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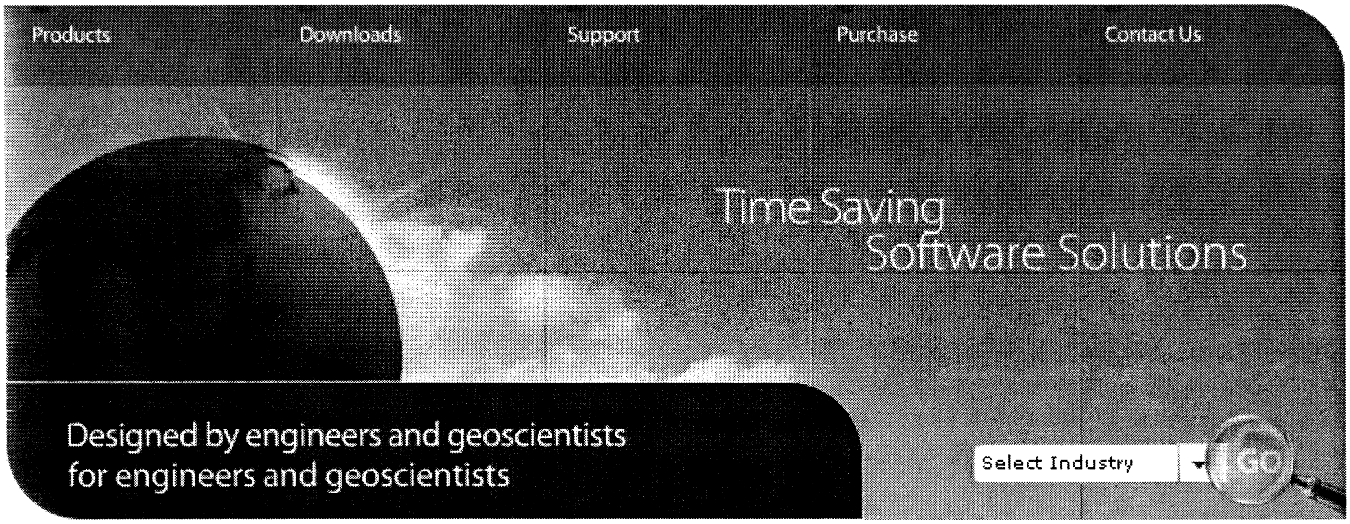

Research Reports

There have been numerous research reports published on contaminant transport modeling and landfill design using the POLLUTE and MIGRATE programs. A partial listing of these reports can be found on our References page.

Below are a few of these reports that we have made available online. These reports are in Adobe Acrobat format. If you do not already have the free **Adobe Acrobat Reader** on your computer, you can download in here.

1-D Pollutant Migration in Soils of Finite Depth

by R.K. Rowe and J.R. Booker

Abstract: A technique for the analysis of 1-D pollutant migration through a day layer of finite depth is presented. This formulation includes dispersive and advective transport in the clay as well as geotechnical reactions and permits consideration of the depletion of contaminant in the landfill with time as well as the effect of groundwater flow in a permeable stratum beneath the clay layer. A limited parametric study is presented to illustrate the effect of considering these factors in the analysis. It is shown that for the most practical situations the concentration of contaminant within the ground water beneath the landfill will reach a peak value at a specific time and will then decrease with subsequent time. It is shown that the magnitude of this peak concentration and the time required for it to occur are highly dependent upon the mass of contaminant within the landfill and the sorption capacity of the clay. Other important factors which re examined include the thickness of the clay layer, the advection velocity (relative to the dispersivity), and the ground-water flow velocity in any permeable strata beneath the clay layer. The implications of these results for optimizing the design of clay liners is then discussed.

A finite layer technique for calculating three-dimensional pollutant migration in soil

by R.K. Rowe and J.R. Booker

Abstract: A technique for the analysis of two— and three—dimensional pollutant migration through a layered soil medium is described. An earlier solution for plane diffusion in a single homogeneous layer of soil is extended using the finite layer method for general three-dimensional diffusion. Particular attention is focused on the effects of horizontal advective velocity and coefficient of hydrodynamic dispersion within the aquifer together with the thickness of the aquifer. A parametric study is presented to demonstrate some characteristics of contaminant migration in a layered soil system, taking into account the fact that the surface concentration does not remain constant because of contaminant transport into the deposit. The advantages of the approach are most pronounced when attempting to determine concentrations away from the landfill at modest to large times.

Analysis of Contaminant Transport through Fractured Rock at an Ontario Landfill

by R.K. Rowe and J.R. Booker

Abstract: The effects of fracture spacing, fracture opening size, Darcy velocity and dispersion upon the calculated contaminant plume in a fractured shale are examined. It is shown that the calculated contaminant plume, based on a limited, extent of the contaminant plume at a 15-year-old landfill in Burlington, Ontario. The results demonstrate that matrix diffusion can play a very significant role in the attenuation of contaminant migrating in fractured porous media.

An Efficient Analysis of Pollutant Migration through Soil

by R.K. Rowe and J.R. Booker

A Semi-analytical Model for Contaminant Migration in a Regular Two or Three Dimensional Fractured Network: Conservative Contaminants

by R.K. Rowe and J.R. Booker

Abstract: A new semi-analytical solution for the transport of a conservative contaminant species in a fractured medium having a regular two—or three—dimensional fracture network is presented. The application of the technique and some of the practical implications arising from an examination of contaminant migration in fractured systems is discussed. Particular consideration is given to the effects of Darcy velocity, fracture spacing, matrix porosity, dispersivity and the mass of the contaminant available for transport. The implications of uncertainty with respect to fracture opening size and groundwater velocity is also discussed and it is shown that provided one can obtain a reasonable estimate of the hydraulic gradient and hydraulic conductivity for the rock mass, uncertainty regarding the magnitude of the opening size and groundwater velocity does not have a significant effect on predicted contaminant migration for the class of problems being considered.

