Simultaneous leakage and diffusion of organic pollutants through damaged geomembranes

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ABSTRACT: Geomembranes offer excellent protection against the flow of leachate and the diffusion of non-organic pollutants found in waste. However, leakage through defective parts of the geomembrane and diffusion of organic compounds through its intact parts, reduce its effectiveness. Leakage and diffusion have been studied extensively but separately. This paper assesses the impact on groundwater quality of the two processes acting together. Finite-element analyses of the migration of dichloromethane through an HPDE geomembrane with wrinkles, over a compacted clay liner (CCL), an attenuation layer and an aquifer, are performed. An equivalent boundary condition is used to represent mass transfer through the geomembrane while conserving mass in the waste. Saturated conditions, steady-state seepage and time-dependent mass transfer are assumed. The paper answers two questions: 1. Is the impact of the two processes acting together significantly more critical than their separate effects? 2. Are simpler models able to simulate this problem?

1 INTRODUCTION

Groundwater protection is a major goal of geo-environmental engineering. Composite liners involving a geomembrane over a clay liner are crucial components of many barrier systems designed to protect surface and ground water. Research over the last two decades has painted a more realistic picture of the performance of such material, over the long timescales required for adequate protection, (Franz and Rowe, 1993; Rowe, 1998; Rowe and Sangam, 2003; Rowe, 2005). Leakage through holes in geomembranes has been analyzed and quantified by a number of authors. Giroud and Bonaparte (1989) and later Giroud (1997) developed simple equations for predicting the leakage rate through holes in the geomembrane. Rowe (1998) offered a new set of equations which reflects more accurately the hydraulic transmissivity of the layer between the geomembrane and the underlying buffer layer. Rowe (1998, 2005) also provided solutions for leakage when there are wrinkles in the geomembrane and demonstrated that to get a good prediction of leakage it is often necessary to take account of the presence of wrinkles. It has been demonstrated that, with good design and construction quality control, HDPE geomembranes used as part of a composite liner system, provide an excellent diffusive and advective barrier to most inorganic substances. However

some organic compounds are known to readily diffuse through geomembranes (Rowe, 1998; Mueller et al., 1998; Sangam and Rowe, 2001, 2005; Kalbe et al., 2002). Therefore, it is of interest to examine the effect of simultaneous leakage through defects in the geomembranes and diffusion of organic compounds through its intact parts. Rowe et al. (2004) provided the methodology for simple, but approximate, 1D approach for calculating the combined contaminant transport and implemented it in the program POLLUTEv7 (Rowe and Booker, 2005). Since the problem is essentially two-dimensional, the validity of one-dimensional approximation needs to be evaluated. This paper reports a two-dimensional analysis of combined leakage and diffusion, using an equivalent-boundary condition approach, developed earlier by the first author (El-Zein, 2006; El-Zein, 2007). The approach represents the geomembrane as a boundary surface, while conserving mass of contaminants in the waste and accounting for leakage and diffusion. A finite-element analysis of steady-state seepage and time-dependent mass transport of Dichloromethylene (DCM) through a landfill with a compacted clay liner (CCL) is conducted using program CONFEM (El-Zein, 2005; El-Zein et al., 2005). Two questions are addressed: 1. Is the impact of the two processes acting together significantly more critical than their separate effects? 2. Are existing approaches able to simulate this

problem? In particular, the accuracy of 1D approach, such as that implemented in POLLUTEv7, will be evaluated. In the remainder of the paper, the seepage and transport equations, including the equivalent boundary condition for leaking geomembranes, are briefly presented. Next, the problem of simultaneous diffusion and leakage through geomembranes is described in detail. Finally, results of the analyses are reported and preliminary conclusions drawn.

