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Landfill Base Liners: Assessment of Material Equivalency and Impact to Groundwater

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Abstract This paper gathered available flow and transport solutions and used them for two composite liners, consisting of geomembrane (GM) overlying either a compacted clay liner (CCL) or a geosynthetic clay liner (GCL). Its aim is to provide a guiding framework for the possible choices of (a) approaches to bottom liner design, (b) respective analytical solutions to flow and transport equations, as well as (c) parameters required for each type of solution. On the basis of the obtained results, the following recommendations are made. When the goal of analysis is to determine material equivalency, leachate flow rate is an adequate key parameter for GM-CCL composite liners. For GM-GCL composite liners, it is necessary to compute contaminant concentration or mass flux, considering (a) transport through defects for inorganic contaminants and (b) diffusion and the contribution of any available attenuation layer for organic contaminants. When the goal of analysis is to assess impact to groundwater, it is advised to calculate both discharge rate and contaminant mass flux regardless of liner type. The critical parameter for the transport calculations is the retardation factor of the contaminant, for the case of CCLs, while the results for GCLs are much less sensitive to this parameter.

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1 Introduction

The design of landfill base liners has attracted the attention of many researchers. Early publications, recognizing that geomembrane defects can be minimized but not avoided, provided closed-form expressions to assess leakage through composite liners (Giroud and Bonaparte 1989; Giroud et al. 1989, 1992). These methods were improved upon with time (Giroud 1997; Rowe 1998), while comparisons with numerical results indicated their strengths and limitations (Foose et al. 2001a). Meanwhile, it started being acknowledged that liner design should be based not only on leachate flow calculations but also on transport considerations (Foose et al. 1999; Katsumi et al. 2001). The role of the geomembrane was recognized as important in the transport behavior of composite liners, since it is a very effective barrier for inorganic contaminants, but not for organics (Rowe 1998). Prompted by the requirement of regulations (e.g. EC 1999) for the use of compacted clay, some researchers focused on the issue of equivalency between alternative liners, comparing the performance of composite liners with either compacted clay or geosynthetic clay underneath the geomembrane (Foose et al. 2002; Rowe and Brachman 2004). Moreover, it was proposed that, when the design goal is protection of the underlying aquifer, the contribution of the soil underlying the liner can also be considered (Foose 2002; Rowe and Brachman 2004).

Concerning the tools employed in the aforementioned research projects, numerical solutions were most common for transport studies. Numerical solutions have the advantages of offering various options for specifying boundary conditions at the liner faces and accounting explicitly for layers of varying properties. Foose et al. (2002) used a numerical model to address equivalency issues by comparing GM-CCL and GM-GCL combinations. In addition, they studied the effect of boundary conditions assumed. They found that for inorganic contaminants, for which transport takes place through defects, GCLs are better not only in terms of flow rate but also in terms of contaminant mass flux. However, when transport has a large diffusive component, as is the case with organic contaminants, GCLs perform worse compared to CCLs. Recognizing this drawback of GCLs, Rowe and Brachman (2004) showed, using numerical solutions, that the protection offered by a GM-CCL composite liner can be equivalent to that offered by a GM-GCL in combination with an underlying attenuation layer (GM-GCL-AL).

However, numerical models are not tools readily available to engineering practitioners addressing issues of landfill liner designs. Recognizing this difficulty, Katsumi et al. (2001) presented simplified analytical transport solutions. Katsumi et al. (2001) applied these solutions to GM-CCL liners, and investigated the effect of the values of input parameters on calculation results. Sharing the practical emphasis of Katsumi et al. (2001), the authors of this paper compiled analytical solutions from the literature, which require only the use of readily available software. Preference was given to solutions that have been shown to be in good or reasonable agreement with numerical results. These solutions are suitable for performance-based design criteria that consider either flow or transport. The variety of existing analytical solutions offers the option to select between two alternative boundary conditions and to evaluate the contribution of an attenuating layer. The basic features of these solutions are described in Sect. 2, their application is discussed in Sect. 3 and their results are presented in Sect. 4. For some solutions, their application requires several input parameters, which may not be practical to determine in the laboratory for case-specific situations. To this end, the paper includes a detailed discussion on parameter selection (Sect. 3.3) and results from a parametric study (Sect. 5). The recommendations in the concluding section are based on joint consideration of the goal of the analysis, the comparison of the results given by each method and the sensitivity of results to input parameters.

2 Background on Calculation Methods Considered

This paper considers bottom liners that consist of a geomembrane (GM) overlying either a compacted clay liner (CCL) or a geosynthetic clay liner (GCL). Throughout the paper, these are referred to as GM-CCL or GM-GCL composite liners, respectively. For these composite liners, leachate flow and contaminant transport have two components: through the defects of the geomembrane and through the remaining intact portion of the liner. It will be shown that the contribution of one of the two components may be insignificant compared to the other, depending on the calculated quantity of interest, the type of leachate constituent considered and the material properties of the liners. This section gives the necessary background to solutions for flow and transport calculations that can be applied either by hand or by using readily available spreadsheet or mathematical software.

The study of the hydraulic behavior of a liner focuses on the volume of leachate reaching the natural soil, hence the quantity of interest is flow rate: these methods are discussed in Sect. 2.1. In the complementary study of the transport of leachate constituents, the quantity of interest is the magnitude of either the contaminant concentration or the contaminant mass flux at a point of compliance, which can be the downstream face of the liner or of an attenuation layer below the liner: these methods are discussed in Sect. 2.2.

2.1 Flow Modelling

2.1.1 Flow Through the Intact Liner

The flow rate of leachate, Q, through the parallel layers of the intact liner can be calculated by using the expression for the equivalent hydraulic conductivity, k_{eq}, of two (or more) layers for one-dimensional (1D) flow perpendicular to layering:

$$k_{eq} = \frac{h_{GM} + h_s}{\frac{h_{GM}}{k_{GM}} + \frac{h_s}{k_s}} \quad (1)$$

where h_{GM} and k_{GM} are the thickness and the hydraulic conductivity of the geomembrane, respectively, while h_s and k_s are the thickness and the hydraulic conductivity of the compacted (h_{CCL}, k_{CCL}) or geosynthetic clay layer (h_{GCL}, k_{GCL}). Flow rate is calculated for a reference area of the landfill base A, with Darcy's law, as:

$$Q = k_{eq} \cdot i \cdot A. \quad (2)$$

The hydraulic gradient, i, across the liner can be approximated as

$$i = (h_w + h)/h \quad (3)$$

where h_w is the height of the leachate accumulated at the landfill base and h is the total thickness of the composite liner ($h = h_{GM} + h_s$).

2.1.2 Flow Through Geomembrane Defects

Flow through liner defects is more complex, as shown schematically in Fig. 1. Leachate flows first through the defect, then along the space between the geomembrane and the clay layer and finally through the portion of the clay liner affected by the defect, which is referred to as the wetted area. Accordingly, flow rate is affected by the quality of the contact between the geomembrane and the clay liner, which determines the transmissivity, θ, of the geomembrane-clay interface, and by the geometry of the defect. Several expressions have been proposed for calculating flow rate of leachate through defects, mainly circular. These include: (1) solutions for idealized boundary conditions of either perfect contact between clay and geomembrane or infinite hydraulic conductivity of the space below the geomembrane, which give the lower and upper bound of flow rate, respectively (Rowe et al. 2004), (2) empirical expressions with parameters determined through fitting of calculated values to experimental results (Giroud 1997) and (3) analytical expressions assuming 1D flow through the clay layer in Fig. 1 (Rowe 1998). Different defect shapes have also been considered, in order to better approximate tears in the geomembrane rather than holes (Giroud 1997; Giroud and Touze-Foltz 2005), as well as the situation where a hole is located on a wrinkle (Rowe 1998). The effect of the assumed type of defects has been addressed elsewhere (Rowe et al. 2004). Two different approaches will be considered herein, the empirical expression of Giroud (1997) and the analytical solution of Rowe (1998). Both consider flow through a circular defect.