Background documentation for programs POLLUTE and MIGRATE

by R.K. Rowe

Composite Liners as Barriers: Critical Considerations

by R.K. Rowe and M.J. Fraser

Abstract: The finite service life of engineered components of composite liner systems is a critical consideration in the design of such systems. Four different barriers incorporating composite liners are examined with respect to service life, leakage through the geomembrane, and the hydraulic conductivity of the geosynthetic clay liner.

Consideration of Uncertainty Regarding the Service Lives of Engineered Systems in Assessing the Potential Contaminant Impact

by R.K. Rowe and M.J. Fraser

Abstract: The modeling of contaminant transport through barrier systems will be discussed in the context of uncertainty regarding the service life of various components of the engineered barrier systems. A technique for performing a stochastic analysis that takes consideration of finite but uncertain service lives of different components of the system is discussed and will be illustrated by a number of examples. The barrier systems to be considered will include conventional clay liner systems that include multiple leachate collection systems, systems

involving geosyntheitc clay liners.

Contaminant Impact Assessment and the Contaminating Lifespan of Landfills

by R,K. Rowe

Abstract: Some of the factors to be considered in performing impact assessments for proposed municipal and non-hazardous waste landfill sites are discussed. These factors include the effect of the mass of contaminant, infiltration, and attenuation in the hydrolgeologic system on the contaminating lifespan of a landfill. The potential impact of fracturing of the soil separating the landfill from n underlying aquifer is examined. The influences of a compacted clay liner and (or) a natural, intact clayey layer below the fractured soil are examined. The concept of developing "triggers" to initiate leachate control measures, and the associated potential impact on groundwater, is discussed in the context of the potential design life of the underdrain system in a landfill.

Contaminant migration through fractured till into an underlying aquifer

by R.K. Rowe and J.R. Booker

Abstract: This paper examines the potential impact on groundwater quality of contaminant migration from a landfill site, through a fractured till, and into an underlying aquifer. The paper describes a simple, semi-analytic technique for modeling contaminant transport through the fractured till, including consideration of diffusion of contaminants from the fractures into the till matrix, sorption, and radioactive decay. The model also considers the finite mass of contaminant and dilution due to the flow of groundwater in the aquifer. The model can be readily implemented on a microcomputer. The model allows examination of variations in fracture spacing, fracture opening size, thickness of the fractured zone, diffusion coefficient, dispersivity, effective porosity of the matrix, radioactive decay, Darcy velocity, thickness of the aquifer, distribution coefficient, and mass of contaminant and dilution due to the flow of groundwater in the aquifer. The model can be readily implemented on a microcomputer. The model allows examination of variations in fracture spacing, fracture opening size, thickness of the fractured zone, diffusion coefficient, dispersivity, effective porosity of the matrix, radioactive decay, Darcy velocity, thickness of the aquifer, distribution coefficient, and mass of contaminant. The paper describes the results of a limited parametric study that, *inter alia,* examines the effects of uncertainty in fracture spacing, the thickness of the fractured till, and the effective porosity of the till matrix. Some of the practical implications are discussed.

Effect of multiple contaminant migration on diffusion and adsorption of some domestic waste contaminants in a natural clayey soil

by F.S. Barone, E.K. Yanful, R.M. Quigley, and R.K. Rowe

Evaluation of the Hydraulic Conductivity of Aquitards

by R.K. Rowe and P. Nadarajah

Abstract: The evaluation of the bulk vertical hydraulic conductivity of an aquitard based on its response to the pumping of an adjacent aquifer is examined using Biot's theory. Consideration is given to the errors in interpretation of the results of pumping tests which arise as a result of the time lag associated with different types of piezometers as well as the length of the piezometer. Factors to allow for correction of these errors are presented. Although these factors are originally developed for isotropic aquitards, they can be used for anisotropic aquitards with appropriate modifications described in the paper. A comparison is made between the results obtained fro diffusion theory (as assumed in the development of techniques currently used in practice) and the more rigorous Biot's theory. The application of the technique is illustrated by two examples.

Fractured Till: Its implications for Contaminant Impact Assessment

by R.K. Rowe

Abstract: Some of the factors to be considered in performing impact assessments associated with proposals to locate landfill sites in fractured till are discussed. These factors

include the effect o the mass of contaminant, contaminating lifespan of a landfill. The effects of fracturing of the till on the potential impact of contaminants on underlying aquifers are examined with respect to a hypothetical case. The influence of both a man-made (compacted clay liner) and natural intact clayey layer in contact with the fractured till is examined. The concept of developing "triggers" to initiate leachate control measures, and the associated potential impact on groundwater, is discussed in the context of the potential design life of the primary engineering (i.e. the underdrain system) in a landfill.

Geosynthetics - Environmental Applications in Waste Containment

by R.K. Rowe and J.D. Smith

Abstract: This paper reviews the applications for Geosynthetics in waste containment. Consideration is given to geotexiles as filters and separators in otherwise conventional landfill design, the use of drainage mats as a replacement for conventional granular drainage layers, the use of geomembrane liners as a supplement to natural or compacted clay barriers, and finally to fully "geosyntheitc design" which incorporates geotexiles, geosyntheitc drainage mats, geomembranes and geogrids (for reinforcement).

