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Steady-state advective and diffusive pollutant transport through landfill barrier systems

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ABSTRACT: The paper presents a simplified model for the preliminary design of landfill layered barrier systems taking into account diffusive and advective transport in steady state conditions. The model allows the evaluation of the contaminant relative concentration and flux beneath the considered landfill. A graphical representation of the proposed model results has been carried out for practical application purposes. Using the model, the role played by the main components of the modern barrier systems, such as geomembrane and attenuation layer, has been pointed out. In particular the variation of relative concentration in the aquifer versus the thickness of the attenuation layer has been estimated. Looking at these results it is interesting to observe that, for steady state conditions, not always the increase of attenuation layer thickness leads to significant decrease of pollutant concentration in the aquifer. On the basis of this observation a tentative procedure for the preliminary optimization of the attenuation layer thickness has been proposed.

1 INTRODUCTION

The main role of the landfill bottom barrier system is to minimize the pollutant transport towards the underlying aquifer. Usually, the landfill barrier is a multilayered system composed by compacted clay liner and/or geosynthetic clay liner and one or more sheets of geomembrane. The use of geosynthetics can increase the landfill capacity by decreasing the thickness of the barrier and/or can offer important advantages in terms of construction economy and time saving.

In order to carry out a consistent landfill design it is necessary to evaluate and compare the performance of the different types of composite barriers today available. The performance design can be done only by evaluating the flux and concentration of the pollutant flowing through the different barrier profiles and comparing the solute concentrations of the pollutants downstream the landfill with admissible concentrations given by the local regulations. The mathematical models used for simulating the pollutant transport must take into account the main physical and chemical processes listed in Table 1.

Table1. Main physical and chemical contaminant transport processes (Shackelford & Rowe, 1998)

Process	Definition	Significance
Advection	Mass transport due to bulk water flow	Most dominant process in high flow rate media
Diffusion	Mass spreading due to concentration gradients	Most dominant process in low flow rate media
Dispersion	Mass spreading due to heterogeneities in the flow field	Results in greater mass spreading than predicted by advection
Sorption	Mass immobilization by the solid skeleton	Important process with ionic species in fine grained soils

At the low seepage velocities associated with flow through low permeability soil barriers, dispersion can be considered to be negligible (Mitchell, 1992 quoted by Manassero & Shackelford, 1994). Sorption can be very important during the transient phase but does not play any role in the steady state conditions that are considered in the simplified closed form mathematical model illustrated in the following parts of paper.

This model describes the long-term contaminant transport through multi-layer barriers due to diffusion and advection phenomena therefore it is able to consider the presence of natural and/or manmade attenuation layers below the landfill. Moreover the main features of the under-laying aquifer and groundwater can also be taken into account.

2 PROPOSED MATHEMATICAL MODEL

Considering a typical landfill as shown in figure 1, the steady state contaminant flux due to diffusion and advection phenomena, Jv, per unit area of the barrier is given by the following equation (Manassero & Shachelford, 1994):

$$J_v = q \frac{c_0 \cdot e^P - c_x}{e^P - 1} \tag{1}$$

where:
c_0 – contaminant source concentration (in the leachate);
c_x – contaminant concentration in the aquifer at a horizontal distance x from the upstream side of the landfill;
q – Darcy seepage velocity through the barrier;

$$P = \frac{q \cdot L_e}{n_e \cdot D_e} = \frac{k_e \cdot \Delta h}{n_e \cdot D_e} \tag{2}$$

P - Peclet number of the multilayered barrier (including the attenuation layer) which will be replaced, from the analytical point of view, with an equivalent layer described by the following parameters:

