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A systems engineering and risk assessment-based approach for the design of landfills

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ABSTRACT: The long-term performance of modern landfills is governed by a set of systems, including the landfill cover and the bottom barrier. In order to minimise the environmental impacts of a landfill, a systems engineering approach may be adopted for the landfill design. Such an approach requires analysing the interactions between the different components of each system involved and then evaluating the response of the entire system assembled to quantify its overall engineering performance. The effectiveness of the lining systems is demonstrated through the verification that the risk for human health and the environment due to pollutant migration is limited to an acceptable level. This risk is quantified through the calculation of the pollutant concentration in the groundwater, which is expected to remain less than some prescribed level at a compliance point. The paper describes a simplified approach to the analysis of pollutant transport, which allows the pollutant concentration in the groundwater to be calculated under different boundary conditions and taking into account the role played by several geosynthetics, such as geonets, geomembranes and geosynthetic clay liners, which are used in landfill lining systems.

1 INTRODUCTION

Modern landfills are required to guarantee the safe disposal of waste for the foreseeable future in order to protect human health and the environment from the harm caused by the release of contaminants. The long-term performance of landfills relies upon the effectiveness of the cover and bottom barrier systems. All the barrier or lining systems include a high-permeability component, which is aimed at collecting and removing the percolating liquids, and a low-permeability component (or liner), which limits liquid infiltration and/or contaminant migration.

Rowe (2011, 2018) pointed out that in order to minimize the environmental impacts of a landfill, a system engineering approach to the design should be adopted. This approach involves decomposing the entire system into subsystems that consist of simpler identifiable components. The performance of the individual components, as well as the interactions between different components of the system, have to be assessed before the response of the entire system can be quantified to obtain its overall engineering performance.

A simplified approach is proposed to model the interaction between the waste, the lining system and the aquifer that is located underneath the landfill. The aquifer represents the natural resource to be protected by limiting the impact due to the migration of contaminants from the waste. As a result, the performance criterion adopted for the design is that the lining system must ensure that the concentrations of pollutants in the groundwater remain less than some prescribed threshold level at a specified compliance point, which is typically a monitoring well that is located downgradient from the landfill. The threshold concentration value of a given pollutant is related to a corresponding risk for human health and the environment

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through a toxicological model that takes into account the pollutant features and the exposure paths (Dominijanni & Manassero 2021; Dominijanni *et al.* 2021a).

The lining system typically includes a leachate collection system, which involves a series of perforated pipes in a granular drainage layer that are aimed at minimizing the leachate ponded head. The drainage layer may be replaced by biplanar or triplanar geonets, which are characterized by a high in-plane transmissivity. Geonets are covered with a geotextile on their upper and lower surfaces to preserve their drainage function by preventing direct contact with soil particles. The leachate collection system overlies the low-permeability barrier component, which may consist of compacted clay layers (CCLs) and/or geosynthetic components, such as geomembrane layers (GMLs) and geosynthetic clay layers (GCLs). GMLs can be coupled with CCLs and GCLs to form composite liners that provide optimal groundwater protection performance. Moreover, the aquifer located beneath a landfill is typically separated from the waste not only by these artificial layers but also by a natural foundation or attenuation layer (AL), which plays an important role in limiting contaminant migration (Dominijanni & Manassero 2021).

The interaction analysis between the waste, the lining system and the aquifer can be carried out on the basis of a conceptual model that identifies the leachate produced by the waste with the source of contamination and a monitoring piezometer (which may be real or virtual), placed downstream of the landfill, with the point of compliance, as shown in Figure 1.