Laboratory Determination of Chloride Diffusion Coefficient in an Intact Shale

by F.S. Barone, R.K. Rowe and R.M. Quigley

Abstract: An experimental investigation of diffusive transport of a non-reactive solute (chloride) in saturated, intact Queenston Shale is described. Laboratory tests were preformed by placing distilled water in contact with samples of shale having a high initial concentration of chloride in their pore water. Chloride was then permitted to diffuse out of the shale and into the distilled water reservoir for a period of up to 65 days. At the end of each test, the shale sample was sectioned to determine the variation in chloride pore-water concentration with depth through the sample. Fickian diffusion theory of 22 ± 1ºC ranged from 1.4×10^{-6} to 1.6×10^{-6} $cm^2/_{s,}$ which corresponds to a tortuosity (*r*) ranging from 0.095 to 0.108. Based on pore size measurements and consideration of the ionic diameter of hydrated chloride, the "effective porosity" available for chloride diffusion is estimated to be greater than 75% of the total porosity calculated from the moisture content of the shale.

Laboratory Determination of Chloride Diffusion Coefficient in an Intact Mudstone

by F.S. Barone, R.K. Rowe and R.M. Quigley

Abstract: An experimental determination of chloride diffusion coefficient in saturated, intact Bison mudstone is described. Laboratory tests simulating one-dimensional diffusive transport were preformed by placing distilled water directly above a sample of Bison Mudstone having a high initial concentration of chloride in its pore water. Chloride and other species naturally occurring in the pore water were then permitted to diffuse out of the sample and into distilled water reservoir for a period of up to 34 days. At the end of the test, the sample was sectioned, and the chloride pore water concentration profile measured. Fickian diffusion theory was then used to deduce the diffusion coefficient (D). The diffusion coefficient for chloride at a temperature of 10º c ranged from 1.5 to 2.0×10^{-6} cm^2/sec, from which a corresponding tortuosity factor (*r*) ranging from .15 - .20 can be calculated. Based on the pore size measurement, double layer thickness and consideration of the hydrated ionic diameter of chloride, the "effective porosity" available for chloride diffusion is approximately equal to the total porosity calculated from the moisture content of the rock. For comparison, an attempt was made to obtain the diffusion coefficient for bromide diffusing into the sample, simultaneous with chloride diffusing out. It was found, however, that the concentration profile obtained for bromide could not be fitted by the Fickian diffusion theory, due to interactions between bromide and other species naturally occurring in the rock sample.

Leachate Characteristics for MSW Landfills

by R.K. Rowe

Abstract: Leachate characteristics from five Ontario landfills are compared with typical values for both European and U.S. landfills. The time history of key constituents are examined and the half-life for first order decay is estimated based on the available data.

Leachate Detection or Hydraulic Control: Two Design Options

by R.K. Rowe

Abstract: Some technical advantages and disadvantages associated with different uses for a granular layer constructed beneath a landfill liner are examined. The importance of diffusion is discussed and it is shown that there is potential for significant contaminant impact on an underlying aquifer even if all leachate escaping through the primary liner is collected by the secondary leachate collection system.

Modelling of 2D Contaminant Migration in a Layered and Fractured Zone Beneath Landfills

by R.K. Rowe and J.R. Booker

Abstract: A new 2D finite layer formulation which allows consideration of both vertical and horizontal migration in systems which may consist of both fracture and unfractured layers is described. The practical application of the theory is illustrated with respect to a number of hypothetical cases. The results indicate that even relatively widely spaced small fractures can have a significant effect on potential impact. It is also shown that when dealing with relatively impermeable tills, significant impact on an underlying aquifer may not occur until after the landfill leachate is at a low strength; but the impact may be quite significant and may last for hundreds of years.

Movement of Pollutants through Clayey Soil

by R.K. Rowe

Abstract: This paper examines a number of factors which should be considered when attempting to predict the impact of landfill sites on groundwater contamination. The relative importance of transport mechanisms such as diffusion, dispersion and advection are discussed as well as the significance of attenuation mechanisms. Techniques for determining relevant parameters are outlined and the applicability of laboratory techniques for determining diffusion and distribution coefficients is discussed with respect to the observed migration of contaminants beneath the Sarnia Landfill. Simple but effective models for calculating the migration of contaminant from landfills are discussed and their applications illustrated by a number of examples. Finally, factors such as the impact of the leachate collection system and the migration of contaminant from landfills designed to have an inward gradient is examined.

Municipal Solid Waste Landfilling

by R.M. Quigley

Abstract: The short term and long term performance of clayey barriers (the cheapest way to encapsulate waste) is the subject of this paper. Municipal solid waste leachate varies from a moderately saline, slightly organic, slightly acidic liquid when fresh to a non-threatening liquid once aged and diluted. Biological activity within the waste is responsible for extensive carbonate and sulphide dumping which tends to clog drainage systems. Concurrent advection and diffusion play major roles in salt and organic transfer through clay barriers. Typical salt fluxes are presented for barriers of differing thickness to illustrate the great importance of diffusion as a transfer process.

Pollutant Transport through Barriers

by R.K. Rowe

Abstract: Methods of predicting contaminant transport through saturated and unsaturated clayey barriers are reviewed. Particular consideration is given to the relative importance of advection and dispersion as transport mechanisms, the soil properties controlling transport through barriers and into adjacent aquifers, and finally, to methods of obtaining solutions of specific observations and recommendations are made.

