MODELING LEACHATE PRODUCTION FROM MUNICIPAL SOLID WASTE LANDFILLS

E. DEMIREKLER*, R.K. ROWE**AND K. UNLU***

** Environmental Engineering Department, Middle East Technical University, Ankara, 06531,Turkey*
***Department of Civil and Environmental Engineering, University of Western Ontario, Canada, N6A SB9*
**** Environmental Engineering Department, Middle East Technical University, Ankara, 06531,Turkey*

SUMMARY: A three dimensional mathematical model has been developed to estimate the quality and the quantity of the landfill leachate produced. The model takes the effects of changing hydraulic conductivity with overburden pressure and time dependent landfill development into consideration . This mathematical model allows the simulation of the moisture and contaminant distribution through the landfill, the leachate generation rate, the leachate composition in the leachate collection system, and the leachate mound formation during the landfill operation and after landfill closure. Due to space limitations, this paper will focus on results relating to the calculated variation in chloride concentration with time. The model is tested by comparing the calculated results with data from Keele Valley Landfill, Ontario, Canada. A sensitivity analysis is performed to illustrate the sensitivity of the mathematical model to different model parameters.

1. INTRODUCTION

Understanding the evolution of leachate in landfills is an important issue with respect to the potential impacts on environment, landfill stabilisation, and the design of leachate control, collection and recirculation systems. Mathematical models have been developed to simulate the generation and transport of leachate in landfills (Straub and Lynch, 1982; Korfiatis and Demetracopoulos, 1984; Demetracopoulos *et al.*, 1986; Blakey, 1989; Lu and Bai, 1991; Schroeder *et al.*, 1994; El-Fadel et al., 1997).These models have generally not considered two important factors. Firstly, they usually do not consider the effect of overburden stress on landfill hydraulic characteristics. Overburden pressure may make the lower refuse layers much less permeable to vertical water flow than upper layers and this may affect the leachate flow patterns and distribution of the moisture within the landfill; in turn influencing the composition of the leachate leaving the landfill. The second factor that has received attention in previous leachate models is the effect of the progressive development of landfills. Typically, models start the simulation after all the solid waste has been placed in the landfill. In

Proceedings Sardinia 99, Seventh International Waste Management and Landfill Symposium
S. Margherita di Pula, Cagliari, Italy; 4-8 October 1999 Vol. II, pp. 17-24.

reality, it may take many years to reach the final height of the landfill. Significant changes in moisture distribution and leachate quality may occur during this operational period.

The aim of this study is to develop a three dimensional mathematical model to estimate the moisture and leachate constituents distribution through the landfill, taking the effects of changing hydraulic conductivity with overburden pressure and time dependent landfill development into consideration.

2. MATHEMATICAL MODEL

The release rate of highly soluble elements from the solid waste can be described on the basis of a mechanism based on constant release rate since dissolution rates of these elements are independent of their concentrations in the leachate which are normally 10 to 100 times lower than their saturation concentrations. Therefore, the release of very soluble elements such as chlorides can be written as:

$$\frac{dS_s}{dt} = -k \tag{1}$$

where S_s is the mass of the constituent in solid phase at time t per unit bulk volume of waste (mg/l), k is the dissolution rate constant (1/d).

Assuming the flow through the refuse is due to gravity alone, the moisture flux out of each refuse layer was estimated as a function of the volumetric water content as:

$$q = K_{sat}\left(\frac{\theta}{\theta_{sat}}\right)^{m} \tag{2}$$

where K_{sat} is the saturated hydraulic conductivity of the solid waste (m/d), θ is the volumetric water content of the solid waste in the landfill, θ_{sat} is the saturated volumetric water content of the solid waste in the landfill, m is a dimensionless empirical constant related to the characteristics of the waste (Korfiatis and Demetracopoulos, 1984; Russo, 1988).

The moisture flux coming out of each refuse layer changes with depth and time since the hydraulic conductivity depends on the overburden pressure, which in turn is related to the depth and the water content of the waste. The change in the water content of each layer is calculated based on mass balance.