2 EQUIVALENT BOUNDARY CONDITION FOR GEOMEMBRANES

The following equations describe steady-state seepage and time-dependent mass transport in the landfill liner and underlying soil (Rowe et al., 2004):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial x}\left(K_{xy}\frac{\partial H}{\partial y}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial H}{\partial y}\right) = 0 \tag{1}$$

$$\begin{aligned} v_x &= -\frac{K_{xx}}{n}\frac{\partial H}{\partial x} \\ v_y &= -\frac{K_{yy}}{n}\frac{\partial H}{\partial y} \end{aligned} \tag{2}$$

$$(n + \rho K_d)\frac{\partial c}{\partial t} = n\frac{\partial}{\partial x}\left(D_{xx}\frac{\partial c}{\partial x}\right) + n\frac{\partial}{\partial x}\left(D_{xy}\frac{\partial c}{\partial y}\right) +$$

$$n\frac{\partial}{\partial y}\left(D_{yy}\frac{\partial c}{\partial y}\right) - nv_x\frac{\partial c}{\partial x} - nv_y\frac{\partial c}{\partial x} - n\lambda c \tag{3}$$

$$D_{xx} = (D_0 + \alpha_T v) + (\alpha_L - \alpha_T)\frac{v_x^2}{v} \tag{4}$$

$$D_{xy} = (\alpha_L - \alpha_T)\frac{v_x v_y}{v} \tag{5}$$

$$D_{yy} = (D_0 + \alpha_T v) + (\alpha_L - \alpha_T)\frac{v_y^2}{v} \tag{6}$$

$$v = \sqrt{v_x^2 + v_y^2} \tag{7}$$

$$\begin{aligned} f_x &= -nD_{xx}\frac{\partial c}{\partial x} + nv_x c \\ f_y &= -nD_{yy}\frac{\partial c}{\partial x} + nv_y c \end{aligned} \tag{8}$$

$$R = 1 + \frac{\rho K_d}{n} \tag{9}$$

where x,y [L] is a Cartesian coordinate system; t [T] is time; H [L] is the total hydraulic head; K_{xx}, K_{xy} and K_{yy} [L.T^{-1}] are coefficients of hydraulic conductivity; v_x [L.T^{-1}] and v_y [L.T^{-1}] are seepage velocities;

c [M.L^{-3}] is concentration of dissolved pollutant; n is the porosity; D_{xx}, D_{xy} and D_{yy} [L^2.T^{-1}] are coefficients of hydrodynamic dispersion which reflects the combined effect of molecular diffusion and mechanical dispersion; α_L [L] and α_T [L] are the longitudinal and transverse dispersivities, respectively; ρ [M.L^{-3}] is the dry density; K_d [L^3.M^{-1}] is the distribution coefficient of linear sorption; λ [T^{-1}] is the coefficient of first-order, rate-limited decay; f_x [M.L^{-2}.T^{-1}] and f_y [M.L^{-2}.T^{-1}] are the fluxes of contaminants and R is the coefficient of sorption retardation. The above equations can be Laplace-transformed and linearized with respect to time, solved by a finite-element technique in the Laplace domain and the solution inverted numerically into the time domain (El-Zein et al., 2005). Special treatment of a leaking geomembrane yields an equivalent boundary condition which conserves mass in the waste (El-Zein, 2006). It is assumed that, under the wrinkles in the geomembrane, the leachate is in direct contact with the top of the clay liner. Outside the wrinkles, the leachate is in contact with the geomembrane. This is justified on the ground that, while the leachate will travel horizontally under the geomembrane away from the wrinkles, the volume of contaminants outside the wrinkles will be relatively small because of the low transmissivity of the interface between the geomembrane and clay liner. The boundary condition under the intact part of geomembrane can be written as:

$$\frac{E_3 E_0}{E_1 e^{(\alpha_1 + \alpha_2)h}}\overline{c}_{si} + \frac{E_2 E_0}{E_1 e^{(\alpha_1 + \alpha_2)h}D_g S_g}\overline{f}_{\eta si} +$$

$$\frac{E_1}{E_3 R_w A_w H_r}\int_{\Gamma_i}\overline{f}_{\eta si}d\Gamma +$$

$$\frac{1}{R_w A_w H_r}\int_{\Gamma_i}\overline{f}_{\eta si}d\Gamma = c_{w0} \tag{10}$$

