Robert M. Quigley[1] *and R. Kerry Rowe*[1]

Leachate Migration Through Clay Below a Domestic Waste Landfill, Sarnia, Ontario, Canada: Chemical Interpretation and Modelling Philosophies

REFERENCE: Quigley, R. M. and Rowe, R. K., **"Leachate Migration Through Clay Below a Domestic Waste Landfill, Sarnia, Ontario, Canada: Chemical Interpretation and Modelling Philosophies,"** *Hazardous and Industrial Solid Waste Testing and Disposal: Sixth Volume, ASTM STP 933*, D. Lorenzen, R. A. Conway, L. P. Jackson, A. Hamza, C. L. Perket, and W. J. Lacy, Eds., American Society for Testing and Materials, Philadelphia, 1986, pp. 93-103.

ABSTRACT: The results of field and laboratory investigations of a domestic waste landfill overlying 30 m of natural clay are presented. Four study phases extending over a ten-year period will be summarized.

Concentration profiles for several soluble constituents (sodium, potassium, calcium, magnesium, Cl^- and dissolved organic carbon) show migration to a maximum depth of ~1.5 m in 15 years. This compares to an advective or seepage advance estimated to be only 3 to 5 cm, indicating migration primarily by diffusion. Concentration profiles for the heavy metals (iron, lead, zinc, and copper) indicate rapid field attenuation with migration to only 10 cm in the carbonate-rich clayey soil.

Graphed solutions to the coupled advection/diffusion equation using constant values for C_o, D, and V_s are only partially successful in predicting the observed chemical profiles because of apparent chemical partitioning at the waste/clay interface. A better fit is obtained by employing an artificial "effective" interface about 25 cm above the observed interface; however, this does not resolve the interface problems.

Recently, new analytical and numerical procedures have been developed for modelling this and other contaminant migration problems. These techniques automatically take into account time-dependent concentration variations within the landfill (for example, because of mass transport into the soil) and allow for a sharp drop in concentration because of surface effects (such as surface smear, drying, and interface partitioning). The numerical solution allows consideration of the effects of a thin but finite interface layer with properties different from those of the underlying soil. Both of these techniques are used in the field case resulting in much superior predictions than earlier models.

[1]Professors of geotechnical engineering, Geotechnical Research Centre, Faculty of Engineering Science, The University of Western Ontario, London, Ontario, Canada N6A 5B9.

Comments are presented on the significance of this work relative to chemical fluxes through thin clay liners.

KEY WORDS: wastes, diffusion, domestic waste leachate, chemical profiles, modelling, clay barriers

Clay barriers, natural or compacted, are a frequently used method of successfully retarding the migration of chemicals from waste disposal sites. The quantity of chemicals (chemical fluxes) exiting from such liners may be kept very small if advective flow is very slow and chemical diffusion is the main transport mechanism.

The purpose of this paper is to present actual field chemical profiles for a variety of dissolved chemical species migrating primarily by diffusion through thick natural clay deposits below a 15-year old domestic waste landfill and to model these profiles. Typical methods used to estimate the time-rate of migration are discussed. These are followed by a new method to handle waste-clay interface effects (partitioning at the interface) and variable input concentrations (reflecting changes in the leachate). These are followed by examples of chemical flux calculations through thin clay liners to illustrate the significance of correctly modelling the migration profiles.

Site Geology and Soil Conditions

The present soil conditions at the landfill site are illustrated on Fig. 1. Approximately 7.5 m of domestic solid waste, with a 0.5 m clay cover, overlies a homogeneous, massive grey silty clay. The waste projects about 2 m above the surrounding ground surface and was placed in a borrow trench excavated about 5.5 m into the original clay.

The calculated effective stresses shown on Fig. 1 incorporate the effects of a slight downward gradient ($i = \Delta h_t/\Delta L = 0.25$) generated by a small groundwater mound in the waste and drainage into bedrock at ~30 m depth. The variability of this gradient with time and depth is discussed extensively by Goodall and Quigley [*1*]. From extensive laboratory and field measurements of hydraulic conductivity, the average linearized downward pore fluid velocity is believed to be about 0.24 cm/annum [*1*].