The effect of overburden pressure on the hydraulic properties of refuse (based on laboratory test results and field tests) have been reported in literature (Oweis *et al.*, 1990; Bleiker, 1992; Landva *et al.*, 1998). The results of these studies, presented in Figure 1, show that the hydraulic conductivity decreases with increasing overburden pressure. Table 1 shows that there is a strong correlation between the hydraulic conductivity and the vertical stress for the data summarized in Figure 1.

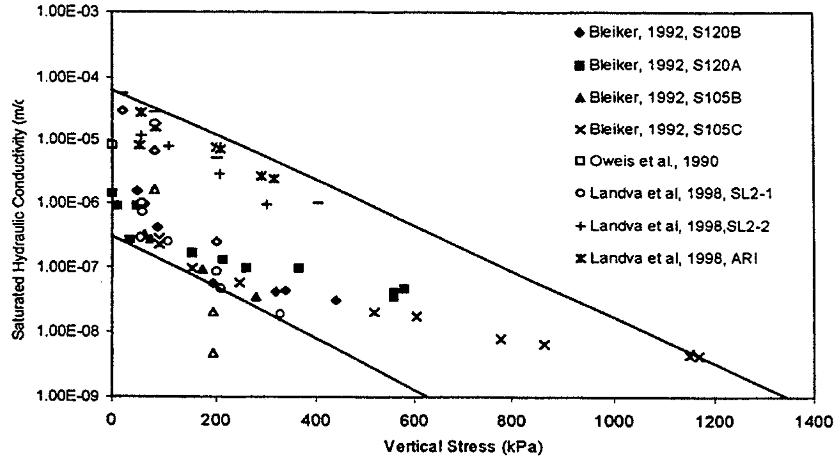

Figure 1. Relation between saturated hydraulic conductivity and effective stress

From Table 1, it is seen that the relation between the total vertical stress in the landfill and the hydraulic conductivity is in the form of

$$K_{sat} = \mathrm{a} \times \mathrm{e}^{-\mathrm{b} \times \mathrm{S}} \tag{3}$$

where K_{sat} is the hydraulic conductivity of the refuse, S is the total vertical stress in the landfill, and a and b are the constants. In Equation (3), the vertical stress, S, can be calculated based on the initial density of the waste, D_{sw}, volumetric water content of the waste, θ, and the depth below the surface of the landfill, H, as

$$S = 9.81 * H * (D_{sw} + \theta) \tag{4}$$

The change in the hydraulic conductivity through the landfill can then be estimated as a function of vertical stress.

Table 1. Relation between vertical stress and hydraulic conductivity in landfill

Sample	Relation between Vertical Stress (S) and Saturated Hydraulic Conductivity (K_{sat})	Number of Samples	R^2
Landva *et al.*, 1998, Edmonton	6×10^{-4} exp(-0.0445 S)	2	1
Landva *et al.*, 1998, Kingston	5×10^{-5} exp(-0.0265 S)	3	1.000
Bleiker, 1992, S105B	6×10^{-7} exp(-0.0103 S)	4	0.997
Landva *et al.*, 1998, SL-2	2×10^{-5} exp(-0.0103 S)	4	0.994
Ottawa, old fill	6×10^{-5} exp(-0.0105 S)	4	0.983
Landva *et al.*, 1998, Edmonton	6×10^{-5} exp(-0.0454 S)	3	0.943
Bleiker, 1992, S105C	2×10^{-7} exp(-0.0035 S)	11	0.930
Landva *et al.*, 1998, SL2-1	1×10^{-6} exp(-0.0133S)	6	0.904
Bleiker, 1992, S120B	1×10^{-6} exp(-0.0099 S)	7	0.848
Bleiker, 1992, S120A	7×10^{-7} exp(-0.0053 S)	11	0.845
Landva *et al.*, 1998, ARI	3×10^{-5} exp(-0.0072 S)	7	0.796
Oweis *et al.* 1990	-	1	-