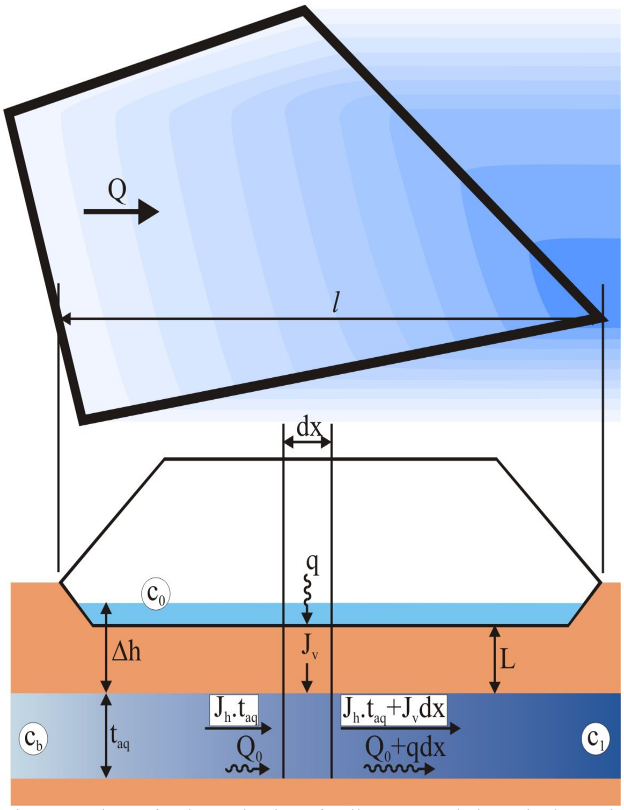

Figure1. Scheme for the evaluation of pollutant mass balance in the aquifer beneath a landfill (after Manassero, Benson, Bouazza, 2000)

$$k_e = \frac{\sum L_i}{\sum \frac{L_i}{k_i}} \quad \text{- equivalent permeability coefficient;} \qquad (3)$$

$$D_e = \frac{\sum \frac{L_i}{n_i}}{\sum \frac{L_i}{n_i D_i}} \quad \text{- equivalent diffusion coefficient;} \qquad (4)$$

$$n_e = \frac{\sum L_i}{\sum \frac{L_i}{n_i}} \quad \text{- equivalent porosity;} \qquad (5)$$

$$L_e = \sum L_i \quad \text{- equivalent thickness.} \qquad (6)$$

where:
L_i – thickness of the i-th layer;
k_i – hydraulic conductivity of the i-th layer;
n_i – porosity of the i-th layer;
D_i – diffusion coefficient of the i-th layer.

The evaluation of the pollutant relative concentration in the aquifer, R_c, at distance x from the upstream boundary of the landfill can be carried out by solving the following differential equation resulting from the pollutant mass balance shown in figure 1 (Manassero, Benson, Bouazza, 2000):

$$\left(\frac{Q_0 + q \cdot x}{q}\right)\left(\frac{dc}{dx}\right) = \frac{e^P (c_0 - c_x)}{e^P - 1} \qquad (7)$$

The solution of equation (7) under the boundary conditions sketched in figure 1 is:

$$R_c = \frac{c_x - c_b}{c_0 - c_b} = 1 - \left(1 + \frac{q \cdot x}{Q_0}\right)^{\left(\frac{e^P}{1 - e^P}\right)} \qquad (8)$$

where:
c_b – background concentration in the aquifer upstream the landfill;
$Q_0 = k_a i_a t_{aq}(eq)$ – effective volumetric flow of the aquifer upstream the landfill per unit horizontal width perpendicular to seepage direction
k_a: horizontal hydraulic conductivity of the aquifer;
i_a: hydraulic gradient in the aquifer;
$t_{aq}(eq)$: operative effective thickness of the aquifer.

The operative effective thickness of the aquifer, $t_{aq}(eq)$, must be evaluated on the basis of the following equation (E.P.A.,1996):

$$t_{aq}(eq) = \sqrt{2\alpha_z \cdot l} + t_{aq}\left(1 - e^{\frac{q_0 \cdot l}{k_a \cdot i_a \cdot t_{aq}}}\right) \text{ and } t_{aq}(eq) \le t_{aq} \qquad (9)$$

where: t_{aq} is the actual thickness of the aquifer and α_z is the aquifer dispersivity (see also fig 2).

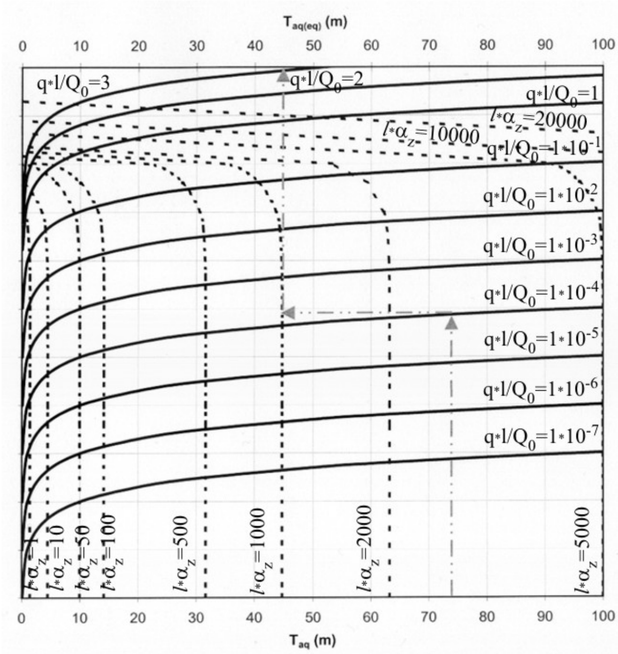

Figure 2. Diagram for the evaluation of the operative effective aquifer thickness from the actual one