The empirical solutions presented by Giroud (1997) are the result of successive efforts based on analytical studies and model tests. Specifically, Giroud (1997) built on earlier work (Giroud and Bonaparte 1989; Giroud et al. 1992) and derived, by interpolation of calculated data points, closed-form expressions that are valid for a smaller number of necessary assumptions compared to their earlier versions. Flow rate through a circular defect of area α is given as (Giroud 1997):

$$Q = c_q \cdot \left[1 + (h_w/h_s)^{0.95}\right] \cdot \alpha^{0.1} \cdot h_w^{0.9} \cdot k_s^{0.74} \quad (4)$$

where c_q is a dimensionless factor that accounts for the quality of contact between the geomembrane and the underlying clay liner. On the basis of representative values for transmissivity of the geomembrane-clay interface, $\theta_{\text{GM-CCL}}$, determined with laboratory experiments, Giroud et al. (1992) found that the contact quality factor was equal to $c_q = 0.21$ and $c_q = 1.15$, for good and poor contact quality, respectively. The units of Q are (m^3/s), while all other quantities in Eq. 4 must be expressed in units of the international system (SI). The limits of validity of Eq. 4 restrict the range of the diameter of the defect to 0.5–25 mm, and the leachate height to values less than or equal to 3 m. There is an additional restriction on the maximum value of the hydraulic conductivity of the clay layer, which is expected to be satisfied for the typical clay material, compacted or geosynthetic, used in landfill

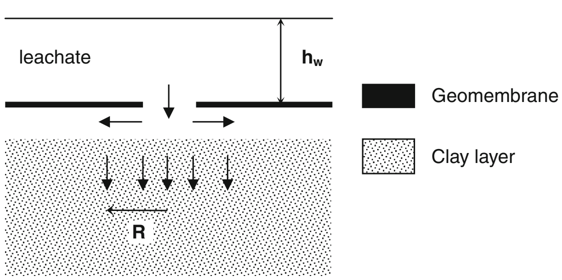


Fig. 1 The three components of flow in the vicinity of a geomembrane defect. For a circular defect, flow within the clay layer takes place in an area of radius R (*wetted area*)

liners. Although the application of Eq. 4 does not require the independent determination of the wetted area, it is useful to also give the equation that gives the radius of the wetted area, R (Giroud et al. 1992; Giroud 1997):

$$R = \frac{\alpha^{0.05} \cdot h_w^{0.45} \cdot k_s^{-0.13}}{\sqrt{\frac{\pi}{c_q} \cdot \left[1 + 0.1\left(\frac{h_w}{h_s}\right)^{0.95}\right]}}. \tag{5}$$

The approach followed by Rowe (1998) is analytical and rests on the assumption that flow within the clay layer (see Fig. 1) is one-dimensional. Its application is significantly complicated, since it involves the following equations (Rowe et al. 2004):

$$Q = \pi k_s \left(r_o^2 i + 2i\Delta_1 + 2i\Delta_2 - \frac{2h_w}{h_s}\Delta_2 \right) \tag{6}$$

$$\begin{aligned} \Delta_1 = &- \frac{[R \cdot \lambda_1(r_o, R) \cdot K_1(zR)]}{z} \\ &- \frac{[R \cdot \lambda_2(r_o, R) \cdot I_1(zR)]}{z} \\ &+ \frac{r_o \cdot \lambda_1(r_o, R) \cdot K_1(zr_o)}{z} \\ &+ \frac{[r_o \cdot \lambda_2(r_o, R) \cdot I_1(zr_o)]}{z} \end{aligned} \tag{7}$$

$$\begin{aligned} \Delta_2 = &\frac{[-R \cdot \lambda_1(R, r_o) \cdot K_1(zR)]}{z} \\ &+ \frac{[-R \cdot \lambda_2(R, r_o) \cdot I_1(zR)]}{z} \\ &+ \frac{r_o \cdot \lambda_1(R, r_o) \cdot K_1(zr_o)}{z} \\ &+ \frac{[r_o \cdot \lambda_2(R, r_o) \cdot I_1(zr_o)]}{z} \end{aligned} \tag{8}$$

$$\lambda_1(X, Y) = \frac{I_o(zY)}{K_o(zX)I_o(zY) - K_o(zY)I_o(zX)} \tag{9}$$

$$\lambda_2(X, Y) = \frac{K_o(zY)}{K_o(zX)I_o(zY) - K_o(zY)I_o(zX)} \tag{10}$$

$$z^2 = \frac{k_s}{h_s \theta} \tag{11}$$

where r_o is the radius of the circular defect, i is the average hydraulic gradient given by Eq. 3 for $h = h_s$, K_o, I_o are modified Bessel functions of zero order, K_1, I_1 are modified Bessel functions of order one, and R is the radius of the wetted area (see Fig. 1). The value of R can be determined by the condition that at the boundary of the wetted area, the derivative of hydraulic head, dH/dr, is equal to zero (Rowe et al. 2004):

$$\frac{dH}{dr} = (-h_w - h_s)\Lambda_1 - h_s \Lambda_2 \tag{12}$$

$$\Lambda_1 = \frac{-zK_1(zR)I_o(zR) - zK_o(zR)I_1(zR)}{K_o(zr_o)I_o(zR) - K_o(zR)I_o(zr_o)} \tag{13}$$

$$\Lambda_2 = \frac{-zK_1(zR)I_o(zr_o) - zK_o(zr_o)I_1(zR)}{K_o(zR)I_o(zr_o) - K_o(zr_o)I_o(zR)}. \tag{14}$$

The radius R is found iteratively, starting from $R = r_o$ and searching for the value for which Eq. 12 is equal to zero.

Other than the assumption of 1D flow in the wetted area, Rowe's (1998) approach does not have any applicability restriction related to boundary conditions or to material properties. On the other hand, it requires one additional input parameter, namely the value of transmissivity, θ, of the geomembrane-clay interface, which is not easily determined on the basis of laboratory experiments. Foose et al. (2001a) showed that, for transmissivity values expected in the field, Rowe's (1998) solution agrees well with results of 3D numerical analysis of flow.

2.2 Transport Modelling

The solutions presented in this section for contaminant transport do not take into account geochemical transformations or biodegradation processes. Hence, their results are conservative.

2.2.1 Transport Through the Intact Liner

Similarly to flow modelling, contaminant migration through the intact liner is considered first. For homogeneous soil layers, the solution of the advection–dispersion equation, assuming that the accumulated leachate acts as a source of constant contaminant concentration c_o ($c(x = 0, t \geq 0) = c_o$) and that the contaminant concentration at infinite distance from the liner remains equal to zero at all times ($c(x = \infty, t \geq 0) = 0$), gives the concentration of the contaminant c at a distance x from the source as a function of time t (Fetter 1999):

$$\frac{c(x,t)}{c_o} = \frac{1}{2}\left[erfc\left(\frac{x-(v/R_d)\cdot t}{2\sqrt{(D/R_d)\cdot t}}\right) + \exp\left(\frac{vx}{D}\right) erfc\left(\frac{x+(v/R_d)\cdot t}{2\sqrt{(D/R_d)\cdot t}}\right)\right] \quad (15)$$

where v is advection velocity, R_d is retardation factor and D is coefficient of hydrodynamic dispersion. Equation 15 can be used for composite liners as well, by calculating advection velocity as:

$$v = \frac{k_{eq}\cdot i}{n_s} \quad (16)$$

where i is calculated from Eq. 3, n_s is clay porosity (n_{CCL} or n_{GCL}), and by replacing the term (D/R_d) with an equivalent coefficient of hydrodynamic dispersion, $D_{eq,Rd}$, which is the sum of the weighted diffusion coefficient proposed by Foose et al. (1999) and a second term that accounts for mechanical dispersion:

$$D_{eq,Rd} = \left(\frac{h_{GM}+h_s}{\frac{h_{GM}}{K^p_{GM}\cdot D_{GM}} + \frac{h_s}{(D_s/R_d)\cdot n_s}}\right) + a_L\cdot\frac{k_{eq}\cdot i}{n_s\cdot R_d} \quad (17)$$

where K^p_{GM} is the leachate-geomembrane partition coefficient for the contaminant considered, D_{GM} and D_s are diffusion coefficients in the geomembrane and the clay (D_{CCL} or D_{GCL}), respectively, and a_L is longitudinal dispersivity. When Eq. 15 is evaluated at $x = h$, it gives the concentration of a leachate constituent at the downstream face of the liner.

Alternatively, instead of the contaminant concentration, it may be of interest to calculate the contaminant mass flux exiting the liner, i.e. a quantity that evaluates impact to groundwater more directly. Total mass flux is the sum of the advective flux, J_A, and the flux due to hydrodynamic dispersion, J_D, which are given for a homogeneous layer of hydraulic conductivity k and porosity n as (Shackelford 1990):

$$J_A(x,t) = \frac{1}{2}k\cdot i\cdot c_o\left[erfc\left(\frac{x-(v/R_d)\cdot t}{2\sqrt{(D/R_d)\cdot t}}\right) + \exp\left(\frac{v\cdot x}{D}\right) erfc\left(\frac{x+(v/R_d)\cdot t}{2\sqrt{(D/R_d)\cdot t}}\right)\right] \quad (18)$$

$$J_D(x,t) = \frac{1}{2}nDc_o\left\{\frac{2\exp\left[-\left(\frac{x-(v/R_d)t}{2\sqrt{(D/R_d)t}}\right)^2\right]}{\sqrt{\pi\cdot(D/R_d)t}} - \frac{v}{D}\exp\left(\frac{v\cdot x}{D}\right) erfc\left(\frac{x+(v/R_d)t}{2\sqrt{(D/R_d)t}}\right)\right\}. \quad (19)$$

Equations 18 and 19 can be used for composite liners as well, with the following modifications. In both equations, advection velocity, v, is calculated with Eq. 16 and the term (D/R_d) is replaced by the equivalent weighted coefficient of hydrodynamic dispersion, $D_{eq,Rd}$, given by Eq. 17. In addition, for Eq. 18, hydraulic conductivity, k, is replaced by the equivalent hydraulic conductivity given by Eq. 1 and the hydraulic gradient, i, is given by Eq. 3. Finally, in Eq. 19, porosity (n) is assigned the value of clay porosity (n_{CCL} or n_{GCL}), which is a conservative assumption. The total mass flux exiting the liner is given by the sum of Eqs. 18 and 19, evaluated at $x = h$, and multiplied by the total area of the landfill base.