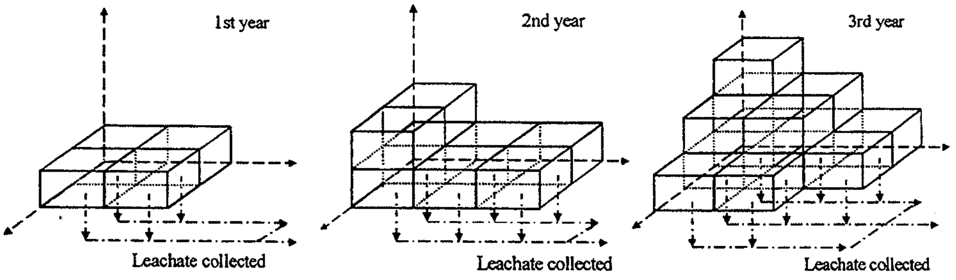

Figure 2. Time dependent development of the landfill

To account for the changes occurring during the development stage of the landfills, the model considers the landfill to consist of cells that are constructed progressively with time. Each time step represents the period of time after which a new lift or cell is finished. At the end of each time step, the new lift or cell is introduced into the system. In this way, the three dimensional development of the landfill is simulated (Figure 2). A cascade model is used in which each cell is separated into layers. Each layer is assumed to be a completely mixed reactor containing uniformly distributed solid waste, moisture, gases and microorganisms. The use of cascade model enables the incorporation of the changes in the hydraulic properties of the landfill into the model and also makes it possible to model the spatial distribution of contaminants.

Using this mathematical model it is possible to simulate the moisture and contaminant distribution through the landfill, the leachate generation rate, leachate composition in the leachate collection system, and the leachate mound formation during the landfill operation and after landfill closure.

3. MODEL CALIBRATION

The parameters of the model must be estimated for the specific landfill situation. Some of the parameters can be taken from the literature or measured in specific tests. However, it is not always possible to obtain these data. In such cases these parameters must be established by calibration. For this model, the parameters, particularly those concerning the flow through refuse and pollutant release (constants, m, k, a, and b, saturated moisture content, θ_{sat}, initial moisture content, θ_O, and initial pollutant concentration, C_O) are established by a calibration procedure. For this purpose, a modified version of the computer program NONLIN (Environmental Systems & Technologies, Inc., 1989) developed for nonlinear least-squares analysis was used.

NONLIN estimates the unknown model parameters by solving the non-linear least squares problem

$$\min_{u} \Phi(u) = \sum_{i=1}^{N} \left\{ q_i(t) - \tilde{q}_i(t:u) \right\}^2 \qquad (5)$$

where q_i are observed landfill leachate chloride concentrations, and $\tilde{q}_i$ are the corresponding model predicted concentrations for a given parameter vector u, where u = (m, k, a, b, θ_{sat}, θ_O, C_O). Equation (5) is solved by adjusting the parameters until the residual sum of squares, Φ, is minimized.

Table 2. Correlation matrix for the model parameters

	m	k	a	b	θ_{sat}	θ_0	C_0
m	1.0000						
k	.9406	1.0000					
a	-.8404	-.8934	1.0000				
b	-.1603	-.2374	.5306	1.0000			
θ_{sat}	-.9312	-.8910	.9321	.2657	1.0000		
θ_0	.9519	.9755	-.9480	-.3685	-.9344	1.0000	
C_0	.8158	.7153	-.7801	-.2320	-.8431	.8170	1.0000

The model was calibrated using chloride data from the Keele Valley Landfill, Ontario, Canada. The Keele Valley Landfill covers an area of 99 hectares. The landfill has a design capacity of 33,000,000 m^3 and has been developed in four stages, with Stage 1 starting operation in 1983. At the present time, the landfill is still under operation and Stage 4 is being developed.