Graphical representations of equation (8) have been reported in figures 3 and 4 for practical application purposes.

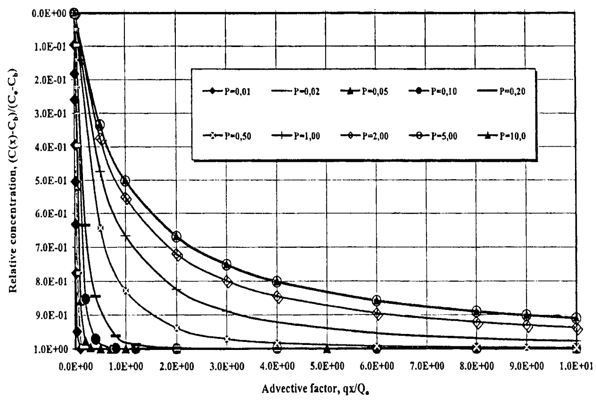

Figure 3. Steady state pollutant concentration in the aquifer beneath a landfill (Manassero, Benson, Bouazza, 2000)

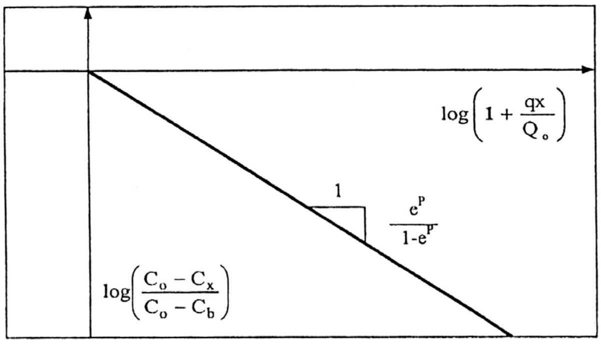

Figure 4. Steady state concentration in the aquifers below landfills vs. advective factor of the aquifer and Peclet number of the barrier (Manassero, Benson, Bouazza, 2000)

The contaminant mass flux in the aquifer below the barrier at a distance x from the upstream landfill side can be evaluated by the integration of equation (1) along the horizontal direction (x axis):

$$\frac{J_h}{c_0 \cdot q_{h0}} = \left(1 + \frac{q \cdot x}{Q_0}\right) - \left(1 - \frac{c_b}{c_0}\right) \cdot \left(1 + \frac{q \cdot x}{Q_0}\right)^{\frac{1}{1-e^P}} \tag{10}$$

A representation in dimensionless units of equation (10) is shown in figure 5.

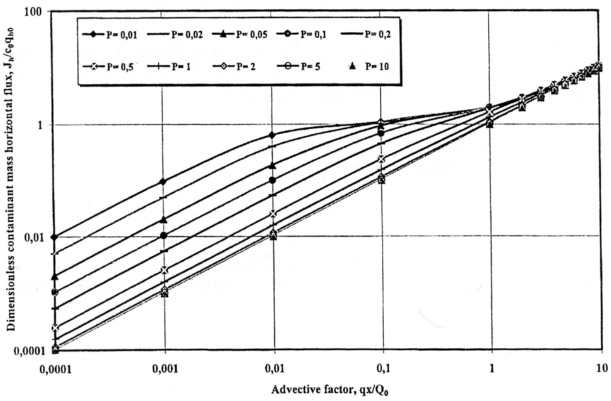

Figure 5. Evaluation of contaminant mass flux (J_h) in an aquifer with c_b=0 (Manassero, Benson, Bouazza, 2000)

3 SOME APPLICATION EXAMPLES

The proposed simplified model has been used in the following for a preliminary evaluation of the performance of some types of waste containment systems and for pointing out the roles played by the main barrier components.