The soil in the 3-m zone directly below the waste contains ~34% carbonate, ~25% illite, ~24% chlorite, ~15% quartz and feldspar, and ~2% smectite. About 40 to 45% of the soil is <2 μm in size, and the cation exchange capacity of the <74-μm fraction is ~15 meq/100 g [*2,3*].

The in-situ vertical effective stress plots σ_v' on Fig. 1 show that the clays are overconsolidated by about 90 kPa with a slight increase near the interface. This overconsolidation results in water content values w_n of about 23%, which are mid-way between plastic limits w_p, averaging 11% and liquid limits w_L averaging 32%. In most of our water content profiles there is indication of

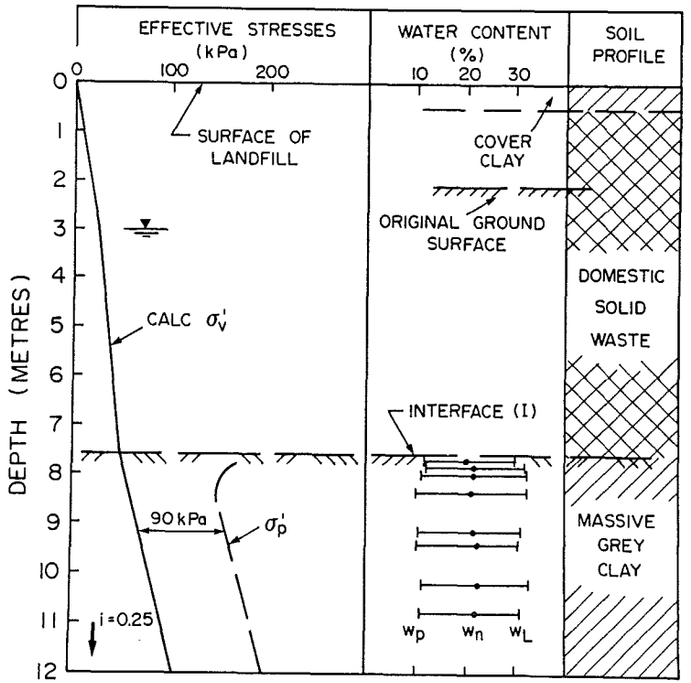

FIG. 1—*Soil conditions at Confederation Road landfill site, 1967 to present (σ_v') = vertical effective stress; σ_p' = preconsolidation pressure; w_p = plastic limit; w_n = natural water content; and w_L = liquid limit).*

a water content reduction of 2 or 3% very near the interface as discussed later.

Visually the clay at the interface is a homogeneous grey clay with scattered pebbles and no evidence of staining by the presently overlying black organic sludges. The particulates forming the sludge are generally not identifiable after 15 years and seem to have collected in a firm mat 0.2 to 0.5 m thick. Also, no fissures have ever been encountered in tube samples of the clay even though the base of the landfill probably did not quite penetrate to the bottom of the preconsolidated desiccation crust that exists around the site.

The nature of this crust is further illustrated on Fig. 2 by the preconsolidation versus depth profile drawn from a combination of oedometer measurements and in-situ vane strength results. The upper, 4-m-thick portion of the crust, which has been completely removed at the site, was a stiff to hard, brown oxidized, and fissured clay. The lower portion of the crust was a grey clay about 2.5 m thick with widely spaced brown fissures in the upper 1.5 m.