The landfill development sequence (refuse tipping locations and amount of refuse tipped each year) was estimated based on the staging plan. The density of the refuse was known from the previously conducted tests (Bleiker, 1992). The leachate chloride concentrations for the years between 1983 and 1997 was monitored and chloride data for 1983-1993 was used for the calibration procedure. The model results obtained by using calibrated model parameter values are given in Figure 3. The coefficient of determination, R^2, between the fitted data and the real landfill data is 0.843 for this plot indicating a good fit between the calibrated model results and the measured data.

The correlation coefficients given in Table 2 shows the degree of correlation between parameters. The high correlation coefficients indicate high linear dependency between parameters, and as the dependency increase it becomes more difficult to estimate both parameters simultaneously, therefore, it may be necessary to measure at least one of these parameters. From Table 2, it is seen that for the calibrated parameter values, there is a high correlation between most of the parameters. More reliable results can be obtained by measuring some of these parameters and using the measured values of these parameters in the model.

4. RESULTS AND DISCUSSION

For the validating the model, estimation of the temporal and spatial change in the chloride concentration through Keele Valley Landfill for the years 1993-1997 was used. Figure 3 shows the comparison of the calculated chloride concentrations with the real landfill data for this period. The agreement is generally quite good.

A sensitivity analysis was performed to illustrate the sensitivity of the mathematical model to different model parameters. Figure 4 and Figure 5 shows the results of the sensitivity analysis for time step, layer height, and the model parameters m, chloride dissolution rate constant, k, a, b, saturated moisture content, θ_{sat}, initial moisture content, θ_0, moisture influx into landfill, q, and density of refuse, D_{sw}.

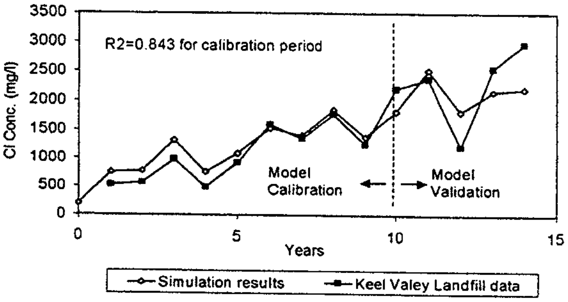

Figure 3. Model results obtained from the calibration and validation procedures and comparison of the model results with real landfill data

The model assumes the landfill to be consisted of layers. Figure 4 shows the sensitivity of the model to layer height, delh. It is seen that the model is not sensitive to the layer heights upto 1.0 m whereas increasing delh to 2.0 meters changed the model results and lower chloride concentrations were obtained. When different time steps between 1 day and 52 days were used in the model, the model results do not change (Fig. 4(b)).

Figure 5 shows the effects of changing the model parameters on the chloride concentration in the landfill leachate. When all the model parameters were considered, it was seen that the model was most sensitive to the chloride dissolution rate constant, k (Figure 5(a)) and the initial moisture content, θ_0 (Figure 5(g)). The chloride concentrations in the leachate was highly dependent on the value of k since k is the most important parameter affecting chloride release rate from the refuse. It is seen from Figure 5 that changing the values of m, a, and θ_{sat} together with θ_0 caused changes in the degree of the fluctuations in chloride concentrations. These parameters affected the moisture flowrates through the refuse and increasing the moisture flowrates resulted in increased fluctuations in chloride concentrations. Among these four parameters, θ_0 was observed as the most important parameter affecting the moisture flowrate since for low moisture contents, the moisture flowrate would be expected to be very low as most of the water would be held by the refuse. It is seen from Figure 5(g) that for an initial moisture content of 0.15, the fluctuations in chloride concentration were much less than for those of higher initial moisture contents. Changing the m value influenced the moisture flow more than changing a and θ_{sat} values, therefore, the model was more sensitive to changes in m values than those in a and θ_{sat} values. The sensitivity analysis results show that the model was not very sensitive to the initial chloride concentration in leachate, C_0 (Figure 5(b)) and almost insensitive to the refuse density, D_{sw} (Figure 5(i)).