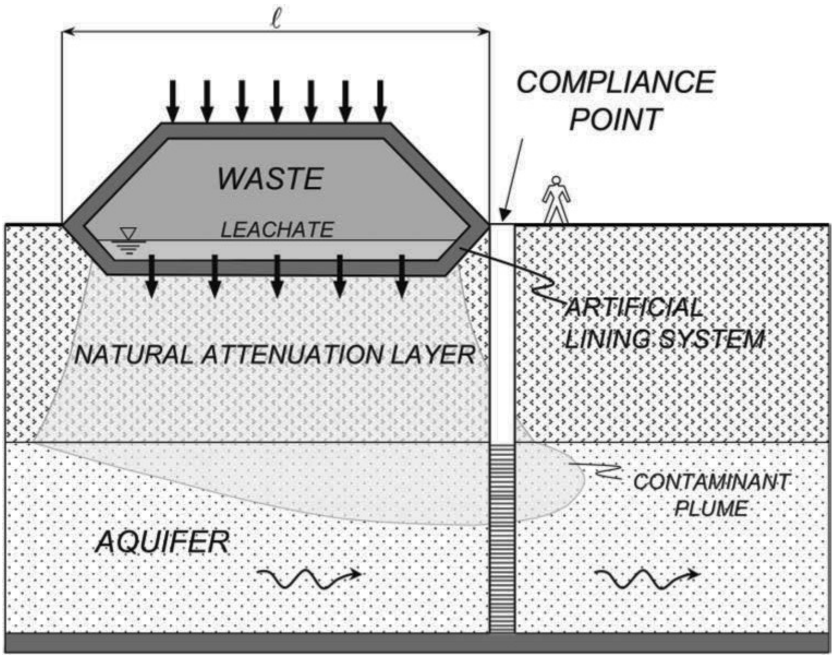

Figure 1. Reference scheme for the interaction analysis between the waste, the lining system and the aquifer. The pollutant released by the waste migrates vertically through the engineered lining system and the natural attenuation layer up to the underlying aquifer, where pollutant transport becomes horizontal.

2 ASSESSING THE LANDFILL SYSTEMS INTERACTION

The waste, the lining system and the aquifer are considered as control volumes characterized by an internal homogeneous concentration.

The contaminant mass in the waste disposal facility decreases over time due to degradation processes and migration through the barrier system. The mass balance may be expressed as follow:

$$H_w B_l \cdot \frac{dc_l}{dt} = -J_{s,ad} - J_{s,d} - \lambda H_w c_l \tag{1}$$

where H_w is the waste thickness, B_l is the bulk leachate partition coefficient, c_l is the contaminant concentration in the leachate, $J_{s,ad}$ is the contaminant advective flux through the barrier system, $J_{s,d}$ is the contaminant diffusive flux through the barrier system and λ is the decay constant of a linear or first-order decay reaction.

The contaminant migration has been decomposed into a pure advective flux, $J_{s,ad}$, and a pure diffusive flux, $J_{s,d}$, for the sake of simplicity, although the two transport mechanisms are actually coupled in a single advective-diffusive flux. Accepting this modelling simplification allows the advective flux to be expressed as follows:

$$J_{s,ad} = a_w \cdot q \cdot c_l \tag{2}$$

where a_w is the portion of barrier area that is wetted by the leachate and q is the vertical volumetric liquid flux that takes place through the mineral barrier underlying the geomembrane.

The parameter a_w depends on the number, size and shape of the holes in the geomembrane. An empirical equation for the calculation of the leakage rate through a circular hole with a diameter ranging from 100 mm to 600 mm in a geomembrane with imperfect contact with the underlying mineral layer was provided by Giroud (1997):

$$Q = C_q \cdot A_h^{0.1} \cdot h_p^{0.9} \cdot k_{eq}^{0.74} \cdot \left[1 + 0.1\left(\frac{h_p}{L}\right)^{0.95}\right] \tag{3}$$

where Q is the flow rate, C_q is a dimensionless quality coefficient of the contact between the geomembrane and the underlying mineral layer, which can be assumed equal to 0.21 for good contact conditions and 1.15 for poor contact conditions, A_h is the circular hole area, h_p is the hydraulic head on top of the geomembrane, k_{eq} is the equivalent hydraulic conductivity of the underlying mineral barrier and L is the thickness of the mineral barrier.