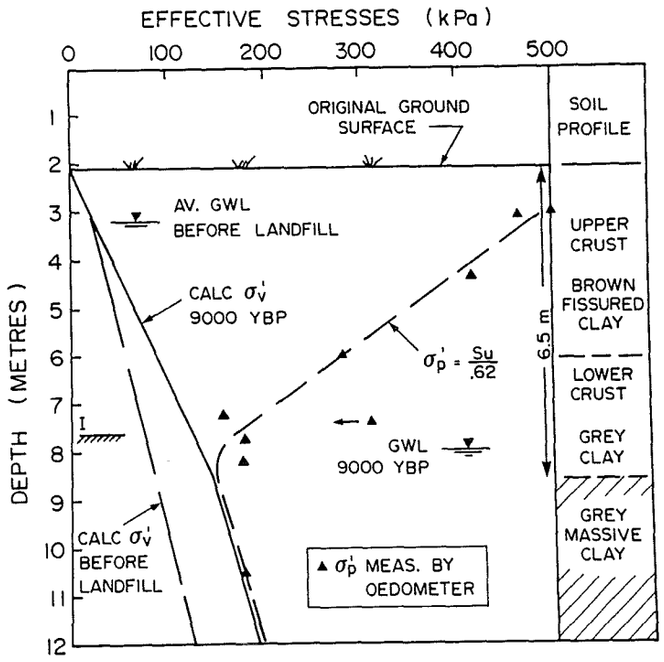

FIG. 2—*Soil conditions 9000 years before present (YBP) and before cutting landfill trench in 1966 (1 is waste/clay interface; S_u = undrained shear strength, GWL = ground-water level; see also the legend on Fig. 1).*

All but 1 m of the crust is believed to have been excavated as shown by the figure. A persistent slight decrease in water content of the clays near the interface would in part be due to the effects of the crust.

Chemical Profiles

The range in chemical concentration of Na^+ and $C\ell^-$ in the clay below the waste is presented in Fig. 3 in milligrams per litre of pore fluid. The data indicate overall migration of up to 1.5 m with the erroneous visual impression that $C\ell^-$ is in advance of Na^+. If the same data are plotted in more useful "ground-water" units of mol/m^3, however, the rates of migration of Na^+ and $C\ell^-$ look quite similar (Fig. 4). Since advective transport is believed to have advanced only ~3 cm [2], the mechanism of transport must be chemical diffusion from the waste.

The width of the concentration versus depth zones is related to a combination of factors, the most important being scatter in the chemical data associated with sample contamination during tube sampling and a wide variation in

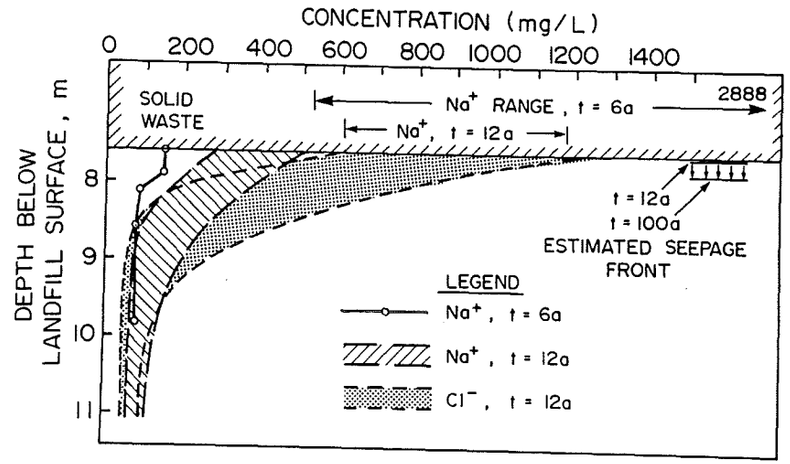

FIG. 3—*Pore fluid concentration of Na^+ and $C\ell^-$ (mg/L) in clay below waste after 6 and 12 years of diffusion* (t = 6a *and* 12a) [2].

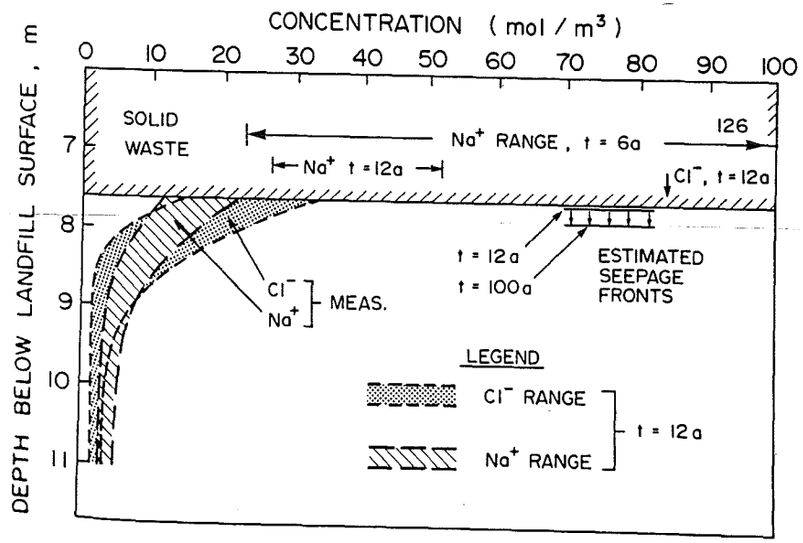

FIG. 4—*Pore fluid concentration of Na^+ and $C\ell^-$ (mol/m³) in clay below waste at* t = 12 years (t = 12a) [2].

concentration of Na^+ and $C\ell^-$ in the waste from one original dumping spot to another.