Recent Advances in Modelling of Contaminant Impact due to Clogging

by R.K. Rowe

Abstract: Recent advances in the development of finite layer theory allow the modelling of changes in the operation of an engineered barrier system for landfills. Factors that can be considered include changes in the operation of the system as the primary leachate system clogs, changes in the operation of secondary leachate collection and hydraulic control layers, and changes in the diffusive and hydraulic characteristics of geomembranes.

Theoretical Solutions for Calculating Leakage through Composite Liner Systems

by R.K. Rowe

Abstract: A new semi-analytic solution for the leakage of fluid through a circular hole in an otherwise essentially impermeable geomembrane underlain by a clay liner is presented. This solution covers a full range of layer thickness between very thin and infinitely thick. It demonstrates that in general, the flow is greater than that predicted by the limiting cases. The solution can be used for a wide range of practical problems where the radius of the hole may range from a pinhole to a large quasi-circular wrinkle in a perforated geomembrane.

Two-dimensional pollutant migration in soils of finite depth

by R.K. Rowe and J.R. Booker

Waste Disposal Site Selection and Design Considerations

R.K. Rowe and M.J. Fraser

Abstract: Considerations associated with the selection and design of a suitable waste disposal facility are discussed. These considerations include the potential for protection of groundwater quality, predictability of groundwater movement, and potential for disruption of groundwater users. In the design of a waste disposal facility engineered systems re often incorporated, and the service life of these systems must be considered when assessing their potential impact. The role of modeling in predicting the potential impacts due to the interaction between the hydrogeology and the proposed engineering is discussed. The potential impact of different landfill designs on groundwater quality is examine3d for a hypothetical.

COMPOSITE LINERS AS BARRIERS: CRITICAL CONSIDERATIONS

R.Kerry Rowe and M.J. Fraser

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London, Ontario, N6B 5B9, Canada

Abstract

The finite service life of engineered components of composite liner systems is a critical consideration in the design of such systems. Four different barriers incorporating composite liners are examined with respect to service life, leakage through the geomembrane, and the hydraulic conductivity of the geosynthetic clay liner.

Introduction

Composite liners consisting of geomembranes over compacted clay and geomembranes over geosynthetic clay liners (GCL) are gaining wide acceptance in the design of barrier systems for waste disposal. This paper examines a number of key considerations with respect to the design of these systems, with particular emphasis on the finite service life of the engineered systems and the effective hydraulic conductivity of the geomembrane and GCL.

The primary goal of barrier systems in landfills is to minimize the migration of contaminants. The effectiveness of a barrier design can be assessed by examining the impact of the landfill on an underlying aquifer. For the purposes of this paper the migration of chloride and dichloromethane will be examined. Initial source concentrations of 1500 mg/L for Chloride, and 1500 μg/L for dichloromethane are assumed. In addition the mass of the chloride is assumed to represent 0.2% of the total mass of waste, which is has a density of 600 kg/m^3. It is also assumed that the mass of dichloromethane is in direct proportion to the initial source concentration.

The service life of the engineered systems is expected to be finite, due to chemical and biological clogging of the leachate collection systems and ageing (eg. due to chain scission) of the geomembrane. In this analysis the service lives of the engineered systems are assumed to be 50 years for the primary leachate collection system, 125 years for the primary geomembrane, 175 years for the secondary geomembrane, and 200 years for the secondary leachate collection system unless otherwise specified.

Prior to failure of the primary leachate collection system the leachate mound is taken to be 0.3 m above the primary liner, after failure the mound is assumed to build at a rate of 0.25 m/a up to it's full height of 11 m above the primary liner (where the maximum height of the mound is controlled by the thickness of waste in the example being considered).

All the analyses reported herein were performed using a finite layer contaminant transport model [Rowe and Booker, 1985, 1987] as implemented in the computer program POLLUTE v.5 [Rowe and Booker, 1990].

Barrier Designs

Four different composite liners are considered for a hypothetical landfill excavated into a relatively permeable silt till which extends 3 m below the top of the primary composite liner, and overlies a 1 m thick aquifer. The silt till is assumed to have a hydraulic conductivity of 1 x 10^{-5} cm/s, a porosity of 0.25, an effective diffusion coefficient of 0.015 m^2/a for chloride and dichloromethane, with the product of soil density, ρ, and dichloromethane partitioning coefficient, K_d, given by $\rho K_d=2$.

The underlying aquifer is assumed to have a porosity of 0.3, a hydrostatic head of 1 m above the aquifer, and a horizontal flow at the up-gradient edge of 20 m/a. Upon failure of the leachate collection systems the mounding of the leachate will cause an increase in the downward Darcy velocity with a resulting increase in the horizontal flow in the aquifer.

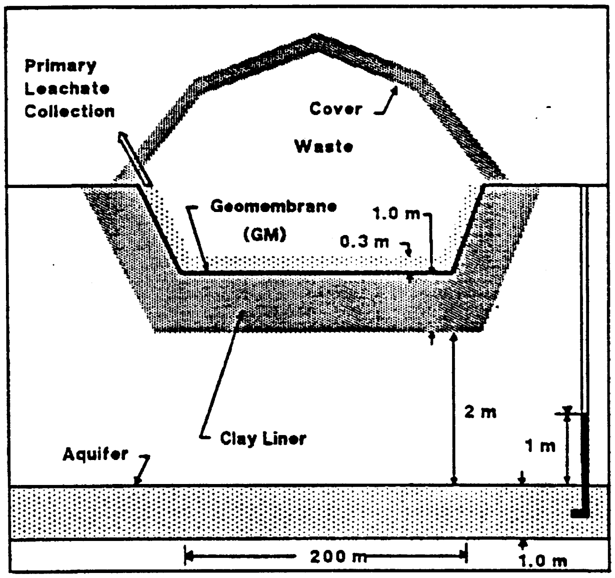

Figure 1. Design 1: Single Liner - Geomembrane & Clay.