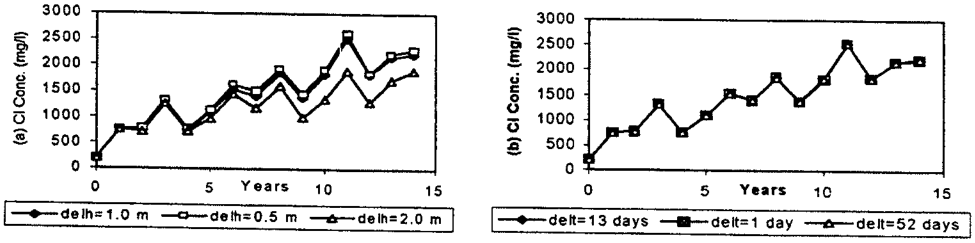

Figure 4. Sensitivity analysis for (a) layer height (b) time step

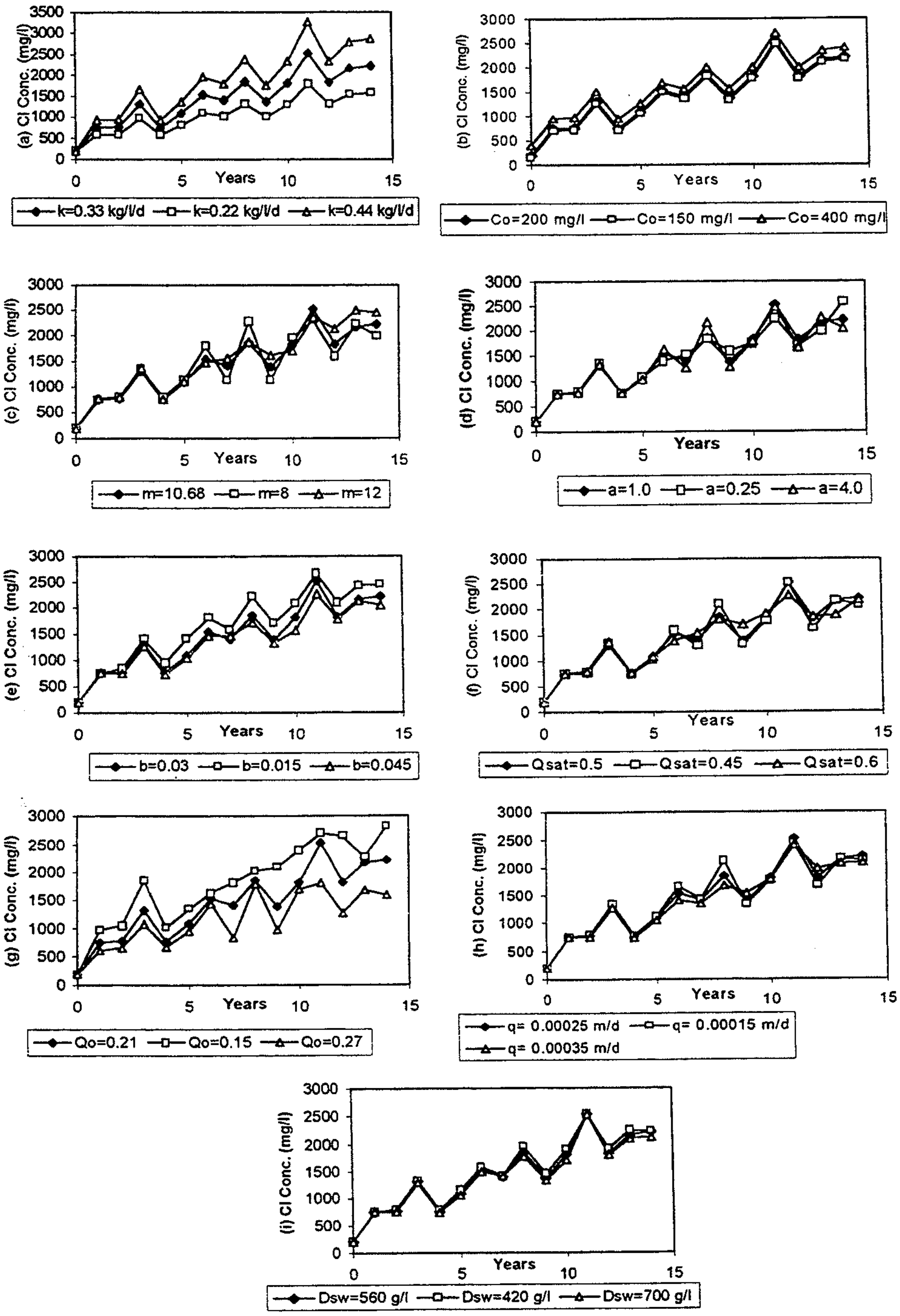

Figure 5. Sensitivity analysis results (a) dissolution constant, k, (b) initial chloride concentration in landfill leachate, C_0, (c) m, (d) a, (e) b, (f) saturated moisture content, θ_{sat}, (g) initial moisture content, θ_0, (h) moisture influx into landfill, q, (i) density of refuse, D_{sw}

5. CONCLUSION

Based on the available evidence, it is concluded that:

- The proposed mathematical model provided encouraging agreement with observed chloride concentrations at the Keele Valley Landfill.
- Overburden pressure and time dependent landfill development are important factors affecting the leachate quality, since they influence the moisture content and moisture flow in the landfill.
- The fluctuations in chloride concentrations of landfill leachate through time can be explained by the changing hydraulic conditions during the operational period of the landfill.
- The model results show that the chloride concentration in landfill leachate is highly sensitive to the chloride dissolution rate constant and initial moisture content.
- Further studies are necessary in order to estimate the fate of the organic pollutants in the landfill leachate.

ACKNOWLEDGEMENTS

The authors are grateful to the Scientific and Technical Research Council of Turkey for their financial support.

REFERENCES

Blakey, N.C., (1989), Predicting landfill leachate production and use of a computer model, Proceedings of Sardinia'89-Second International Landfill Symposium, Cagliari, Italy, 25(1-15).

Bleiker, E., (1992), Landfill performance: Leachate quality prediction and settlement implications, M.Sc. Thesis, University of Waterloo, Ontario, Canada.