Profiles illustrating heavy metal migration are summarized on Fig. 5*a*, which shows total concentrations for copper, lead, zinc, and iron. All of the profiles suggest migration of mobile species to only 10 or 15 cm below the interface, beyond which they stay at background levels. The lead and copper profiles are nearly identical with interface values of ~100 μg/g, zinc values at 150 μg/g, and iron values at 40 000 μg/g. Close examination of the interface showed no discoloration in the "metal" migration zone within which *Eh* values of −300 mV indicated strongly reducing conditions. Selective dissolution techniques presently in progress suggest that the migrated metals exist as a complex assemblage of carbonates, hydroxides, and organics.

A final profile for dissolved organic carbon is shown on Fig. 5*b*. In this case migration of the dissolved (< 0.45 μm) organic carbon-based compounds appears to have advanced about 1.1 m with maximum values of ~40 mol/m³ near the interface.

Prediction

Early attempts at prediction were carried out without knowing that the clay in the region of the interface was probably less "transmissible" than the clays

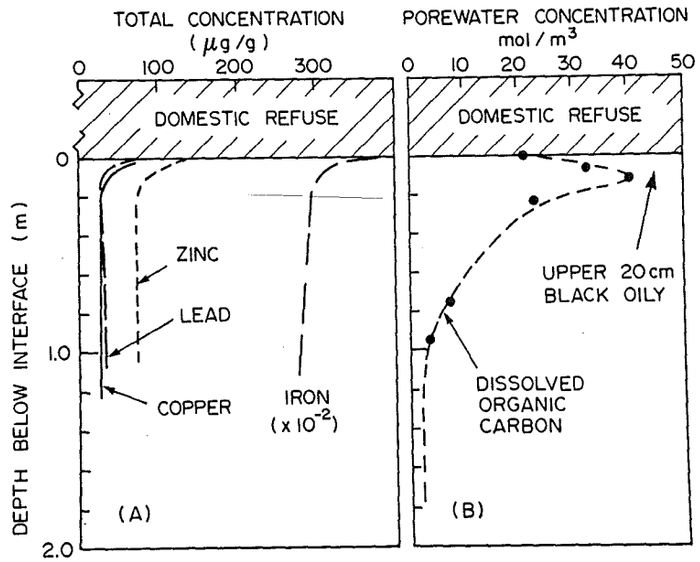

FIG. 5—(a) *Total concentration of heavy metals and* (b) *concentration of dissolved organic carbon* [3].

a metre lower caused by the remaining remnant of the crust and the possibility of partial void plugging by bacteria or precipitated metals. The earliest predictions at $t = 6$ annum [*1*] used an error function technique and ignored the effects of advection. Later predictions [*2*] employed the graphical solution to the one-dimensional contaminant transport equation for coupled diffusion and advection presented by Ogata [*4*]. These predictions assume constant values for influent concentration C_o, diffusion coefficient D, average linearized seepage velocity V_s, and an infinite clay thickness below the waste. Predictions for Na^+ and $C\ell^-$ are plotted on Fig. 6 for $t = 12$ years ($t = 12a$). Input parameters were as shown in Table 1. Although the calculations gave reasonable estimates for the depth of migration, the measured concentrations were well below those predicted in the upper 0.5 m of clay suggesting either very pronounced partitioning at the interface or an "effective interface" above the clay-waste interface observed in the field.