The first example compares four types of liner including compacted clay layers (CCL) or geosynthetic clay liners (GCL) with and without geomembrane (GM) as shown in figure 6. All the systems are provided with an attenuation layer (AL).

The input parameters of the two couple of liner systems have been selected among the current and representative values given by Rowe (1998). A comparison in terms of R_c and $J_h/(c_0q_{h0})$ has been carried out and the following comments can be done:

– the long-term efficiency of both the liner systems without GM is very low observing in particular the concentration reduction parameter R_c. This is due to the high advective transport and to the relevant vulnerability of the considered aquifer;

– the use of a GM gives a huge improvement of the barrier system performances due to the reduction of advective transport and results in an almost identical behavior of the profiles including CCL and GCL.

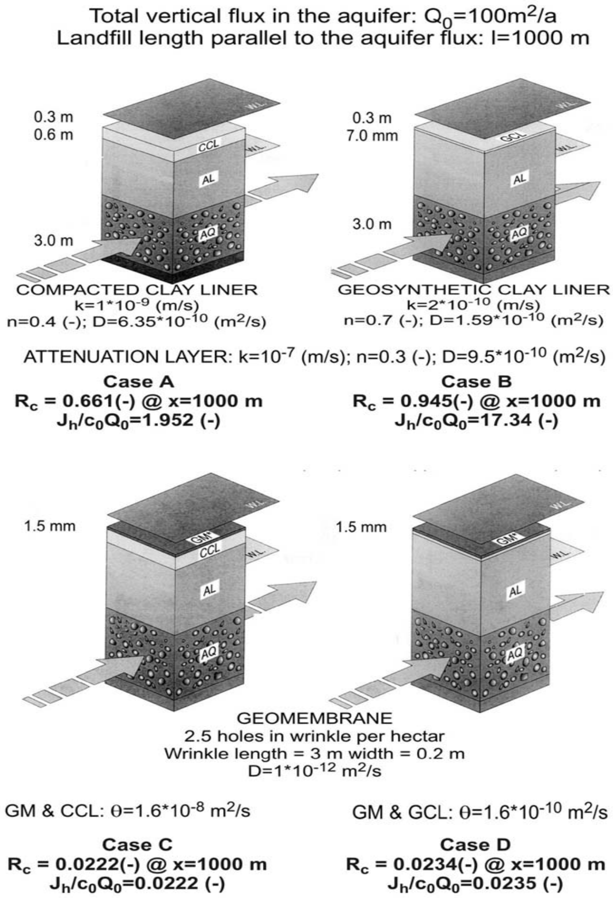

Figure 6. Comparison of steady state transport performances of simple and composite liners using GCL and CCL

Table 2. Performances of composite barriers with and without attenuation layer (AL)

CCL+GM			GCL+GM		
AL thickness (m)	R_c	J_h/c_0Q_0	AL thickness (m)	R_c	J_h/c_0Q_0
0	0.0787	0.0788	0	0.1868	0.1869
3	0.0222	0.0222	3.6	0.0234	0.0235

Figure 7 shows the increase of the landfill storage capacity decreasing the thickness of the AL. On the other hand an appropriate thickness of the AL can be fundamental for improving the barrier performances in terms of diffusive transport.

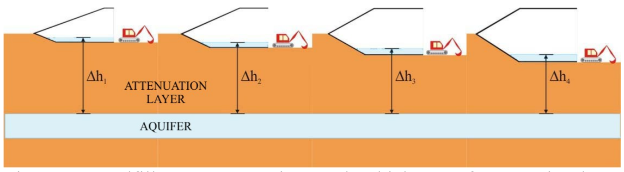

Figure 7. Landfill storage capacity vs. the thickness of attenuation layer (AL)

The importance of the attenuation layer (AL), for the limitation of the diffusive pollutant migration, can be pointed out by evaluating the performances of the aforementioned composite barrier systems without AL. As shown in table 2, when GM is used (therefore the diffusive transport prevails) the AL is very effective in reducing the diffusive transport looking in particular to the composite barriers using GCL.

A tentative approach for a preliminary optimization of the AL thickness can be carried out using the simplified model proposed in this paper.

As an example the Rc variation in the aquifer versus the thickness of AL, for the barrier system "c" of figure 6, was estimated and the results are presented in figure 8. As it can be observed, the pollutant concentration is minimum for a thickness of the attenuation layer of about 14 m.