Demetracopoulos, A.C., Sehayek, L., Erdoğan, H., (1986), Modeling leachate production from landfills, Journal of Environmental Engineering, 112(5), 849-866.

El-Fadel M., Findikakis A.N., Leckie J.O., (1997), Modeling leachate generation and transport in solid waste landfills, Environmental Technology, 18, 669-686.

Korfiatis, G.P., Demetracopoulos, A.C., (1984), Moisture transport in a solid waste column, Journal of Environmental Engineering, 110(4), 780-795.

Landva, A.O., Pelkey, S.G., Valsangkar, A.J., (1998), Coefficient of permeability of municipal refuse, Environmental Geotechniques, Balkema, Rotterdam, Vol. 1, pp. 63-68.

Lu, C., Bai, H., (1991), Leaching from solid waste landfills, Part I: Modeling, Environmental Technology, 12, 545-558.

Oweis, I.S., Smith, D.A., Ellwood, R.B., Green, D.S., (1990), Hydraulic characteristics of municipal refuse, Journal of Geotechnical Engineering, ASCE, 116(4), 536-553.

Russo, D., (1988), Determining soil hydraulic properties by parameter estimation: On the selection of a model for the hydraulic properties, Water Resources Research, 24(3), 453-459.

Schroeder, P.R., Lloyd, C., Zappi, P., Aziz, N., The Hydrologic Evaluation of Landfill Performance (HELP) Model, User's Guide for Version 3, US EPA Office of Research and Development, Washington DC, EPA/600/R-94/168a, September 1994.

Straub, W.A., Lynch, D.R., (1982(a)), Models of landfill leaching: Moisture flow and inorganic strength, Journal of Environmental Engineering, ASCE, 108, EE2, 231-250.

User's Guide to NONLIN: A program for non-linear least squares analysis of tracer breakthrough data, Version 1, Environmental Systems & Technologies, Inc., Blacksburg, USA, 1989.