The equivalent hydraulic conductivity, k_{eq}, is calculated as the harmonic mean of the hydraulic conductivities of individual layers:

$$k_{eq} = \frac{L}{\sum_{i=1}^{N} \frac{L_i}{k_i}} \tag{4}$$

where k_i and L_i are the hydraulic conductivity and the thickness of the i-th layer, respectively, and N is the number of layers and $L = \sum_{i=1}^{N} L_i$.

The vertical flux through the mineral barrier underlying the geomembrane is given by Darcy's equation:

$$q = k_{eq} \frac{h_p + L}{L} \tag{5}$$

If the holes are assumed to be all equal to each other and their number per unit area is n_h, the wetted portion of the barrier area may be estimated as follows (Dominijanni *et al.* 2021a, b; Giroud 1997; Katsumi *et al.* 2001):

$$a_w = \frac{n_h Q}{q} \tag{6}$$

where Q is the flow rate through a single hole.

In the absence of the geomembrane, the parameter a_w is equal to 1 as the whole barrier area is wetted by the leachate. Instead, the condition $a_w = 0$ corresponds to a geomembrane without holes.

An approximate estimation of the diffusive flux, $J_{s,d}$, in Equation 1 can be obtained by introducing mass transfer coefficients or diffusivities to account for the transport through the barrier system. Under such assumptions, $J_{s,d}$ may be expressed as follows:

$$J_{s,d} = a_w \Lambda_{d,w}\left(c_l - c_{b,w}\right) + (1 - a_w)\Lambda_{d,nw}\left(c_l - c_{b,nw}\right) \tag{7}$$

where $c_{b,w}$ and $c_{b,nw}$ are the average contaminant concentrations in the barrier system in correspondence to the wetted and non-wetted portions of the landfill barrier, respectively, and $\Lambda_{d,w}$ and $\Lambda_{d,nw}$ are the related diffusivities. $\Lambda_{d,w}$ and $\Lambda_{d,nw}$ are related to the diffusion coefficients of the components of the barrier system as follows:

$$\Lambda_{d,w} = \frac{1}{\sum_{i=1}^{N} \frac{L_i}{n_i D_i^*}} \tag{8}$$

$$\Lambda_{d,nw} = \frac{1}{\frac{L_g}{K_g D_g} + \sum_{i=1}^{N} \frac{L_i}{n_i D_i^*}} \tag{9}$$

where n_i and D_i^* are the porosity and the effective diffusion coefficient of the i-th layer, respectively, L_g is the thickness of the geomembrane, K_g is the partition coefficient between the geomembrane and the contaminant, and D_g is the diffusion coefficient of the geomembrane.

The average concentrations $c_{b,w}$ and $c_{b,nw}$ in the barrier system are found from the contaminant mass balances in the corresponding control volumes:

$$n_b R_{d,b} L \cdot \frac{dc_{b,w}}{dt} = qc_l + \Lambda_{d,w}(c_l - c_{b,w}) - qc_b - \Lambda_{d,w}(c_{b,w} - c_{aq}) - \lambda \cdot n_b R_{d,b} L \cdot c_{b,w} \tag{10}$$

$$n_b R_{d,b} L \cdot \frac{dc_{b,nw}}{dt} = \Lambda_{d,nw}(c_l - c_{b,nw}) - \Lambda_{d,nw}(c_{b,nw} - c_{aq}) - \lambda \cdot n_b R_{d,b} L \cdot c_{b,nw} \tag{11}$$

where n_b is the average porosity of the mineral layers of the barrier system, $R_{d,b}$ is the average retardation factor of the contaminant through the barrier system and c_{aq} is the contaminant concentration in the aquifer that is located underneath the barrier system.