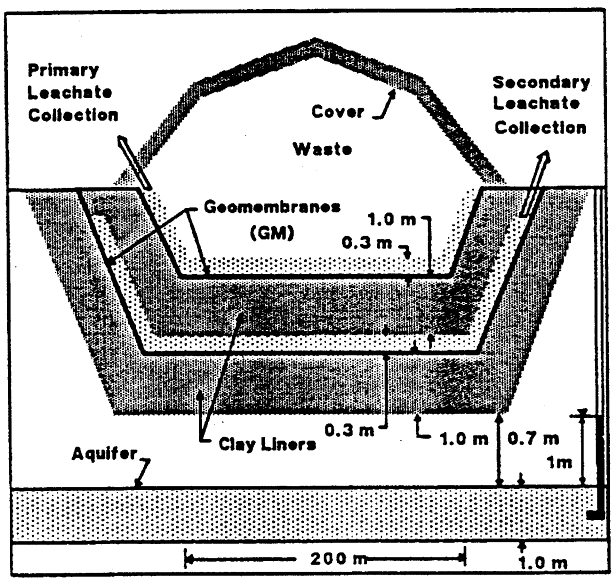

Figure 2. Design 2: Double Liner - Geomembrane & Clay.

The first barrier design incorporates a primary leachate collection system and composite primary liner consisting of a 80 mil geomembrane and 1 m of compacted clay (Figure 1). In this and subsequent designs the geomembrane is assumed to have an effective hydraulic conductivity of 10^{-12} cm/s which has been backfigured based on consideration of the likely leakage through a "well constructed" composite liner, with some holes (using information provided by Giroud and Bonaparte, 1989), and an effective diffusion coefficient of 3 x 10^{-5} m^2/a, unless otherwise stated.

The compacted clay for this and the second barrier design is 1 m thick and has a hydraulic conductivity of 2 x 10^{-8} cm/s, a porosity of 0.35, an effective diffusion of 0.019 m^2/a. The sorption of dichloromethane is controlled by $\rho K_d=2$. Leachate collection systems in these designs consists of a granular layer normally 0.3 m thick with a porosity of 0.3. In this design there is 2 m of silt till, below the liner.

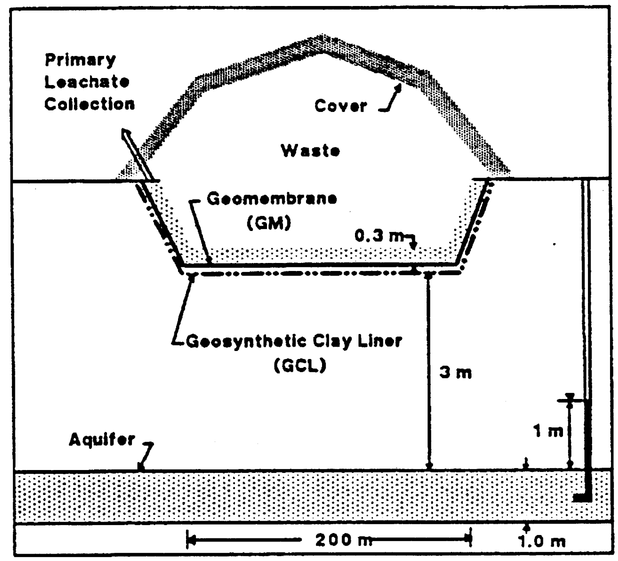

Figure 3. Design 3: Single Liner - Geomembrane & Geosynthetic Clay Liner.

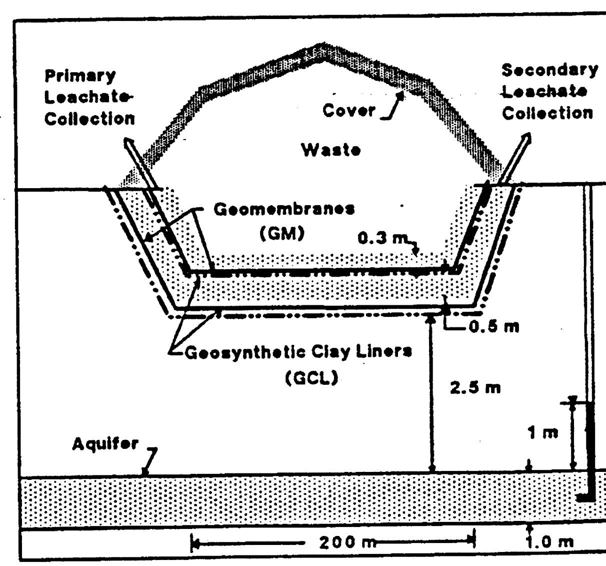

Figure 4. Design 4: Double Liner - Geomembrane & Geosynthetic Clay Liner.