The total mass flux given by the sum of Eqs. 18 and 19 corresponds to the boundary conditions of Eq. 15. However, the boundary condition $c(x = \infty, t \geq 0) = 0$ implies that the natural soil below the liner impedes migration of contaminants to the same degree as the liner, which is not a conservative assumption. For a more conservative estimate of landfill impact, an alternative assumption can be made, namely that any contaminant arriving at the downstream face of the liner is instantaneously removed by transport mechanisms in the underlying soil, so that contaminant concentration remains zero at the downstream face at all times ($c(x = h, t \geq 0) = 0$). This boundary condition corresponds to higher total mass flux exiting the liner, i.e. at $x = h$, which is equal to (Rabideau and Khandelwal 1998):

$$J(x,t) = c_o \exp\left(\frac{x \cdot v}{2D}\right)\left\{\frac{nv}{2\sinh\left(\frac{x \cdot v}{2D}\right)} + \frac{2\pi^2 nD}{x^3} \cdot \sum_{m=1}^{\infty} \frac{(-1)^m m^2 4(D)^2 x^2}{x^2 v^2 + 4m^2\pi^2 (D)^2} \cdot \exp\left[-\frac{t}{R_d}\left(\frac{v^2}{4D} + \frac{Dm^2\pi^2}{x^2}\right)\right]\right\}. \quad (20)$$

It was not deemed relevant to apply Eq. 20 for the intact composite layer. Instead, it will be used for the transport calculations in the case of geomembrane with defects, which are presented next. Because the effectiveness of the geomembrane is significantly different for inorganic and organic contaminants, the two cases are considered in separate sections.

2.2.2 Geomembrane with Defects: Transport of Inorganic Contaminants

Geomembranes are very effective barriers to the transport of inorganic contaminants (Rowe et al. 2004). Hence, in the case of geomembrane with defects, transport in the area around them is the main concern (Katsumi et al. 2001).

The concentration of the inorganic contaminant is given by Eq. 15, which concerns only the area around a defect within the clay layer. It follows that Eq. 15 is evaluated by replacing v with the advection velocity in clay, $v_s = k_s\, i/n_s$, where i is given by Eq. 3 for $h = h_s$, and D with the coefficient of hydrodynamic dispersion in clay, $D_s + a_L v_s$.

Similarly, the mass flux of the inorganic contaminant is calculated by using Eqs. 18 and 19, evaluated using $v = v_s$ and $D = D_s + a_L v_s$, as previously defined. In addition, Eq. 18 is evaluated for $k = k_s$ and i from Eq. 3 for $h = h_s$. The total mass flux exiting the liner is equal to:

$$J_{total} = [J_A(x = h_s, t) + J_D(x = h_s, t)] \cdot N \cdot A_e \quad (21)$$

where N is the frequency of the defects and A_e is the effective transport area around the defect, which can be approximated, according to Katsumi et al. (2001), as:

$$A_e = Q/k_s \cdot i \quad (22)$$

where Q is the flow rate associated with the defect, which can be calculated with Eq. 4 (Giroud 1997) or Eq. 6 (Rowe 1998) and i is given by Eq. 3 for $h = h_s$.

As previously mentioned, instead of using Eqs. 18 and 19, a more conservative estimate of mass flux is obtained by Eq. 20, which corresponds to the boundary condition $c(x = h_s, t \geq 0) = 0$, or $c_{hs} = 0$ for short, evaluated for the parameters corresponding to the clay liner, v_s and $D_s + a_L v_s$. The total mass flux is again found by multiplying Eq. 20 with the frequency of the defects, N, and the total effective area, A_e, from Eq. 22.

2.2.3 Geomembrane with Defects: Transport of Organic Contaminants

In contrast to inorganic contaminants, geomembranes are not effective barriers to organic contaminants. Molecular diffusion takes place over the entire area of the geomembrane, hence the contribution of defects is considered negligible, as shown by Foose et al. (2002). Katsumi et al. (2001) proposed the following additional simplifications, which are supported by comparisons between analytical and numerical results obtained by Foose et al. (1999): (1) due to the geomembrane's small thickness, diffusion through the geomembrane is ignored as insignificant, in comparison to diffusion through clay and (2) advection through the clay can also be ignored. Under these conditions, the main transport mechanism is diffusion through the clay layer and the concentration at its downstream face is given as (Fetter 1999):

$$\frac{c(x = h_s, t)}{c_o} = erfc\left[\frac{h_s}{2\sqrt{(D_s/R_d) \cdot t}}\right]. \quad (23)$$

The total mass flux is calculated by multiplying the entire area of the landfill base with the following simplified version of Eq. 19 (Katsumi et al. 2001):

$$J(h_s, t) = \frac{n_s c_o}{\sqrt{\pi t / D_s R_d}} \exp\left[-\frac{h_s^2 R_d}{4 D_s t}\right]. \quad (24)$$

The conservative estimate for the mass flux for the boundary condition of $c_{hs} = 0$ is obtained as the limit of Eq. 20, i.e. as the advection velocity within the clay, v_s, tends to zero (Foose et al. 2001b):

$$\lim_{v_s \to 0} J(h_s, t) = \frac{c_o D_s n_s}{h_s}\left\{1 + \frac{2\pi^2}{h_s^2} \cdot \sum_{m=1}^{\infty} \frac{(-1)^m m^2 4(D_s)^2 h_s^2}{4m^2\pi^2 (D_s)^2} \cdot \exp\left[-\frac{t}{R_d}\left(\frac{D_s m^2 \pi^2}{h_s^2}\right)\right]\right\}. \quad (25)$$

2.2.3.1 Evaluating Mass Flux at a Compliance Point Below the Liner It is sometimes of interest to take into account the contribution to impeding migration of organic contaminants provided by the soil layer underneath the liner. For this case, the mass flux can be calculated for diffusion through a two-layer system, i.e. the combined clay liner-attenuation layer, at some point x_{AL} within the attenuation layer as follows (Foose 2002):

$$J(\xi_{\mathrm{A}}, \mathrm{T_A}) = \frac{2c_o D_{AL} n_{AL} \psi_{\mathrm{A}}}{1 + \eta_{\mathrm{A}} \sqrt{\pi T_A}} F_N \tag{26}$$

$$\xi_{\mathrm{A}} = \frac{\psi_{\mathrm{A}} x_{AL}}{h_s} \tag{27}$$

$$\psi_{\mathrm{A}} = \sqrt{\frac{D_{AL} \cdot R_{d,AL}}{D_s \cdot R_{d,s}}} \tag{28}$$

$$T_A = \frac{D_{AL} t}{R_{d,AL} x_{AL}^2} \tag{29}$$

$$\eta_{\mathrm{A}} = \frac{D_{AL} \cdot n_{AL}}{D_s \cdot n_s} \psi_{\mathrm{A}} \tag{30}$$

$$F_N = \sum_{v=0}^{\infty} \left(\frac{\eta_A - 1}{\eta_A + 1} \right)^v \exp\left[- \left(\frac{(2v+1) + \xi_A}{2\xi_A \sqrt{T_A}} \right)^2 \right] \tag{31}$$

where D_{AL}, n_{AL} and $R_{d,AL}$ are diffusion coefficient, porosity and retardation factor for the attenuation layer, respectively, and $R_{d,s}$ is retardation factor for clay. It should be noted that instead of using Eq. 31, the term F_N can be determined from graphs provided by Foose (2002), as a function of η_A, ξ_A, T_A. It should also be added, that the analytical method proposed by Foose (2002) agreed very well with the results of numerical solutions of the two-layer diffusion problem (Foose et al. 2001b).

3 Application of Methods

For all solutions, calculations can be made with readily available spreadsheet applications. In this study, calculations were performed with Excel®, with the exception of Eqs. 20 and 25, for which the series evaluation feature of Maple® was preferred.

3.1 Flow and Transport Domain

The methods presented in Sect. 2 were applied for the two composite liners shown in Fig. 2. Composite liner 1 (GM-CCL) consists of geomembrane underlain by 1 m of compacted clay (Fig. 2a). Composite liner 2 (GM-GCL) consists of geomembrane underlain by a geosynthetic clay layer of thickness equal to 7 mm (0.007 m) (Fig. 2b). For both liners, the thickness of the geomembrane is equal to 1.5 mm (0.0015 m). For the GM-GCL liner, the contribution of a 1 m-thick attenuation layer (Fig. 2c) will also be considered.