Under the leaking part:

$$E_0 \overline{c}_{sl} + \frac{E_1}{E_3 R_w A_w H_r}\int_{\Gamma_i}\overline{f}_{\eta si}d\Gamma +$$

$$\frac{1}{R_w A_w H_r}\int_{\Gamma_i}\overline{f}_{\eta sl}d\Gamma = c_{w0} \tag{11}$$

$$E_0 = s + \frac{\lambda_w}{R_w} - \frac{\alpha_1 \alpha_2 E_2 D_g S_g}{E_3 R_w H_r} \tag{12}$$

$$E_1 = \alpha_2 - \alpha_1 \tag{13}$$

$$E_2 = e^{\alpha_2 h} - e^{\alpha_1 h} \tag{14}$$

$$E_3 = \alpha_2 e^{\alpha_2 h} - \alpha_1 e^{\alpha_1 h}. \tag{15}$$

$$\alpha_1 = \sqrt{(s + \lambda_g)/D_g} \qquad (16)$$

$$\alpha_2 = -\sqrt{(s + \lambda_g)/D_g} \qquad (17)$$

where s is the Laplace operator; $\bar{p}(s)$ is the Laplace transform of p(t); h [L] is the thickness of the geomembrane; D_g [$L^2.T^{-1}$] and S_g are the diffusion and partitioning coefficients in the geomembrane, respectively; λ_g [T^{-1}] is the decay coefficient in the geomembrane; A_w [L] is the surface area of the landfill per unit width; H_r [L] is the reference height of leachate in the waste; R_w and λ_w are the retardation and decay coefficients in the waste, respectively; c_{si}[$M.L^{-3}$] is the concentration of contaminants at the bottom surface of the geomembrane; and $f_{\eta si}$[$M.L^{-2}.T^{-1}$] and $f_{\eta sl}$ [$M.L^{-2}.T^{-1}$] are the fluxes of contaminants at the bottom surface of the geomembrane, normal to the geomembrane, over the intact and leaking surfaces, respectively.

3 SIMULTANEOUS LEAKAGE AND DIFFUSION THROUGH GEOMEMBRANES

Analyses were conducted using finite element program CONFEM. The program had been modified to incorporate the equivalent boundary condition for intact and damaged geomembrane, referred to earlier. Figure 1 shows the general outline of the model. The landfill liner and underlying soil are simulated as a 200 m-long cell, whose top coincides with the lower surface of the geomembrane. A leaking-geomembrane boundary condition, which conserves mass in the waste, is applied at this surface. Below the geomembrane there are three layers: a 0.1 mm thick hydraulic transmissive layer (TL), a 0.75 m thick compacted clay liner (CCL) and a 3 m thick attenuation layer (AL). The bottom line of the system coincides with the top surface of an aquifer (AQ), 3 m in depth with porosity of 0.3. A thin aquifer boundary condition is applied at this surface (Rowe et al., 2004). It is assumed that the horizontal Darcy velocity is 1 m/a^{-1} in the aquifer. The porosities of the various layers are 1., 0.4, 0.35 for the TL, CCL and AL, respectively. The hydraulic pressure heads over the leaking part of the geomembrane and the top of the aquifer are 0.3 m and 3.75 m, respectively. Waste density is 25 t.m^{-2} and the proportion of dichloromethane (DCM) in the waste is 2.3 mg.kg^{-1}. The initial concentration of DCM in the leachate is 3300 μg.l^{-1}. The reference height of leachate is hence calculated at 17.4 m. The geomembrane is assumed to be 1.5 mm in thickness and to have 5 wrinkles with a hole per hectare. Each wrinkle is assumed to be 0.3 m in width and 100 m in length. Diffusion and partition coefficients of DCM in the geomembrane are taken as 6.5e−13 m^2.s^{-1} and 6, respectively (Rowe
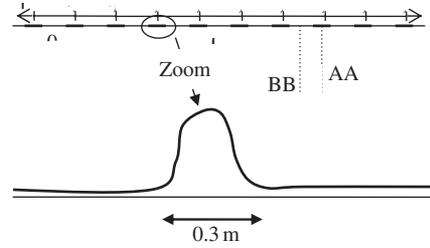
a. Wrinkles on the geomembrane (lines AA and BB are shown in reference to Figure 4)
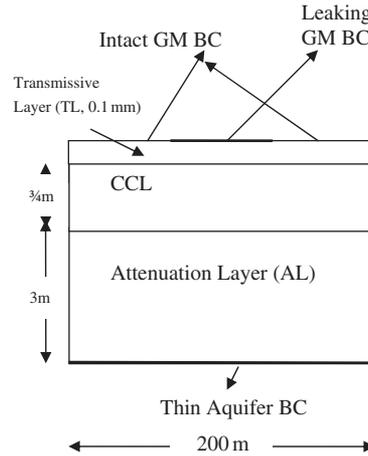
b. Model and boundaries