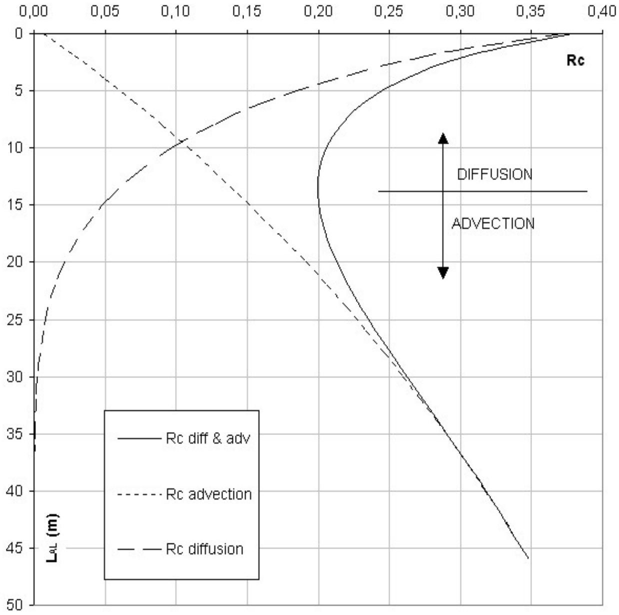

Figure 8. Pollutant concentration in the aquifer vs. thickness of AL

It is interesting to observe that, under the simplified assumptions of the proposed model, not always the increase of attenuation layer thickness leads to a significant decrease of pollutant concentration in the aquifer. This is due to the different trends of the advective and diffusive transport contributions versus the AL thickness as shown in the same figure (Olinic, 2000).

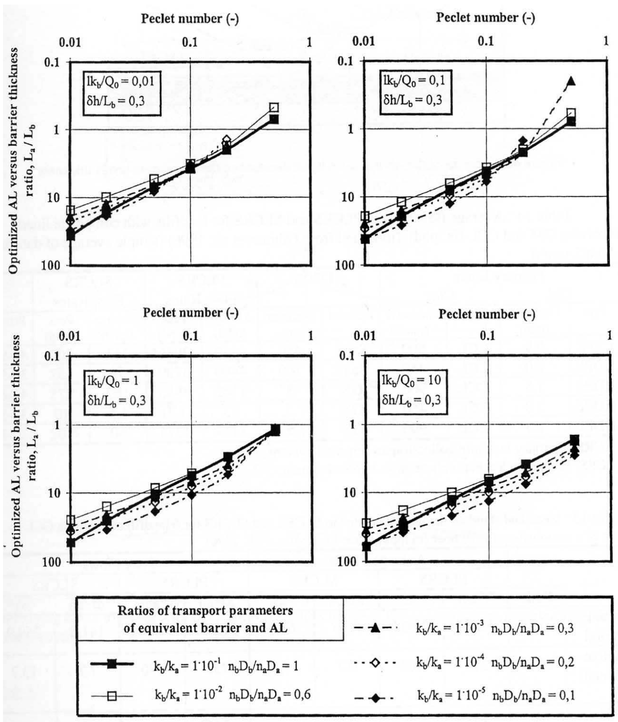

Figure 9. Optimized thickness of AL referring to steady state conditions (Manassero, Benson, Bouazza, 2000)

Figure 9 shows the ratio between the thickness of the attenuation layer (L_a) and barrier system (L_b), that minimizes the groundwater concentration in the aquifer, versus the Peclet number of the barrier evaluated assuming unitary hydraulic gradient (i.e. $P_{b1}=k_b/n_b \cdot D_b$). Figure 9 has been plotted assuming a ratio between hydraulic leachate head (δh) and thickness of the barrier (L_b) equal with 0,3 but the plots can be used also with other $\delta h/L_b$ ratios by simply including, in the equivalent barrier, a part of the attenuation layer or, viceversa, in order to get, with the known value of δh, the ratio $\delta h/L_b$=0,3 (Manassero, Benson, Bouazza, 2000).

Even thought many of the assumptions of the proposed model are very simplified and conservative, nevertheless the plots of Figure 9 can be useful for a preliminary calibration of the position of the landfill bottom avoiding to over-thicken the AL without getting appreciable advantages in terms of minimization of pollutant impact on the groundwater.

Finally, it is still interesting to observe from figure 9 that an effective composite barrier, characterized by $P_{b1} \cong 0.1$ requires an AL thickness ranging between 3 to 10 m, that is the minimum distance of the landfill bottom from the groundwater level indicated by the regulations of most European countries.

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