In the second barrier design, primary and secondary leachate collection systems and primary and secondary composite liners are utilized (Figure 2). Both the primary and secondary liners consist of a 80 mil geomembrane over 1 m of compacted clay. The remaining silt till is only 0.7 m thick, if the base of the landfill is maintained at approximately the same elevation as the first design.

The third and fourth barrier designs (Figures 3 and 4) are similar to the first and second designs respectively, except in these designs the composite liners consist of a 80 mil geomembrane over a geosynthetic clay liner (GCL). The thickness of silt till is 3 m below the engineering for the third design and 2.5 m for the fourth design in order to keep the base of the landfill at the same level above the aquifer as in the first and second designs. In these designs the GCL is assumed to have a hydraulic conductivity of 4×10^{-10} cm/s, a porosity of 0.75, an effective diffusion coefficient of 0.0047 m^2/a, and the sorption of dichloromethane is given by $\rho K_d=2$. In the fourth design the secondary leachate collection system was assumed to be 0.7 m thick to allow for a granular - geosynthetic cushioning layer above and below a coarse stone collection layer.

In the analysis that follows the infiltration through the cover is taken to be 0.15 m/a based on experience in Southern Ontario, the waste thickness is 12.5 m, and the landfill length is 200 m in the direction of groundwater flow. The effect of the mass of contaminant was modelled as described by Rowe [1991]. Due to space limitations, only one hydrogeologic system is considered here. However, as noted by Rowe [1992], the impact of a given landfill will depend on the interaction between the engineered barrier system and the hydrogeology. Thus care should be taken not to generalize the numerical results beyond the level discussed in the paper.

Service Life of Geomembrane

The service life of the geomembranes is assumed to be finite, due to ageing (eg. chain scission caused by chemical attack). To illustrate the effects of the service life of the geomembrane on the migration of contaminants, a range of service lives of the primary geomembranes were examined for the four designs. Once the primary geomembrane ceases to be effective there will be a significant increase in contaminant contact with the secondary leachate collection system and secondary geomembrane for designs 2 and 4. This increased contact is then expected to accelerate degradation of these systems. Thus, for this paper the secondary geomembrane and secondary collection leachate system are assumed to fail at 50 years and 75 years respectively after failure of the primary geomembrane. Space does not permit an examination of the effect of this assumption which will be discussed in another paper.

If the service lives of the geomembrane are assumed to be effectively infinite (ie. it's hydraulic containment characteristics are maintained for the entire contaminating lifespan of the landfill) then the impact on the aquifer would be controlled by diffusion of contaminants through the barrier system, even with failure of the primary leachate collection system. For this case the calculated peak increase in chloride concentration would be 14, 10, 12, and 8 mg/L and the peak dichloromethane concentration would be 4, 3, 3, and 2 μg/L for the first, second, third and fourth designs respectively.

For comparison purposes, Figures 5 and 6 show the calculated impact on the aquifer for chloride and dichloromethane, assuming that the service life of the geomembranes is finite and that the service life of the primary geomembrane is between 100 and 150 years. It can be seen that the peak concentration of the contaminants decreases with increasing service life, with the decrease being most noticeable for the barrier designs having primary barriers only (i.e. the first and third designs).

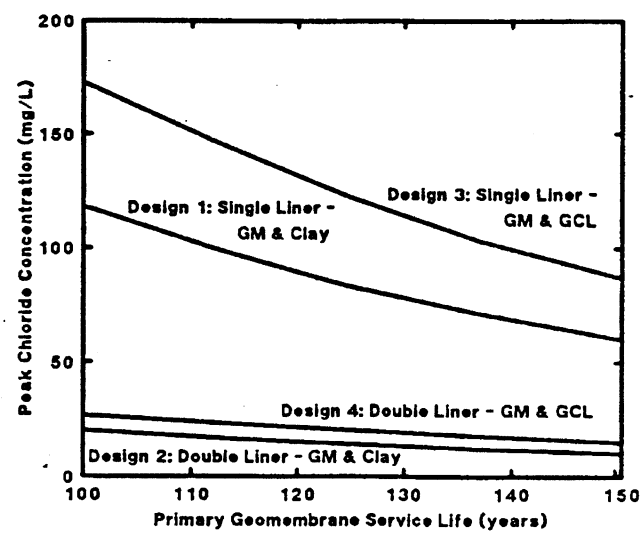

Figure 5. Geomembrane Service Life - Chloride.

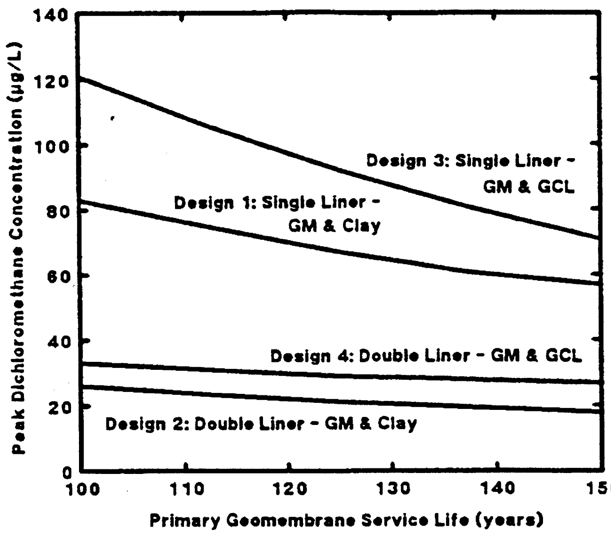

Figure 6. Geomembrane Service Life - Dichloromethane.