Figure 1.   Problem and model outline; not to scale.

et al., 2004). Hydraulic conductivities in the CCL and AL are 1e−9 m.s^{-1} and 1e−7 m.s^{-1}, respectively. A hydraulic transmissivity (k_{xx}xdepth) of 2e−8 m^2.s^{-1} is used under the intact part of the TL and infinity under the wrinkles. Diffusion coefficients of 4e−10 m^2.s^{-1} and 8e−10 m^2.s^{-1} are used in the CCL and AL, respectively. Half lives of 2 years in the waste and 50 years in the CCL, AL and AQ are adopted. No decay is assumed to take place in the GM. Sorption is assumed to be negligible everywhere. These properties were chosen to yield a typical upper limit of leakage, around 150 litres per hectare per day (lphd).

For numerical expediency, only the steady-state seepage part of the analysis includes a TL, with an artificial thickness of 0.1 m, a hydraulic conductivity K_{xx} adjusted so as to maintain the required transmissivity and a K_{yy} of infinity. In the time-dependent diffusion-advection part of the analysis, the geomembrane boundary condition is applied directly to the top of the CCL layer. This scheme has no effect on accuracy. In concert with the equivalent boundary condition for geomembranes, it removes a spatial scale from the model, dramatically reduces the computational cost of
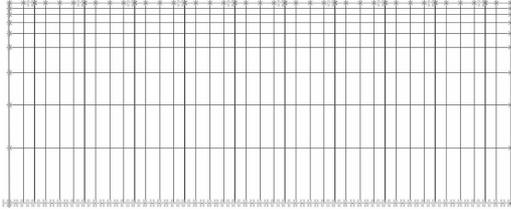
Figure 2. Finite element mesh for seepage analysis (not to scale; mass-transport is identical except for the removal of the transmissive layer; dense vertical lines are under-wrinkle elements).

the analysis and allows the modeling of more realistic frequency of wrinkles in 2D. The FEM mesh is automatically generated. In the seepage analysis, 450 eight-noded, parabolic elements are used, yielding 1469 degrees of freedom before the application of constraints (see Figure 2).

In the mass-transport analysis, 400 elements with 1312 degrees of freedom are generated. A convergence analysis is conducted to ensure that the solution is numerically accurate. More refined meshes yielded better estimates of seepage velocities but had no discernible effect on hydraulic head, leakage rates and contaminant concentrations. This can be explained by the reduced or improved accuracy when numerical differentiation or integration is performed, respectively.

4 RESULTS

Figure 3 shows the pressure hydraulic head on top of the CCL layer, derived from the finite-element analysis. In addition, results from the Rowe equation are shown. These are derived by adding the effect of each of the ten wrinkles over the entire length of the landfill base. Clearly, the Rowe equation generates accurate predictions, even when multiple wrinkles are present (Rowe, 2004). The discrepancy at the edge of the landfill base is due to the no-seepage boundary condition used in the numerical analysis. For comparison purposes, the leakage rate Q from the geomembrane into the CCL is calculated by means of the Rowe equation and CONFEM. In CONFEM, leakage is defined as:

$$Q = L_w \int_{\Gamma_{CCL}} n v_y \, d\Gamma \qquad (18)$$

where Γ_{CCL} is the top surface line of the CCL and $L_w = 100$ m is the length of each wrinkle. The Rowe equation and CONFEM yield almost identical leakage rates: $3.15\mathrm{e}{-}7\,\mathrm{m}^3.\mathrm{s}^{-1}$ (136 lphd) and $3.16\mathrm{e}{-}7\,\mathrm{m}^3.\mathrm{s}^{-1}$ (137 lphd), respectively. Finally, DCM concentration profiles along the depth under wrinkles are shown in Figure 4 after 35 years. The effect of leakage can be seen by comparing the three solid lines in the figure. Maximum concentration C is around 90% greater
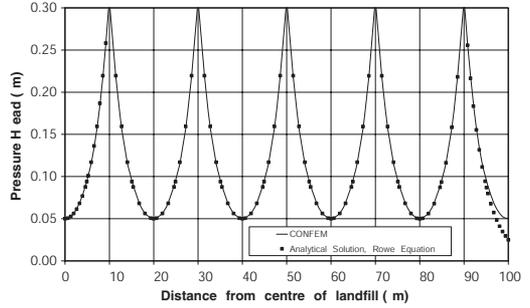

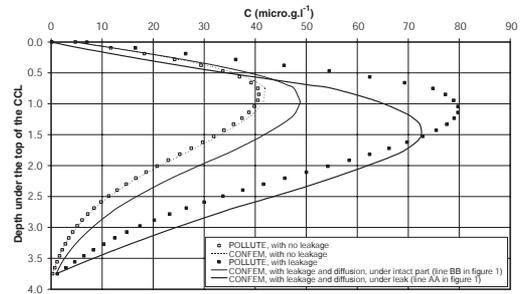Figure 3. Pressure head on top of the CCL layer along half the landfill base.

Figure 4. Profile of DCM concentration under the leaking part of the geomembrane after 35 years.

under wrinkles, compared to the non-leaking case, and the location of the maximum concentration is lower because of the stronger advective fluxes. Under the intact parts of a leaking geomembrane, the location of maximum C is close to the case of a non-leaking geomembrane. However, its magnitude is around 30% greater due to the horizontal diffusive transport from the areas under the leaks. When no leakage is present, as expected, predictions of POLLUTEV7 and CONFEM agree. In the case of leaking geomembranes, POLLUTEV7 generates conservative results, as far as the maximum concentration in the soil at t = 35 years is concerned. However, it appears to underestimate concentrations in the lower part of the attenuation layer. The reason for the discrepancy may lie in the way leakage is treated in both programs. In POLLUTEV7, a leakage rate is estimated based on a seepage formula and used to derive an average downward Darcy velocity over the entire base. DCM is then assumed to migrate through the geomembrane by both diffusion and advection. In CONFEM, when the equivalent boundary condition is used, seepage velocities are calculated numerically in 2D, albeit in a manner consistent with the analytic approach followed in POLLUTEV7. However, as stated earlier, mass transport through the geomembrane is treated

differently to POLLUTEV7. In the area under the wrinkles, it is assumed that the leachate is in direct contact with the CCL and the geomembrane offers no protection against downward diffusion and advection. In the area outside the wrinkles, the geomembrane operates as it is meant to do, allowing only diffusion to take place. This is consistent with the case, studied by Giroud (1997) and Rowe (2005), where the size of the hole in the wrinkle is large enough to place no restriction on the leakage rate. Further analyses are clearly required to evaluate the level of approximation associated with the 1D solution as compared with the 2D predictions, under various, commonly-encountered conditions. This will allow the derivation of correction factors that could be applied to 1D analyses in the case of organic contaminants.

5 CONCLUSIONS

Diffusion and leakage through a geomembrane liner were considered simultaneously in a 2D finite-element analysis using an equivalent boundary condition to represent a wrinkled geomembrane. While seepage predictions of simpler models were found to be accurate, some discrepancies between 1D contamination profiles and 2D predictions were found with the 1D giving conservative prediction of the maximum concentration when compared with the results from the more rigorous 2D solution. Further research will consider a geosynthetic clay liner (GCL), instead of a CCL, a wider range of hydraulic conductivities in the liner and attenuation layers, and different frequencies of wrinkles. The effect of time on the 1D and 2D analyses will also be examined. More definite conclusions can then be drawn regarding the limitations of the approximate 1D approach in analyzing organic migration through leaking geomembranes.

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