The mass balance of the contaminant in the underlying aquifer allows c_{aq} to be determined:

$$\begin{aligned} n_{aq} R_{d,aq} L_{aq} \cdot \frac{dc_{aq}}{dt} &= a_w q c_{b,w} + a_w \Lambda_{d,w}(c_{b,w} - c_{aq}) + (1 - a_w)\Lambda_{d,nw}(c_{b,nw} - c_{aq}) + \\ &\quad q_{aq,0} c_{aq,0} - \left(q_{aq,0} + a_w q \frac{\ell}{L_{aq}}\right) c_{aq} - \lambda \cdot n_{aq} R_{d,aq} L_{aq} \cdot c_{aq} \end{aligned} \tag{12}$$

where n_{aq}, $R_{d,aq}$ and L_{aq} are the porosity, the retardation factor and the thickness of the aquifer, respectively. $q_{aq,0}$ and $c_{aq,0}$ are the aquifer horizontal specific discharge and the contaminant concentration in the aquifer upstream from the landfill, respectively.

Equations 1, 10, 11 and 12 describe the interaction between the waste, the barrier system and the aquifer. The aquifer represents the natural resource to be protected from the potential harm caused by the contaminant migration from the waste leachate. As a result, the determination of c_{aq} allows the impact of landfill contamination on the potential use of the groundwater to be assessed. For instance, c_{aq} may be compared with a threshold value related to the production of drinkable or irrigation water from a well located in correspondence with the compliance point just downstream from the landfill.

3 APPLICATION EXAMPLE

The following example is provided to illustrate how the previously defined set of equations can be employed in order to assess the effectiveness of a landfill barrier system. The solution of Equations 1, 10, 11 and 12 may be obtained numerically by using the forward Euler method to integrate with respect to the time t, or analytically by using similarity transformations.

The barrier system consists of a composite liner constituted by a 2.5 mm thick geomembrane liner (GML) and a 1 m thick compacted clay liner (CCL), which overlies a 3 m thick attenuation layer (AL), as shown in Figure 2.

The height of the ponded leachate in the leachate removal and collection layer, h_p, is assumed equal to 0.3 m, and the hydraulic head difference between the top of the mineral layers and the bottom of the attenuation layer, is supposed equal to 3 m (Figure 2).

The physical, hydraulic and transport parameters that have been assigned to the geomembrane and the mineral layers are reported in Figure 2 and in Table 1.

The analysis is developed for benzene, which is a common component of municipal solid waste landfill leachates. The release of benzene is assumed to occur from a 30 m-thick waste deposit, which is characterized by a bulk leachate partition coefficient $B_l = 4$. The decay constant λ is calculated from the upper value for the half-life of benzene given by Howard *et al.* (1991), which is 730 days, and results in being equal to $1.1 \cdot 10^{-8}$ s^{-1}.