The designs with a secondary system (ie. 2 and 4) result in substantially reduced impact compared to those with only a single composite liner (ie. 1 and 3). Neglecting biodegradation of dichloromethane, it is seen that for designs 1 and 3 the calculated impacts are quite significant compared to a drinking water objective of 50 µg/L, even with a substantial service life of 150 years for the primary geomembrane.

In the Province of Ontario, Canada, the Ministry of Environment and Energy's 'Reasonable Use' Policy [MOEE, 1993a] would limit increases in the concentration of contaminants in the aquifer to a maximum of 125 mg/L for chloride and 12 µg/L for dichloromethane, assuming a negligible background concentration. Under this policy the first, second, and fourth barrier designs would be acceptable for chloride for all the service lives examined, however the third design would require a geomembrane service life greater than 125 years to be acceptable for the conditions assumed. None of these designs would be acceptable for dichloromethane with service lives of the primary geomembrane of 150 years or less, although the second design is close to being acceptable if the service life of the primary geomembrane is 150 years.

Leakage through the Geomembrane

The leakage through a geomembrane which forms part of a composite liner system depends primarily on the applied leachate head, the number of 'holes' in the geomembrane and the nature of the contact between the geomembrane and the underlying clay liner [Giroud and Bonaparte, 1989]. In order to allow an 'intuitive' comparison with traditional geotechnical barrier materials (eg. clay liners) it is convenient to backfigure a effective hydraulic conductivity of the geomembrane (considering the factors discussed above) as a measure of the quality of the installed geomembrane and hence to examine the effect of reasonable variation in workmanship in terms of this effective hydraulic conductivity as illustrated in Figures 7 and 8.

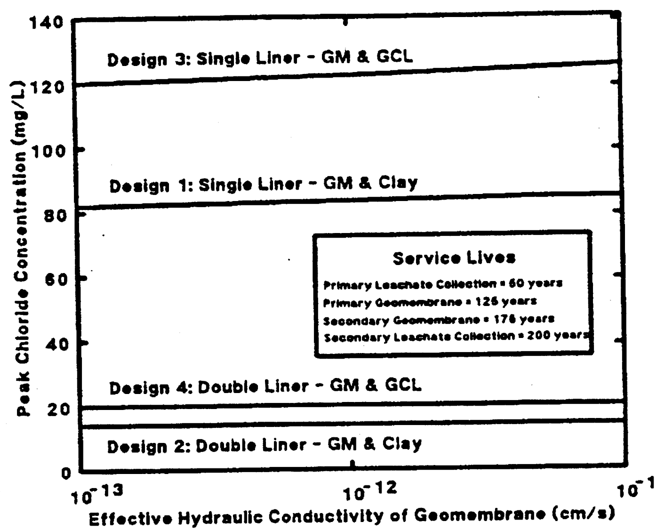

Figure 7. Effective Geomembrane Hydraulic Conductivity - Chloride.

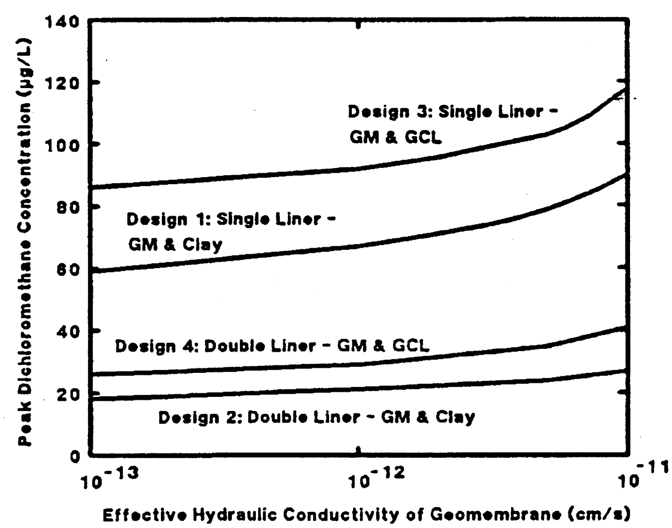

Figure 8. Effective Geomembrane Hydraulic Conductivity - Dichloromethane.

Over the range of effective hydraulic conductivities examined, the peak chloride concentration does not vary appreciably for the four designs (Figure 7). This insensitivity is due to the contaminant migration process being predominantly diffusive while the geomembranes are intact, and then being dominated by advection upon failure of the geomembranes. Due to the effect of sorption, the peak concentration of dichloromethane is more sensitive to the leakage through the geomembrane and the results show a moderate decrease in peak concentration with decreasing effective geomembrane hydraulic conductivity (Figure 8), with the effect being greatest for the single composite liner systems (ie. designs 1 and 3).

The effectiveness of the geomembrane(s) can be assessed by comparison of the peak impacts given in Figures 7 and 8 with those that would be predicted for designs 1, 2, 3, and 4 assuming no geomembrane: namely 199, 40, 349, and 192 mg/L for chloride and 164, 37, 350, and 98 μg/L for dichloromethane.

When examined with respect to the MOEE's 'Reasonable Use' Policy, all of the designs would be acceptable for chloride over the range of workmanship (ie. effective geomembrane hydraulic conductivity) considered. None of the designs would be acceptable for dichloromethane, however the second design comes close to being acceptable for excellent workmanship (ie. an effective geomembrane hydraulic conductivity of 10^{-13} cm/s).