Since the black solid waste sludge seemed to be packed rather firmly against the clay, the next prediction attempt involved shifting the "effective" chemical interface 25 cm above the observed interface and the predictions repeated as shown on Fig. 7 [*3*]. Using $C_o = 86$ mol/m³, the erratic values

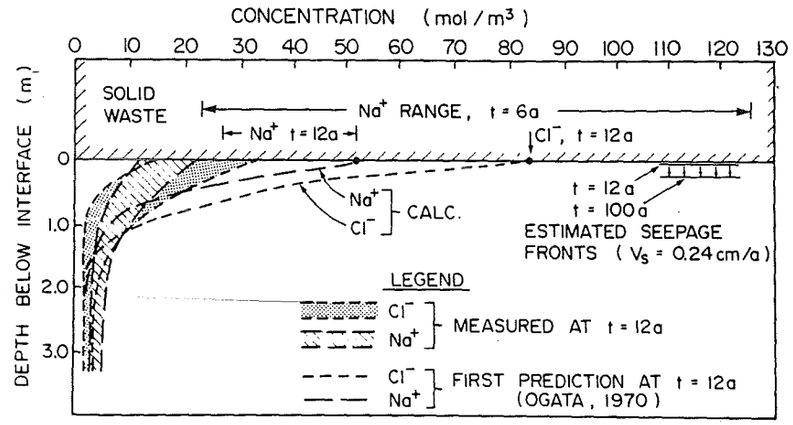

FIG. 6—*Predicted* Na^+ and $C\ell^-$ *profiles using constant values for* C_o, D, *and* V_s [4].

TABLE 1—*Input parameters.*

Na^+	$C\ell^-$
$C_o = 51$ mol/m³	$C_o = 84$ mol/m³
$D = 3.5 \times 10^{-6}$ cm²/s	$D = 6 \times 10^{-6}$ cm²/s
$V_s = 0.24$ cm/*a*	$V_s = 0.24$ cm/*a*

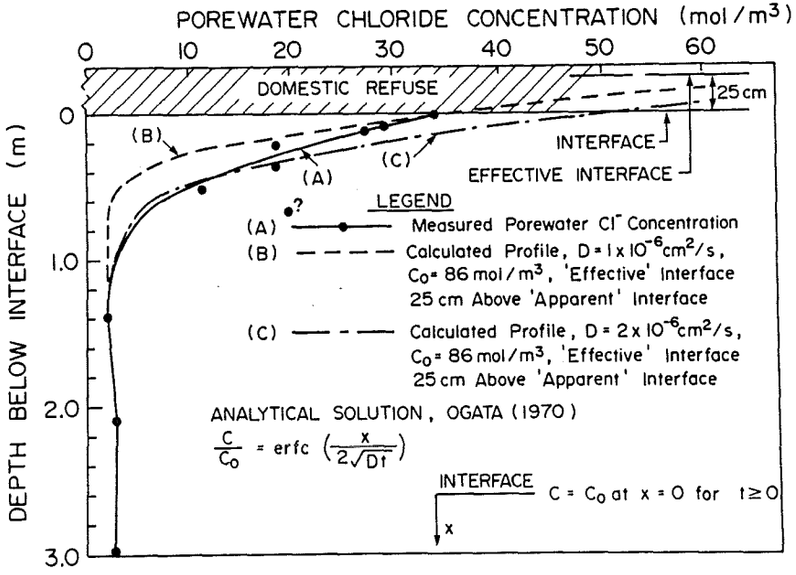

FIG. 7—*Predicted Cl^- profile using "effective" interface 25 cm above observed interface (borehole 83-2, t = 15a).*

plotted for the measured chloride profile (A) could be encased reasonably well by two predicted profiles (B) and (C) using values for $D = 1 \times 10^{-6}$ and 2×10^{-6} cm²/s, respectively. These calculations suggest that the sludge mat could indeed have a thickness within the visually estimated range of 0.2 to 0.5 m. As in all of our work to date, there continued to be considerable scatter in our measured values.