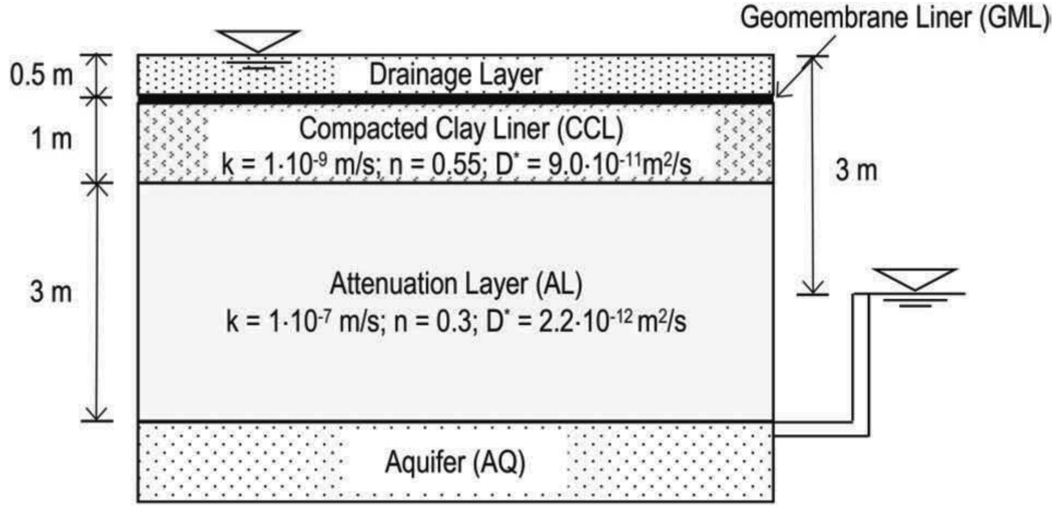

Figure 2. Scheme of the barrier system considered in the example analysis.

Table 1. Physical, hydraulic and transport parameters of the geomembrane and the mineral layers of the barrier system.

	Mineral layers	
Parameter	CCL	AL
Thickness, L (m)	1	3
Hydraulic conductivity, k (m/s)	$1{\cdot}10^{-9}$	$1{\cdot}10^{-7}$
Porosity, n (-)	0.55	0.3
Effective diffusion coefficient, D* (m^2/s)	$9.0{\cdot}10^{-11}$	$2.2{\cdot}10^{-10}$
	Geomembrane	
Thickness, L_g (m)	0.0025	
Partition coefficient for benzene, K_g (-)*	30	
Diffusion coefficient for benzene, D_g (m^2/s)*	$0.35{\cdot}10^{-12}$	

*data from Sangam and Rowe (2001).

The average porosity n_b of the barrier system is equal to 0.36. The retardation factor $R_{d,b}$, which is estimated from a distribution coefficient $K_d = 1.33$ ml/g (Hrapovic 2001) and an average dry density $\rho_d = 1.6$ g/cm^3, results equal to 6.9.

The aquifer located beneath the landfill is assumed to be characterized by a porosity n_{aq} equal to 0.3, a retardation factor $R_{d,aq}$ of 8.1 and a thickness L_{aq} of 10 m. The horizontal groundwater volumetric flux just upstream from the landfill, $q_{aq,0}$, is equal to $1{\cdot}10^{-6}$ m/s (= 31.6 m/ year). The concentration of benzene upstream from the landfill, $c_{aq,0}$, is assumed to be null.

The analysis has been conducted to simulate the decrease in benzene concentration in the leachate released by the waste over time and the simultaneous increase in benzene concentration in the aquifer located beneath the landfill. The obtained results are shown in Figure 3. The benzene concentration in the waste leachate starts from a value of 1,000 mg/l and reduces to a value of about 1 mg/l after 20 years and 10^{-3} mg/l after 40 years. The reduction in benzene concentration is governed by the degradation process, which is modelled as a first-order decay reaction.