Hydraulic Conductivity of GCL

A range of hydraulic conductivities of the geosynthetic clay liner were examined to illustrate the sensitivity of the peak aquifer contaminant concentration to this parameter. Only the third and fourth designs incorporate GCLs and would be sensitive to changes in the hydraulic conductivity of the GCL, in the figures that follow the peak aquifer concentrations of the first and second designs are plotted as constants for reference purposes only.

Figures 9 and 10 show the calculated peak concentration of chloride and dichloromethane in the aquifer, for a range of GCL hydraulic conductivities. The third and fourth designs are quite sensitive to the hydraulic conductivity, since after the geomembrane fails the migration process is predominantly advective with the rate being controlled by the hydraulic conductivity of the GCL. The third design is the most sensitive since there is no secondary leachate collection system to remove contaminant after failure of the geomembrane, whereas in the fourth design the majority of the contaminant is removed by the secondary leachate collection system prior to the failure of the secondary geomembrane.

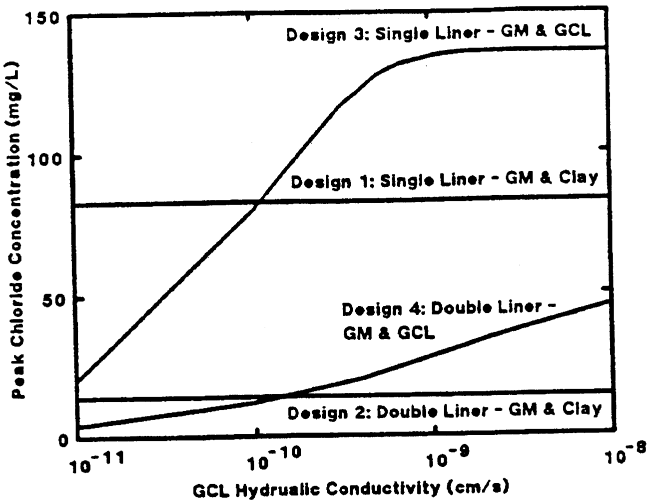

Figure 9. GCL Hydraulic Conductivity - Chloride.

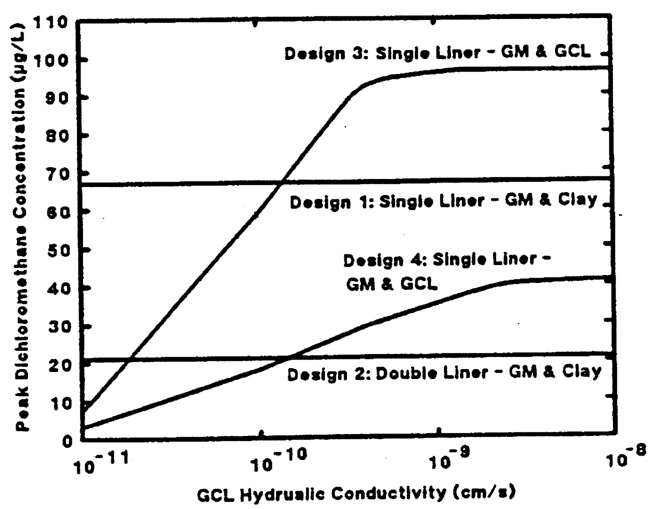

Figure 10. GCL Hydraulic Conductivity -Dichloromethane.

From these figures one can assess the hydraulic conductivity of the GCL at which it outperforms a 1 m thick compacted clay liner with a hydraulic conductivity of $2x10^{-8}$ cm/s. It is seen that for the cases examined this typically occurs for a GCL hydraulic conductivity of between about 10^{-11} and 10^{-10} cm/s.

Based on the maximum allowable increase in chloride concentration permitted by the MOEE's 'Reasonable Use' Policy, the fourth design may be acceptable at all the GCL hydraulic conductivities examined, and the third design may be acceptable for GCL hydraulic conductivities less than 4 x 10^{-10} cm/s. For dichloromethane the fourth design would require a GCL hydraulic conductivity less than 4 x 10^{-11} cm/s, and the third design would require a GCL hydraulic conductivity less than 1.3 x 10^{-11} cm/s.

Discussion and Conclusions

Some regulators (eg. MOEE, 1993b) require that when assessing the potential impact of a landfill on an underlying aquifer, the service life of the engineered systems must be considered. When composite liners are utilized the service life of the geomembranes must also be considered, in addition to the service life of the leachate collection systems. The service life of the geomembrane for barrier systems involving only primary liners has a much greater effect than for systems involving both primary and secondary systems.

Although the geomembranes and geosynthetic clay liners are engineered components, there is still uncertainty regarding their hydraulic conductivity and effective diffusion coefficients. Since the hydraulic conductivity of a well installed geomembrane is very low, the migration process is primarily diffusive and relatively insensitive to the effective hydraulic conductivity of the geomembrane over the range examined. However, after the geomembrane fails the contaminant transport is controlled by advection and for a composite liner incorporating a GCL, the hydraulic conductivity of the GCL becomes the key factor controlling impact (similarly, of course, with a compacted clay liner it would be the hydraulic conductivity of the clay that would control impact).

This paper demonstrates that even with relatively long service lives (more than a hundred years), consideration of the finite service life of components of the engineered systems can have a profound effect on the estimated impact for a modest sized landfill (approximately 12.5 m average waste thickness); the effect could be expected to be greater for a larger landfill. It is concluded that reasonable uncertainty regarding the service life of engineered systems should be considered when evaluating the potential impact and the health and safety risks associated with proposed waste disposal facilities.

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