3.2 Boundary Conditions

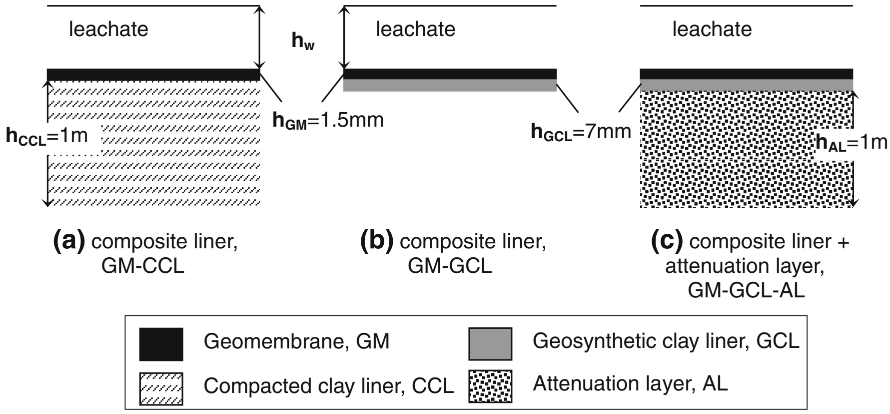
3.2.1 Flow Modelling

One-dimensional steady state flow is assumed for a constant height of accumulated leachate, h_w, at the upstream face of the composite liner. Calculations are carried out for a range of leachate heights. The minimum value considered, $h_w = 0.3$ m, is the maximum height of leachate allowed by US regulations (US EPA 2010). The value of $h_w = 0.3$ m corresponds to normal operating conditions and represents long-term impact. Calculations are repeated for $h_w = 1$, 3 and 6 m, in order to model incidents of failure of the leachate removal system. However, if such incidents occur, they are bound to be of limited duration and, hence, their impact will only be short-term. At the downstream face of the composite liner, leachate is assumed to be at atmospheric pressure.

3.2.2 Transport Modelling

Transport calculations are performed assuming constant concentration of leachate constituents, $c(x = 0, t) = c_o$. The ion of chloride and benzene were selected to model inorganic and organic contaminants in the leachate, respectively. Table 1 gives the range of concentrations of chloride and benzene detected in leachate samples, as reported by Qian et al. (2002), which vary from few to thousands milligrams per liter. Within this range, a value of 200 mg/l was selected for the calculations for both model contaminants. As already mentioned, the other boundary condition assumed is $c(x = \infty, t) = 0$, with the exception of the conservative mass flux calculation corresponding to instantaneous removal of contaminant from the downstream face of the liner, $c(x = h, t) = 0$ for Eqs. 20 and 25.

Fig. 2 Composite liners considered in flow and transport calculations



3.3 Parameter Selection

The values of the input parameters used in the calculations are listed in Table 1, for the composite liners, and in Table 2, for the attenuation layer underlying the landfill liner. Few of the parameters needed are routinely evaluated in the laboratory or in the field, hence guidance from the literature is necessary. To this end, Table 1 also includes for each parameter a range of values reported in the literature, based to a significant extent on the compilation of values provided by Rowe (1998) and Rowe et al. (2004). Additional guiding comments for some of the input parameters are provided in the remainder of this section.

3.3.1 Flow-Related Parameters

Landfill regulations typically require that the *hydraulic conductivity of the clay liner, k_{CCL}*, do not exceed 10^{-9} m/s (US EPA 2010; EC 1999). This is the value used in all calculations. However, a survey of landfills, where typical quality assurance practices were followed and hydraulic conductivity was measured in the field, indicated that only 74% of the surveyed landfills met the regulation requirements for hydraulic conductivity (Benson et al. 1999). For the *porosity of the clay liner, n_{CCL}*, a value of 0.54 was assumed, which is near the upper end of reported measurements (Shackelford and Daniel 1991), whereas no distinction between effective and total porosity was made according to the findings of Kim et al. (1997).

The *hydraulic conductivity of the geosynthetic clay liner, k_{GCL}*, is typically provided by the manufacturer and can also be measured at geotechnical laboratories specializing in testing of geosynthetic materials. Reported values of k_{GCL} are two orders of magnitude lower compared to compacted clay, in the range of 5×10^{-12}–1×10^{-11} m/s (Estornell and Daniel 1992; Ruhl and Daniel 1997; Rowe et al. 2004). Increases in hydraulic conductivity of clay are possible when the composition of the pore fluid varies. However, for leachate of modest strength, these changes were found to be contained within an order of magnitude (Ruhl and Daniel 1997; Rowe et al. 2004). Hence, a value at the high end of the reported values, $k_{GCL} = 10^{-11}$ m/s, is a reasonable choice. For the *porosity of the geosynthetic clay liner, n_{GCL}*, a value of 0.7 was assumed, closer to the upper end of reported measurements (Rowe 1998; Rowe et al. 2004).

The *hydraulic conductivity of the geomembrane, k_{GM}*, is a parameter meriting separate discussion, especially since it is reported to be equal to zero in some product specification documents. Although migration through the geomembrane is not a hydraulic phenomenon, fluids move through the geomembrane in vapor form due to molecular diffusion. Accordingly, a water–vapor transmission test has been employed, whereby the volume of vapor passing through the geomembrane can be measured. On the basis of the measured vapor volume, an equivalent hydraulic conductivity can be determined (Koerner 1998). As a reminder of the diffusive nature of water movement

Table 1 Input parameters required for flow and transport modelling calculations selected from range reported in the literature

Parameter	Value selected		Range reported	References
Leachate constituents				
Concentration, c_o (mg/l)	Chloride	200	31–5,475	Qian et al. (2002)
	Benzene	200	4–1,080	Qian et al. (2002)
Compacted clay liner (CCL)				
Thickness, h_{CCL} (m)		1	–	
Hydraulic conductivity, k_{CCL} (m/s)		1.0×10^{-9}	6.0×10^{-10}–1.0×10^{-8}	Benson et al. (1999)
Porosity, n_{CCL}		0.54	0.3–0.6	Shackelford and Daniel (1991), Kim et al. (1997)
Diffusion coefficient, D_{CCL} (m^2/s)	Chloride	6.3×10^{-10}	4.5×10^{-10}–1.64×10^{-9}	Shackelford and Daniel (1991)
	Benzene	6.3×10^{-10}	2.5×10^{-10}–5.0×10^{-10}	Rowe et al. (2004)
Geosynthetic clay liner (GCL)				
Thickness, h_{GCL} (m)		0.007	–	
Hydraulic conductivity, k_{GCL} (m/s)		1.0×10^{-11}	5.0×10^{-12}–1.0×10^{-11}	Rowe et al. (2004), Estornell and Daniel (1992), Ruhl and Daniel (1997)
Porosity, n_{GCL}		0.7	0.51–0.83	Rowe et al. (2004), Rowe (1998)
Diffusion coefficient, D_{GCL} (m^2/s)	Chloride	1.6×10^{-10}	3.5×10^{-11}–4.0×10^{-9}	Rowe (1998), Lake and Rowe (2000)
	Benzene	1.6×10^{-10}	3.7×10^{-10}–4.0×10^{-10}	Rowe et al. (2005)
Geomembrane (GM)				
Thickness, h_{GM} (m)		0.0015	–	
"Hydraulic" conductivity, k_{GM} (m/s)		1.0×10^{-15}	1.1×10^{-15}–1.2×10^{-15}	Haxo et al. (1984)
Combined partition-diffusion term, $K^p_{GM} \cdot D_{GM}$ (m^2/s)	Chloride	8.0×10^{-17}	8.0×10^{-17}–2.4×10^{-16}	Rowe et al. (2004)
	Benzene	3.4×10^{-11}	2.1×10^{-12}–1.05×10^{-11}	Rowe (1998)
Geomembrane defects				
Radius of circular defect, r_o (mm)		5.65	1–5.65	Giroud and Bonaparte (1989), Gilbert and Tang (1995)
Frequency of defects, N (1/m^2)		2.5/10,000	2.5/10,000–130/10,000	Giroud and Bonaparte (1989), Gilbert and Tang (1995)
Geomembrane (GM)–clay (CCL or GCL) interface				
Transmissivity, $\theta_{GM\text{-}CCL}$ (m^2/s)	Good contact	1.6×10^{-8}	3.2×10^{-9}–5.5×10^{-7}	Rowe et al. (2004)
	Poor contact	1.0×10^{-7}		
Transmissivity, $\theta_{GM\text{-}GCL}$ (m^2/s)	Good contact	6.0×10^{-9}	1.0×10^{-10}–4.0×10^{-9}	Foose et al. (2001a)

through the geomembrane, the term "hydraulic" appears in quotes in Table 1 when it refers to k_{GM}. In this work, the value determined by Haxo et al. (1984) for high-density polyethylene was used.