A third prediction approach was carried out using computer program, POLLUTE, proposed by Rowe and Booker [5]. This technique permits consideration of a thin interface layer (of thickness H_I) with a diffusion coefficient D_I considerably less than that in the rest of the soil. This technique also allows consideration of the variation of source concentration with time (caused by mass transport into the clay) as well as horizontal flow in an aquifer beneath the clay liner (if present). Calculations were performed varying the ratio D_I/H_I and the dispersion coefficient in the clay to obtain a fit with the data at BH 102 at the Sarnia site after twelve years [6]. The best fit was obtained for $D_I/H_I = 0.02$ m/a and $D = 0.018$ m²/a (5.7×10^{-6} cm²/s) as shown in Fig. 8. These parameters were then used to predict the concentration profile at BH 101, and the resulting predictions, also shown in Fig. 8, are in very good agreement with the observed concentration profile. The value of

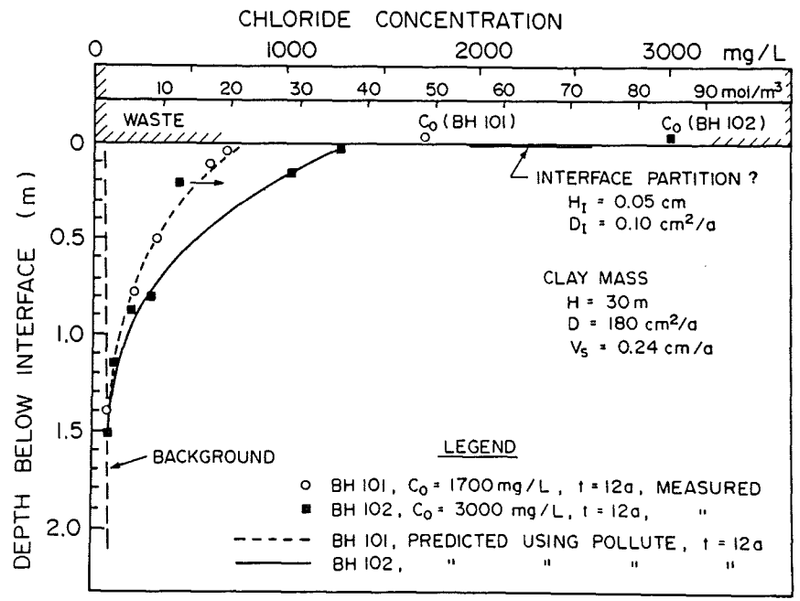

FIG. 8—*Predicted chloride profiles for Boreholes 101 and 102, using POLLUTE* [2,6].

D determined for the main body of the clay is quite consistent with what would be expected in the absence of these data and is, in fact, quite close to the value adopted in the initial attempts to predict the profile shown in Fig. 6.

It is of some interest to note that the precise thickness of the interface layer H_I is not a critical quantity. Essentially, the same concentration profile is obtained for a range of values of H_I provided that the ratio D_I/H_I remains constant (typical values used were $H_I = 0.01$ m and $D_I = 0.0002$ m²/a).

Discussion

It is clear that a reasonable modelling of the concentration profiles at the Sarnia site requires consideration of some form of interface. However, it can also be seen that the backfigured diffusion coefficient of the clay may vary substantially depending upon the assumptions that are made concerning the interface. This may have a substantial effect on the fluxes predicted at any particular time.

Since the chemical diffusion flux F exiting from the base of a liner is directly related to the concentration gradient, $\partial c/\partial x$ at the interface ($F =$

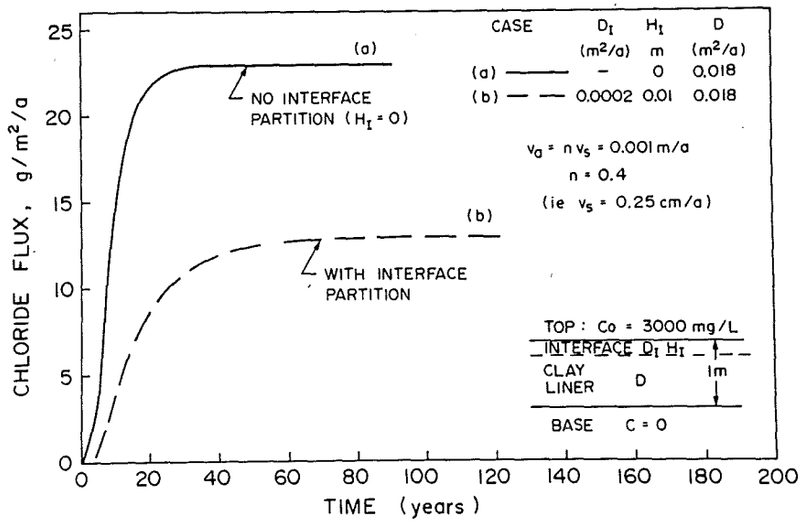

FIG. 9—*Chloride flux-time plots for a 1-m-thick liner:* (a) *no interface partition and* (b) *with interface partition.*