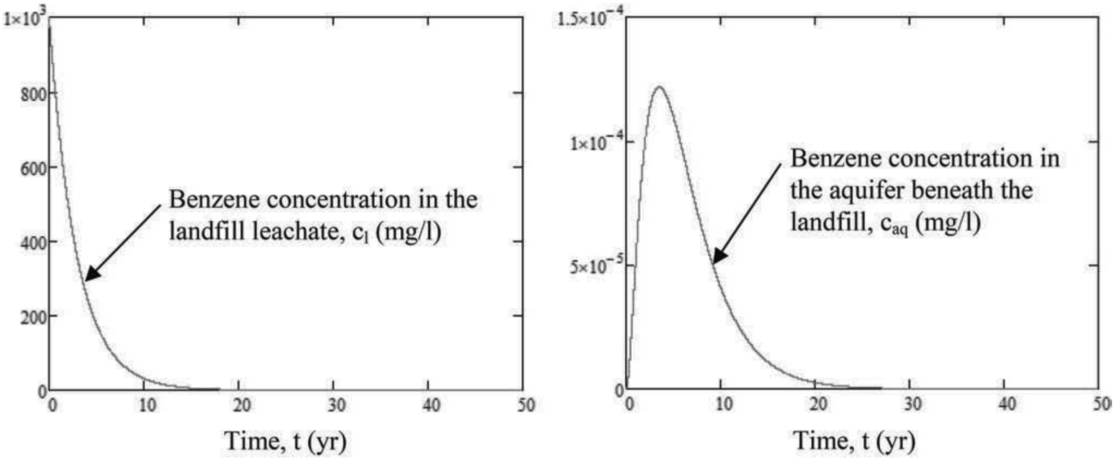

Figure 3. Results of the performed analysis, which show the change in time of the benzene concentration in the landfill leachate, c_l (on the left), and in the aquifer, c_{aq} (on the right).

The analysis takes into account the transport properties of the barrier system, which limits the advective transport through a negligible contribution. Assuming 2 holes/hectare in the geomembrane and poor contact conditions between the geomembrane and the underlying compacted clay liner ($C_q = 1.15$), the portion of the barrier area that results in being wetted is equal to only 0.7%.

The benzene concentration in the aquifer increases up to a peak value that is reached after about 3.5 years. The peak value of about $1.2 \cdot 10^{-4}$ mg/l is lower than the screening value that is indicated by the Italian regulation (10^{-3} mg/l). As a result, the benzene does not appear to cause any harm to the groundwater quality due to the effectiveness of the landfill barrier system.

4 CONCLUSIONS

The proposed approach for modelling the interaction between the waste, the lining system and the aquifer located beneath the landfill allows the impact of contaminant release on the groundwater quality to be assessed. The role played by the geosynthetics and the natural attenuation mechanisms, such as degradation and sorption, in limiting the contaminant migration can therefore be fully appreciated.

REFERENCES

Dominijanni, A. & Manassero, M. 2021. Steady-state Analysis of Pollutant Transport to Assess Landfill Liner Performance. *Environmental Geotechnics* 8(7): 480–494.

Dominijanni, A., Guarena, N. & Manassero, M. 2021a. Risk Assessment Procedure for the Performance-Based Design of Landfill Lining Systems and Cutoff Walls. *Japanese Geotechnical Society Special Publication* 9(5): 199–204.

Dominijanni, A., Guarena, N. & Manassero, M. 2021b. La Progettazione Prestazionale dei Sistemi di Contenimento Degli Inquinanti Nelle Discariche. In *Atti del XXVII Convegno Nazionale di Geotecnica, Reggio Calabria (Italy), 13–15 Luglio 2022*. Roma: Associazione Geotecnica Italiana (*in Italian*).

Giroud, J.P. 1997. Equations for Calculating the Rate of Liquid Migration Through Composite Liners Due to Geomembrane Defects. *Geosynthetics International* 4(3–4): 335–348.

Howard, P.H., Boethling, R.S., Jarvis, W.F., Meylan, W.M. & Michalenko, E.M. 1991. *Handbook of Environmental Degradation Rates*. Chelsea: Lewis Publishers.

Hrapovic, L. 2001. Laboratory Study of Intrinsic Degradation of Organic Pollutants in Compacted Clayey Soil. Ph.D. thesis, The University of Western Ontario: 300 pp.

Katsumi, T., Benson, C.H., Foose, G.J. & Kamon, M. 2001. Performance-based Design of Landfill Liners. *Engineering Geology* 60(1–4): 139–148.

Rowe, R.K. 2011. Systems Engineering the Design and Operations of Municipal Solid Waste Landfills to Minimize Leakage of Contaminants to Groundwater. *Geosynthetics International* 18(6): 391–404.

Rowe, R.K. 2018. Environmental Geotechnics: Looking Back, Looking Forward (16th Croce Lecture). *Rivista Italiana di Geotecnica* 2018(4): 8–40.

Sangam, H.P. & Rowe, R.K. 2001. Migration of Dilute Aqueous Organic Pollutants Through HDPE Geomembranes. *Geotextiles and Geomembranes* 19(6): 329–357.