For the characteristics of the defects, Giroud and Bonaparte (1989) assumed a *frequency* N of 2.5 holes/10,000 m^2 and a *radius* r_o in the range of 1–5.65 mm. Gilbert and Tang (1995), who studied constructed composite bottom liners of hazardous waste landfills, give a range of 3.7–5.5 mm and 7.5–130 holes/10,000 m^2, for the mean values of r_o and N, respectively. Defect size and frequency are expected to decrease with quality control measures; electrical leak detection systems have been demonstrated to be very

Table 2 Input parameters for transport modelling in attenuation layer

Parameter		Value selected
Thickness, x_{AL} (m)		1
Porosity, n_{AL}		0.3
Diffusion coefficient, D_{AL} (m^2/s)	Chloride	9.5×10^{-10}
	Benzene	9.5×10^{-10}

effective in this regard, compared to conventional inspection methods (Darilek and Laine 2001).

Lastly, the value of transmissivity, θ, needs to be determined in Eq. 11 when applying the method proposed by Rowe (1998) for the calculation of flow rate (Eq. 6). It is reminded that Giroud's (1997) solution for flow rate, Eq. 4, also incorporates transmissivity, based on experiments carried out by Brown et al. (1987), but only differentiates between good and poor contact, i.e. lower and higher transmissivity. By equating the flow rates obtained with Eqs. 4 and 6 for $h_w = 0.3$ m, Rowe (1998) obtained for the *transmissivity of the space between geomembrane and clay,* $\theta_{\text{GM-CCL}}$, a range of 3.2×10^{-9}m^2/s (good contact, $k_{CCL} = 10^{-10}$ m/s)–5.5×10^{-7} m^2/s (poor contact, $k_{CCL} = 10^{-8}$ m/s). For $k_{CCL} = 10^{-9}$ m/s, Rowe (1998) found $\theta_{\text{GM-CCL}}$ to be equal to 1.6×10^{-8}m^2/s (good contact) and 1.0×10^{-7} m^2/s (poor contact), which are the values used in this study. For the *transmissivity of the geomembrane-geosynthetic clay interface,* $\theta_{\text{GM-GCL}}$, Harpur et al. (1993) measured in the laboratory a range of 6×10^{-12}–2.2×10^{-10} m^2/s. By taking into account that transmissivity in the field is expected to be higher than in the laboratory, Foose et al. (2001a) estimated that the values measured by Harpur et al. (1993) correspond to a range of field values of 1×10^{-10}–4×10^{-9}m^2/s, for good contact conditions. For the calculations performed herein only the case of good contact between geomembrane and geosynthetic liner was considered, since it is more easily achievable, compared to composite liners with compacted clay.

3.3.2 Transport-Related Parameters

Measured values of *diffusion coefficient in clay,* D_{CCL}, vary in a limited range, both for inorganic and organic contaminants (Rowe et al. 2004). The range of values listed in Table 1 corresponds specifically to chloride and benzene. Since these differ by less than an order of magnitude, the same value of diffusion coefficient was used in the calculations for both leachate constituents, equal to $D_{CCL} = 6.3 \times 10^{-10}$ m^2/s. This value is consistent with the diffusion coefficient range of 5–6 $\times 10^{-10}$ m^2/s measured in a long-term experiment for bromide transport through a field-scale compacted clay liner (Willingham et al. 2004).

Measured values of *diffusion coefficient in geosynthetic* clay, D_{GCL}, are not significantly different than those in clay (Rowe 1998; Rowe et al. 2005), with the exception of a lower value (3.5×10^{-11} m^2/s) reported for chloride by Lake and Rowe (2000). Similarly to compacted clay, the same value of diffusion coefficient was used in the calculations for both leachate constituents. Compared to compacted clay, a somewhat lower diffusion coefficient was selected for geosynthetic clay, equal to $D_{GCL} = 1.6 \times 10^{-10}$ m^2/s.

Transport modelling through the geomembrane involves the mass transfer term $K_{GM}^{p} \cdot D_{GM}$, which combines the effects of the *fluid-geomembrane partition coefficient* K_{GM}^{p} and the *diffusion coefficient within the geomembrane,* D_{GM}. Rowe et al. (2004) provide values of K_{GM}^{p} and D_{GM} for several contaminants, including chloride and benzene. The product of the two parameters is listed in Table 1. As already mentioned, geomembranes are very effective barriers for inorganic constituents, which is consistent with the six orders of magnitude difference between the mass transfer product $K_{GM}^{p} \cdot D_{GM}$ used in the calculations for chloride, 8.0×10^{-17} m^2/s, and for benzene, 3.4×10^{-11} m^2/s.

Longitudinal dispersivity, a_L, was calculated on the basis of the approximation $a_L = 0.1x$ (Fetter 1999), where x is the length of the flow and transport domain, i.e. the thickness of the liner. When compared to dispersivity values determined from measurements (Neuman 1990), this simplified approximation of the relationship between dispersivity and scale of the domain is expected to overestimate dispersivity for the scale of the problems considered herein, i.e. ranging over fractions of the meter to a few meters.

Considering the significant variation in the magnitude of partition coefficients in soils, transport calculations were carried out for the conservative case of zero sorption, corresponding to retardation factor $R_d = 1$. As part of the parametric study (Sect. 5),

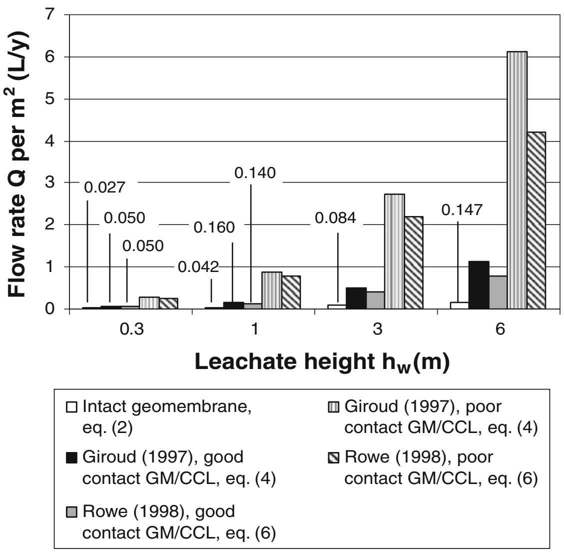


Fig. 3 Calculated flow rate for the geomembrane-compacted clay composite liner with the assumption of intact geomembrane and through geomembrane defects with the solutions of Giroud (1997) and Rowe (1998)

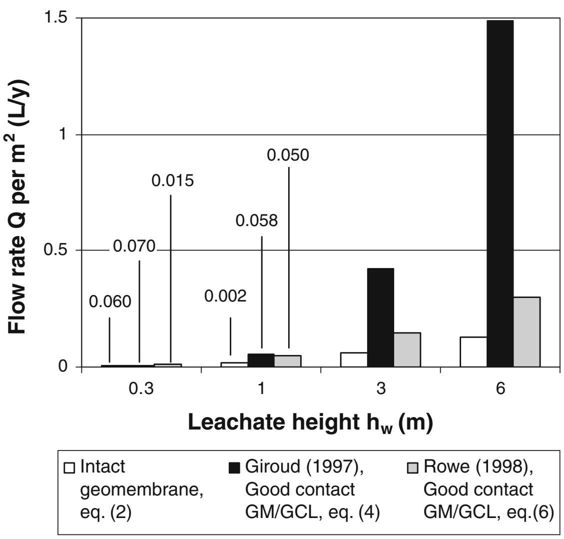


Fig. 4 Calculated flow rate for the geomembrane-geosynthetic clay composite liner with the assumption of intact geomembrane and through geomembrane defects with the solutions of Giroud (1997) and Rowe (1998)

calculations were repeated for higher values, $R_d = 2$ and $R_d = 4$. Measured partition coefficients for inorganic (Shackelford and Daniel 1991) and organic (Rowe et al. 2004) leachate constituents indicate that higher R_d values can be expected for clays of high surface area.

4 Results of Flow and Transport Calculations

4.1 Flow Modelling

For the calculation of flow rate through defects, the solution of Rowe (1998), Eq. 6, has the advantage of demonstrated good agreement with results from numerical solutions (Foose et al. 2001a). However, its application is more complex, compared to Giroud's (1997) solution, Eq. 4. Hence, it is of interest to investigate how the two approaches compare. The results of flow rates obtained with the two approaches, as well as for the assumption of the intact geomembrane, are shown in Figs. 3 and 4 for the composite liners with compacted clay (GM-CCL) and geosynthetic clay (GM-GCL), respectively.

It is reminded that the transmissivity value used in the calculations for composite liner GM-CCL is the value for which Eqs. 4 and 6 give the same flow rate for leachate height $h_w = 0.3$ m. Hence, the agreement of the two methods in Fig. 3 and $h_w = 0.3$ m is expected. Nevertheless, the agreement continues to be good over the entire range of leachate heights considered, i.e. past the limit of applicability of Eq. 4, for the GM-CCL composite liner for the case of good contact. In contrast, the agreement is good only up to $h_w = 1$ m for the GM-GCL composite liner.