$D\,[\partial c/\partial x]$), it is important to obtain a correct value. From the previous discussion, predictions of $\partial c/\partial x$ using POLLUTE [7] and a thin interface partition yield lower, more correct values than the simpler Ogata predictions. The significance of this relative to predicted fluxes of chloride through a 1-m-thick clay liner is illustrated on Fig. 9. For these calculations, it was assumed that the influent concentration was constant at C_o = 3000 mg/L, and the base concentration was zero because of a high horizontal flushing velocity in an underlying aquifer. For the case of no interface partitioning, an ultimate chloride flux of 23 g/m^2/a is calculated. For the possible case of a thin interface, an ultimate chloride flux of 13 g/m^2/a is calculated. This represents a large difference that could be very significant is satisfying environmental conditions for a proposed landfill facility.

Finally, for purposes of design, it is generally conservative to neglect the presence of an interface when calculating concentration profiles and fluxes. However, the results presented here show that particular care should be exercised when backfiguring parameters from field data for situations where an interface effect may be present. It also appears that considerable attention must still be given to the effect of a mat of organic particulates that may settle or deposit on top of a clay barrier.

Conclusions

Using measured field values of sodium and chloride concentration profiles in clay below a domestic waste landfill site, a series of modelling efforts were made resulting in the following conclusions:

1. A chemical partition may occur at the waste-clay interface at some sites resulting in an abrupt drop in concentration in the upper 10 mm of clay compared to values in the waste leachate.
2. A new program, POLLUTE, may be used to model both the interface effects and any reduction in leachate concentration caused by migration into the barrier clays.
3. A proper chemical profile (concentration gradient) is required for calculation of chemical flux through clay barriers. In the absence of field data, computer program, POLLUTE, may be very useful for predicting these gradients.

Acknowledgments

This work was financed by Strategic Grant funds from the Natural Sciences and Engineering Research Council of Canada.

References

[1] Goodall, D. C. and Quigley, R. M., "Pollutant Migration from Two Sanitary Landfill Sites near Sarnia, Ontario," *Canadian Geotechnical Journal*, Vol. 14, No. 2, 1977, pp. 223–236.

[2] Crooks, V. E. and Quigley, R. M., "Saline Leachate Migration Through Clay: A Comparative Laboratory and Field Investigation," *Canadian Geotechnical Journal*, Vol. 21, No. 2, 1984, pp. 349–362.

[3] Quigley, R. M., Crooks, V. E., and Yanful, E., "Contaminant Migration Through Clay Below a Domestic Waste Landfill Site, Sarnia, Ontario, Canada," *Proceedings International Symposium on Groundwater Resources Utilization and Contaminant Hydrogeology*, Public Atomic Energy of Canada, Ltd., Pinawa, Manatoba, Canada, Vol. II, 1984, pp. 499–506.

[4] Ogata, A., "Theory of Dispersion in a Granular Medium," Professional Paper 411-1, U.S. Geological Survey, Washington, DC, 1970.

[5] Rowe, R. K. and Booker, J. R., "I-D Pollutant Migration in Soils of Finite Depth," *Journal of Geotechnical Engineering Division, American Society of Civil Engineers*, Vol. III, No. 4, 1985, pp. 479–499.

[6] Rowe, R. K., Caers, C. J., Booker, J. R., and Crooks, V. E., "Pollutant Migration Through Clay Soils: Observed and Predicted Behaviour," *Proceedings of the XI International Conference on Soil Mechanics and Foundation Engineering*, Vol. 3, Balkema, Rotterdam, The Netherlands, 1985, pp. 1293–1298.

[7] Rowe, R. K. and Booker, J. R., "Program POLLUTE—1-D Pollutant Migration Analysis Program," distributed by SACDA, The Faculty of Engineering Science, The University of Western Ontario, London, Ontario, Canada N6A 5B9, 1983.