr Conservative Solute)

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