When comparing the performance of the two composite liners, it is clear from the different extent of the flow rate axes in Figs. 3 and 4 that the composite liner with the geosynthetic clay offers better protection of the underlying soil. It is also noted that for low values of leachate height, the flow rate through the intact liner is on the same order of magnitude as the flow rate through the defects, and, hence, should not be ignored for the assumed defect size and frequency.

4.2 Transport Modelling

The concentrations of chloride and benzene at the downstream face of the two liners are shown in Figs. 5 and 6, respectively. Figure 5 shows that the assumption of the intact geomembrane is inappropriate for the transport of inorganic contaminants, for both categories of composite liners. On the contrary, transport of organic contaminants is comparable for geomembrane without or with defects (see Fig. 6), since the main transport mechanism in both cases is diffusion over the entire landfill base.

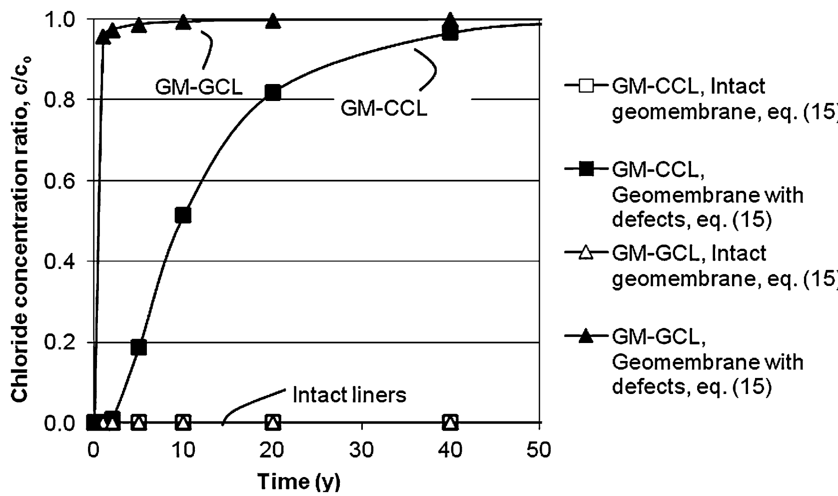


Fig. 5 Calculated concentration ratio of chloride at the downstream face of composite liners GM-CCL and GM-GCL for the cases of intact geomembrane and geomembrane with defects

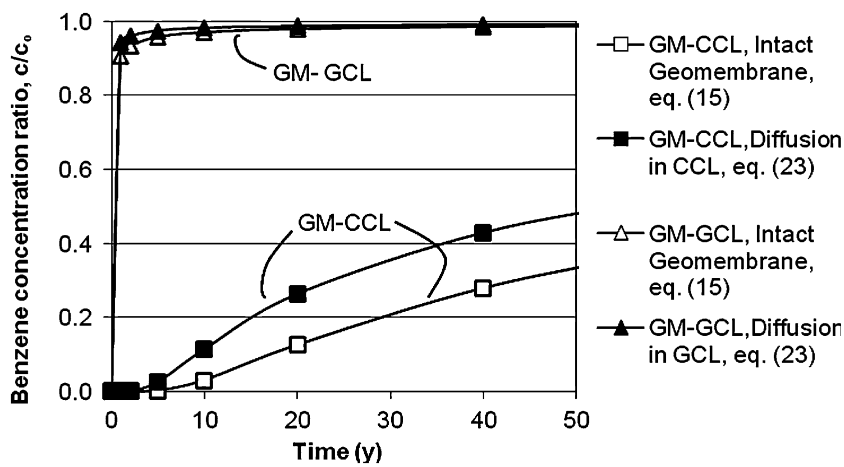


Fig. 6 Calculated concentration ratio of benzene at the downstream face of composite liners GM-GCL and GM-GCL for the cases of intact geomembrane and geomembrane with defects

The comparison of the performance of the two composite liners, as depicted in Figs. 5 and 6, reveals the lower protection offered by the GM-GCL liner, which is more pronounced for organic contaminants. Although the small hydraulic conductivity of the geosynthetic clay liner results in lower flow rates compared to compacted clay, its small thickness cannot provide the effective barrier to contaminant transport offered by the much thicker clay liner. For the GM-CCL liner, it takes a concentration of chloride and benzene equal to $c_o/10$ 4.6 and 9.5 years, respectively, to reach the downstream face, whereas the same concentration reaches the downstream face of the GM-GCL liner in less than a day, for both contaminants.

The results of transport calculations are also presented in terms of chloride (Fig. 7) and benzene (Fig. 8) mass exiting the landfill base per unit area for the cases of geomembrane without and with defects. For the case with defects, mass flux calculations correspond to two cases of boundary conditions: $c(x = \infty, t \geq 0) = 0$ and $c(x = h_s, t \geq 0) = 0$. The latter corresponds to Eqs. 20 and 25 for chloride and benzene, respectively. It is reminded that calculation of the mass of inorganic contaminants involves the flow rate through the defects (Eqs. 21 and 22), which is obtained with Giroud's (1997) solution for good contact conditions for both composite liners.

The results for chloride transport through the intact geomembrane plot below the range of Fig. 7, confirming the inappropriateness of the intact geomembrane assumption when studying the transport of inorganic contaminants through composite liners. From the same figure, it is also apparent that the conservative assumption of $c(x = h_s, t \geq 0) = 0$

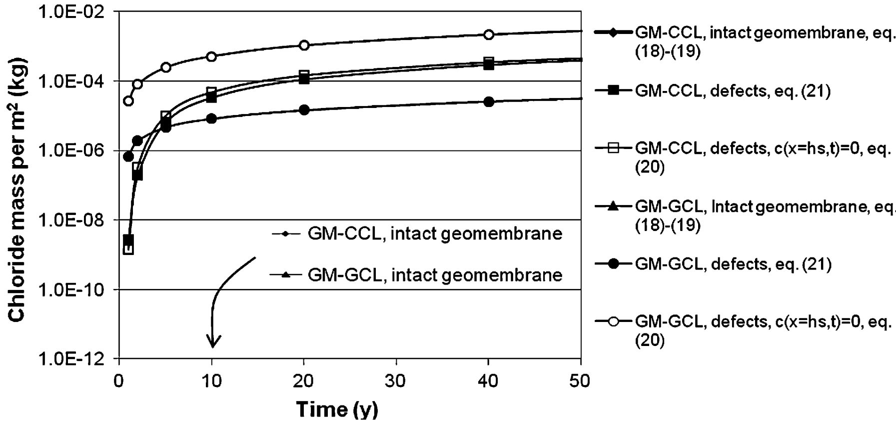


Fig. 7 Calculated mass of chloride at the downstream face of composite liners GM-CCL and GM-GCL for the cases of intact geomembrane and geomembrane with defects for the baseline boundary condition $c(x = \infty, t \geq 0) = 0$ and for $c(x = h_s, t \geq 0) = 0$

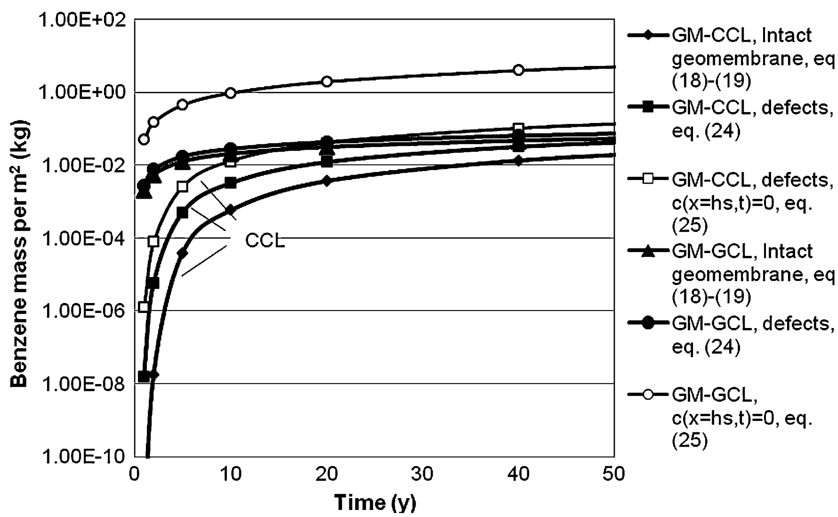


Fig. 8 Calculated mass of benzene at the downstream face of composite liners GM-CCL and GM-GCL for the cases of intact geomembrane and geomembrane with defects for the baseline boundary condition $c(x = \infty, t \geq 0) = 0$ and for $c(x = h_s, t \geq 0) = 0$

(Eq. 20) makes an appreciable difference in the calculated mass, close to two orders of magnitude, for the GM-GCL liner, but not for the composite liner with the compacted clay. Foose et al. (2002) first observed that when performance is evaluated in terms of contaminant mass (instead of contaminant concentration), the long-term protection offered by the GM-GCL liner is more comparable to the GM-CCL liner, due to the lower flow rate through the GM-GCL liner involved in the calculation of mass flux. Herein it is shown that this conclusion is only valid for the non-conservative boundary condition of $c(x = \infty, t \geq 0) = 0$ corresponding to Eq. 21.

When transport of benzene is concerned (Fig. 8), the performance of the GM-CCL liner is again found to be better, with smaller mass exiting the landfill base compared to the GM-GCL liner. It is observed that, again, the assumption of instantaneous contaminant removal at the downstream face makes a difference of about two orders of magnitude for the GM-GCL liner, but less so for the composite liner with the compacted clay. Moreover, the assumptions of intact geomembrane and geomembrane with defects give comparable results, as observed from the concentration plots as well (Fig. 6).

Comparison of Figs. 7 and 8 shows that both composite liners are more effective barriers to transport of inorganic contaminants (Fig. 7) compared to organic contaminants (Fig. 8). The difference in terms of contaminant mass is about three orders of magnitude.

Finally, Fig. 9 again depicts the performance of the two composite liners in terms of benzene mass exiting at the downstream liner face and also includes results obtained from Eq. 26 for the combination of a GM-GCL composite liner with the 1 m-thick underlying

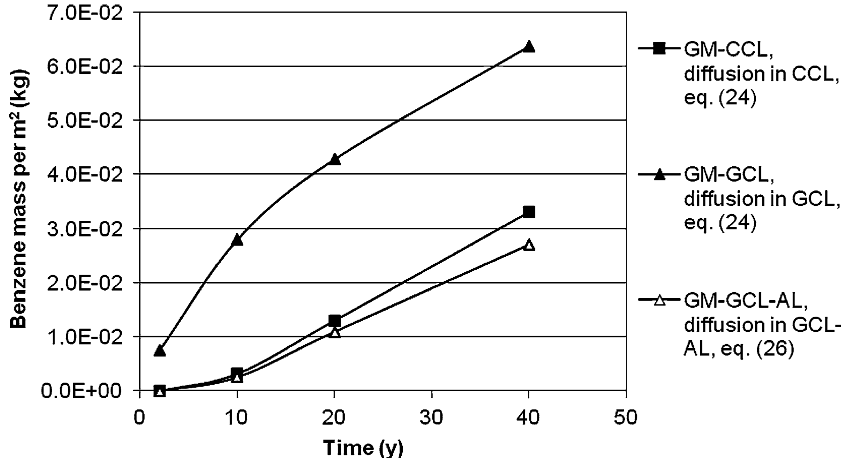


Fig. 9 Calculated mass of benzene at the downstream face of composite liner GM-CCL, composite liner GM-GCL and of the combination of GM-GCL with an attenuation layer (AL)

attenuation layer (AL) shown in Fig. 2c. For the GM-GCL-AL system, benzene mass is calculated at the downstream face of the attenuation layer. According to Fig. 9, in terms of mass flux at 1 m below the geomembrane, the GM-GCL-AL can provide comparable protection to the GM-CCL composite liner.

5 Parametric Study

The sensitivity of the results for flow rate through the intact composite liner to the values of the hydraulic conductivity is discussed herein with the aid of Figs. 10 and 11. The baseline results correspond to the values of hydraulic conductivities for compacted clay, k_{CCL}, geosynthetic clay, k_{GCL}, and geomembrane, k_{GM}, listed in Table 1. Flow rate calculations were repeated for an increase in the hydraulic conductivity of the geomembrane by two orders of magnitude and a further increase also by two orders of magnitude in the hydraulic conductivity of compacted (Fig. 10) and geosynthetic clay (Fig. 11). The increase in hydraulic conductivity of the geomembrane results in a comparable increase of the flow rate in both liners. However, the additional increase in the hydraulic conductivity of the clay results in a slight further increase in flow rate. It follows that the value of the

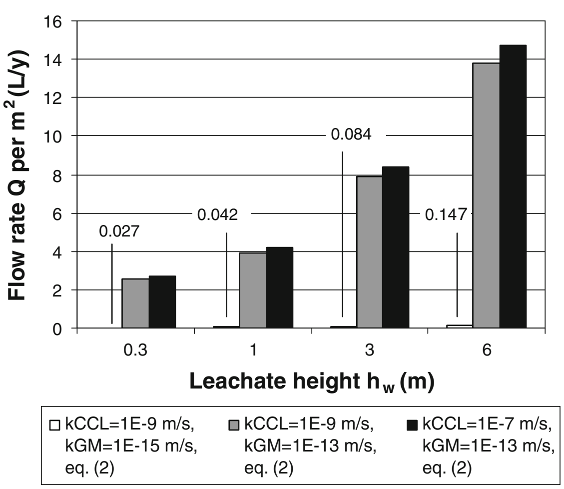


Fig. 10 Calculated flow rate through the intact composite liner with compacted clay for (a) the baseline hydraulic conductivity values k_{GM}, k_{CCL} (Table 1) (b) increased k_{GM} by two orders of magnitude and (c) increased k_{GM} and k_{CCL} by two orders of magnitude

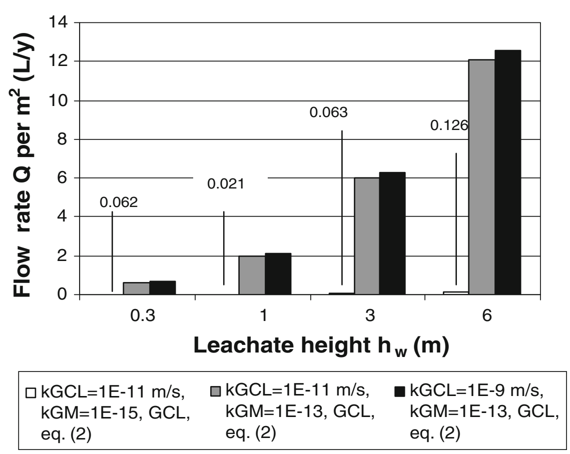


Fig. 11 Calculated flow rate through the intact composite liner with geosynthetic clay for (a) the baseline hydraulic conductivity values k_{GM}, k_{GCL} (Table 1) (b) increased k_{GM} by two orders of magnitude and c) increased k_{GM} and k_{GCL} by two orders of magnitude

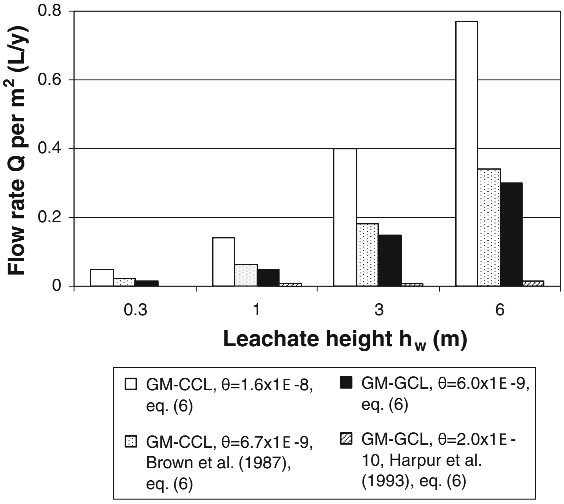


Fig. 12 Calculated flow rate through geomembrane defects with the solution of Rowe (1998) for the baseline transmissivity values $\theta_{GM\text{-}CCL}$ (good contact) and $\theta_{\text{GM-GCL}}$ (Table 1) and for transmissivity values equal to about 1/3 the baseline values

hydraulic conductivity of the geomembrane is the controlling factor in calculating flow rate through the intact composite liner.

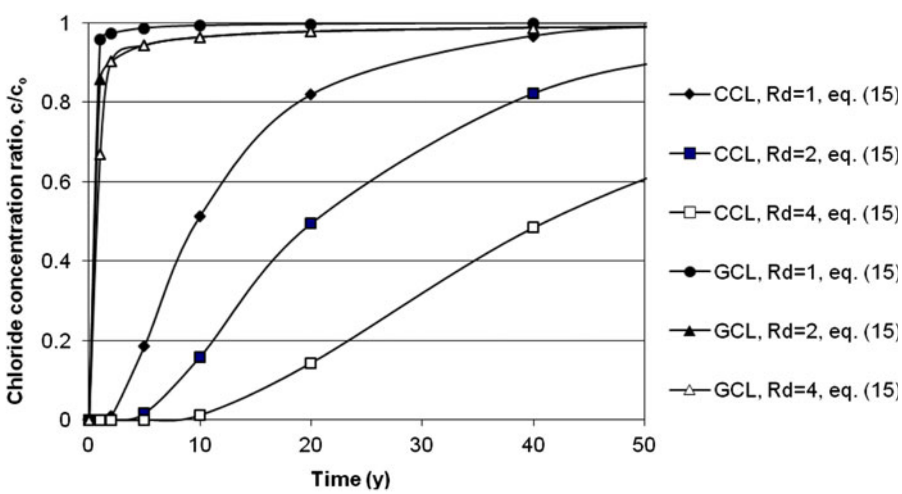
Figure 12 shows the effect of transmissivity of the space between the geomembrane and the clay layer on the flow rate through defects calculated with Rowe's (1998) solution. The baseline results correspond to the transmissivity values listed in Table 1 for good contact conditions. Calculations were repeated for transmissivity values within the range listed in Table 1. The specific values selected correspond to values measured for compacted clay and geosynthetic clay by Brown et al. (1987) and Harpur et al. (1993), respectively, and are about 3 times smaller than the corresponding baseline values. The resulting flow rates were about half the baseline values in the case of the composite liner with compacted clay. The difference is significant for the composite liner with the geosynthetic clay, for which flow rate decreases as much as twenty times.

The effect of sorption, expressed through the value of the retardation factor, R_d, is shown for chloride and benzene in Figs. 13 and 14, respectively. The baseline results correspond to transport through defects and $R_d = 1$, also shown in Figs. 5 (chloride) and 6 (benzene). Comparison of results in both figures for the GM-CCL composite liners shows the significant effect of retardation factor, as also demonstrated by Katsumi et al. (2001). The present study shows that this trend is not observed for composite liners with geosynthetic clay, for which sorption has very little effect.

6 Comparison on Alternative Designs and Design Criteria Used

Results similar to those presented in Sect. 4 are summarized herein in a table format to facilitate conclusions regarding use of alternative liners and of alternative criteria for equivalency or protection. The results for the GM-CCL and GM-GCL composite liners are compared to those of a reference clay layer of $h_{CCL} = 1$ m and $k_{CCL} = 1 \times 10^{-9}$ m/s. In order to facilitate the comparison, the design parameters of the

Fig. 13 Influence of sorption on calculated concentration ratio of chloride at the downstream face of composite liners GM-CCL and GM-GCL for the case of geomembrane with defects



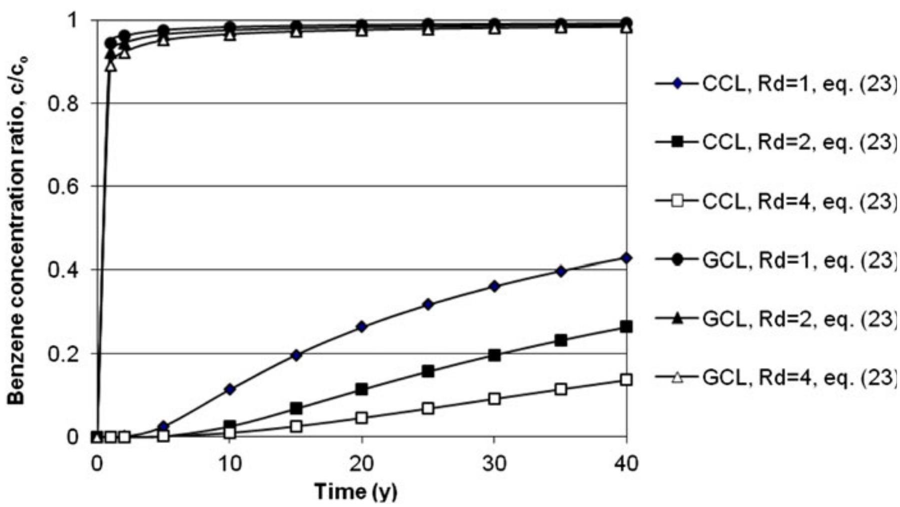


Fig. 14 Influence of sorption on calculated concentration ratio of benzene at the downstream face of composite liners GM-CCL and GM-GCL for the case of geomembrane with defects

GM-CCL were modified from those depicted on Fig. 2a to $h_{CCL} = 0.6$ m and $k_{CCL} = 2 \times 10^{-9}$ m/s; these values were chosen so that the results for the GM-CCL composite liner were close to those of the compacted clay liner (CCL), allowing thus easier comparison with the results of the GM-GCL liner shown on Fig. 2b.

From Table 3, it is apparent that the comparison between the reference CCL and the compacted clay composite liner is similar, whether it is made in terms of flow rate or concentration. However, in terms of the impact of the contaminant transport to the underlying soil, the criterion of contaminant mass flux reveals a higher impact compared to the criterion of concentration for the case of organic contaminants. As for the geosynthetic clay composite liner, its performance in terms of flow rate was superior, as already expected. Again as expected, the opposite trend is observed when the comparison is made in terms of concentration, for both leachate constituents, i.e. the geosynthetic is unable to provide protection comparable to that of the reference layer. Comparisons in terms of concentration and mass are similar for the organic contaminant. On the contrary, for the inorganic contaminant, the comparison in terms of mass is very positive for the GM-GCL composite liner.

7 Summary and Conclusions

This paper addressed two distinct goals for the design of landfill liners: assessing material equivalency and quantifying impact to groundwater. To this end, it compiled analytical solutions suitable for each goal and considered the issue of input material selection. Hence, decisions are differentiated among three levels: (a) goal of analysis, i.e. equivalency or impact analysis, (b) calculation method of the suitable quantity for the analysis goal selected and (c) parameter selection. Comparison of results obtained with the compiled methods shows that decisions at the three levels cannot be made independently of each other or irrespectively of the type of liners considered, i.e. compacted (CCL) or geosynthetic clay (GCL). On the basis of the obtained results, the following recommendations are made.

When the goal of analysis is to determine material equivalency, flow rate of leachate is an adequate key parameter for CCLs. On the contrary, for GCLs, it is necessary to compute contaminant concentration or mass flux, considering (1) transport through defects for inorganic contaminants and (2) diffusion and the contribution of any available attenuation layer for organic contaminants. When the goal of analysis is to assess impact to groundwater, it is advised to calculate both flow rate and contaminant mass flux in all cases. The critical parameter for transport calculations is the retardation factor of the contaminant, for the case of CCLs, while the results for GCLs are much less sensitive to this parameter. Finally, when an extra degree of conservatism is desired, transport calculations can be performed assuming a boundary condition of zero concentration at the downstream face of the composite liner, for cases with small contribution of advective transport. It should be clarified that most of the guidelines above have been previously developed

Table 3 Comparison of protection offered by a reference 1-m thick compacted clay liner (CCL), and two composite liners consisting of 1.5 mm geomembrane (GM) with hydraulic conductivity $k = 10^{-15}$ m/s and (a) 0.6 m of compacted clay with hydraulic conductivity $k = 2 \times 10^{-9}$ m/s (GM-CCL) and (b) 7 mm of geosynthetic clay with hydraulic conductivity $k = 10^{-11}$ m/s (GM-GCL)

Liner type	Design criterion										
	Flow rate per area, Q			Concentration, $c\ (h_s, t)$				Mass per area, $m = \int_0^t J(h_s)dt$			
	$h_w = 0.3$ m	$h_w = 1$ m	$h_w = 3$ m	Inorganic		Organic		Inorganic		Organic	
				$t = 10$ years	$t = 20$ years	$t = 10$ years	$t = 20$ years	$t = 10$ years	$t = 20$ years	$t = 10$ years	$t = 20$ years
	Equation 4, $c_q = 0.21$			Equation 15		Equation 23		Equation 21		Equation 24	
CCL	$Q_{0.3}$	Q_1	Q_3	c_{10}	c_{20}	c_{10}	c_{20}	m_{10}	m_{20}	m_{10}	m_{20}
GM-CCL	$1.7Q_{0.3}$	$1.8Q_1$	$1.9Q_3$	$1.7c_{10}$	$1.2c_{20}$	$1.9c_{10}$	$1.5c_{20}$	$1.5m_{10}$	$1.3m_{20}$	$3.7m_{10}$	$2.3m_{20}$
GM-GCL	$0.3Q_{0.3}$	$0.3Q_1$	$0.4Q_3$	$1.9c_{10}$	$1.2c_{20}$	$8.6c_{10}$	$3.7c_{20}$	$0.04m_{10}$	$0.02m_{20}$	$8.6m_{10}$	$3.4m_{20}$

Protection is quantified as (1) flow rate per unit area under increasing leachate height h_w, (2) concentration and (3) mass per unit area evaluated at the downstream face of the liner, h_s

on the basis of numerical calculations; herein, they are confirmed using analytical flow and transport solutions from the literature. The synthesis of analytical tools and the compilation of guidelines for parameter selection provided in this paper permit engineering practitioners to address similar issues in a simpler and comprehensive manner.

The following conclusions concern specifically the calculation of flow rate. The contribution of flow rate through the intact portion of the composite liner can be significant for liners constructed with good defect detection practices and should be added to the flow rate through defects. The value of the hydraulic conductivity of the geomembrane is the key quantity for this calculation. The equations of Giroud (1997) are adequate for calculating flow rate through defects at low leachate heights, representative of normal operation conditions of the landfill, for both cases of composite liners. For the GM-CCL composite liner, Giroud's (1997) solution gives reasonable results for the larger leachate heights considered, which are representative of failures of the leachate removal system. For composite liners with geosynthetic clay, it is recommended that flow rate be calculated with Rowe's (1998) solution, even at the limit of applicability of Giroud's (1997) solution of leachate height. The dependence of the flow rate through defects on the defect characteristics is self evident. The results presented herein also indicated the importance of transmissivity for the composite liners with geosynthetic clay.

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