Contaminant transport through landfill composite liners due to geomembrane defects

Original
Contaminant transport through landfill composite liners due to geomembrane defects / Guarena, N., Dominijanni, A., Manassero, M.. - ELETTRONICO. - (2024), pp. 1413-1422. (12th International Conference on Geosynthetics Roma, Italy 17-21 September 2023) [10.1201/9781003386889-182].

Publisher:
CRC Press, Taylor & Francis Group

Published
DOI:10.1201/9781003386889-182

Geosynthetics: Leading the Way to a Resilient Planet – Biondi et al (eds)

Contaminant transport through landfill composite liners due to geomembrane defects

N. Guarena, A. Dominijanni & M. Manassero
Politecnico di Torino, Torino, Italy

ABSTRACT: Although a number of studies have been devoted to the assessment of the leachate flow rate through defects in geomembranes, which are routinely used in conjunction with low-permeability mineral layers for the lining of waste disposal facilities, relatively little attention has been paid to the mechanisms that control the transport of contaminants. A theoretical framework is here presented to model the advective-diffusive transport of inorganic contaminants through defects of uniform width and infinite length (holed wrinkles, defective seams, etc.), whereby imperfect contact conditions between the geomembrane and the underlying mineral layer are considered, and the mass conservation condition is imposed for both the solvent and the solute phases. Closed-form analytical solutions have been derived to assess the contaminant mass flow rate for the cases of pure advection and pure diffusion, with a view to quantifying the error associated with the simplified calculation approaches that are currently adopted for the performance-based design of landfill composite liners.

1 INTRODUCTION

Composite liners that include a high-density polyethylene (HDPE) geomembrane (GM), placed over a compacted clay layer (CCL), are prescribed throughout the world for the bottom lining systems of waste disposal facilities, with the goal of minimising the migration of contaminants from the waste fill to the surrounding environment. The regulations in force in many countries typically define a set of minimum requirements that have to be satisfied by both the GM and the CCL layers, depending on the type of waste that has to be disposed of in the landfill. In some cases the presence of a natural or engineered attenuation layer (AL), i.e., a layer of soil placed between the composite liner and the underlying aquifer or water resource that needs to be protected, represents an additional requirement.

The use of alternative lining systems, such as those in which the CCL is replaced with a geosynthetic clay liner (GCL), is permitted in most regulations, provided that equivalency with the prescribed composite liner is demonstrated on the basis of a selected performance criterion. Some of the common performance criteria, which are adopted to demonstrate that the proposed alternative liner is equivalent to, or better than, the prescribed composite liner, include: (1) the leachate flow rate under steady-state conditions; (2) the mass flow rate of a given contaminant under steady-state conditions; (3) the time required for the concentration of a given contaminant to reach a specified value at the bottom of the barrier; and (4) the time required for the mass flow rate of a given contaminant to reach a specified value at the bottom of the barrier (Katsumi *et al.* 2001; Manassero *et al.* 2000; Rowe & Brachman 2004; Shackelford 1990).

As far as the first of the aforementioned performance criteria is concerned, which is closely related to the steady-state advective travel time through the composite liner (Shackelford 1993), several approaches have been developed to calculate the leachate flow rate since the pioneering study of Giroud & Bonaparte (1989), who recognised that intact GMs are nearly impervious to the

DOI: 10.1201/9781003386889-182

liquid flow and, therefore, the only accessible pathway by which the leachate can migrate through landfill composite liners is through defects in the GM layer (e.g. defective seams between adjacent panels, punctures caused by sharp materials beneath and above the GM, and tensile failures induced by the landfilling operations). Rowe (1998) and Touze-Foltz *et al.* (1999, 2001) derived analytical solutions for the leakage rate under the assumption that, after infiltration through the GM defect, the contaminated liquid spreads horizontally in the interfacial zone between the GM and the low-permeability mineral layer up to a certain distance from the defect, prior to percolating vertically through the low-permeability mineral layer. The ability of Rowe's (1998) solutions to represent the actual three-dimensional (3D) flow regime within the composite liner was verified numerically by Foose *et al.* (2001a), who observed that analytical and numerical models yield nearly identical results for the values of the hydraulic transmissivity of the interface and the hydraulic conductivity of the low-permeability mineral layer that are representative of field scenarios. Other numerical studies have addressed specific issues, such as the effects related to the spatial variability in the hydraulic transmissivity of the GM/CCL interface (Cartaud *et al.* 2005a), to the change in the degree of saturation of the mineral layer and to the shape of longitudinal defects of finite length in the GM layer (Cartaud *et al.* 2005b; Saidi *et al.* 2006), to the hydraulic interaction between adjacent defects in the GM layer (Saidi *et al.* 2008), and to the different hydraulic properties of the geotextile and bentonite components of GCLs under unsaturated conditions (Bannour *et al.* 2016). Empirical (Giroud 1997; Touze-Foltz & Giroud 2003, 2005) and semi-empirical solutions (Foose *et al.* 2001a; Giroud & Touze-Foltz 2005) were developed using interpolation methods that combine theoretical (both analytical and numerical) and experimental results, thus providing design engineers with simple equations that allow the leachate flow rate to be assessed once a limited number of input parameters (i.e. the hydraulic head on top of the GM, the area of circular defects or the width of longitudinal defects, and the hydraulic conductivity of the mineral layer) and the contact conditions between the GM and the mineral layer are known.

Compared to the numerous attempts that have been made to propose a rational method to assess the leachate flow rate through composite liners, relatively few studies have been aimed at quantifying the advective-diffusive transport of contaminants in the presence of defects in the GM layer. The latter issue is particularly relevant in the case of inorganic compounds, which, unlike many organic compounds, do not readily diffuse through intact portions of the GM layer. Therefore, although the transport of organic compounds can be modelled under the hypothesis of molecular diffusion being the primary migration pathway over the entire surface of the composite liner (Foose 2002; Foose *et al.* 2002) when GMs are installed under strict construction quality assurance conditions (i.e. with a defect frequency ranging from 2.5 to 5 holes/ha, as reported by Rowe (2012)), the transport of inorganic compounds should be recognised as a 3D process that involves migration through the GM defects, through the interfacial zone between the GM and the underlying mineral layer and, finally, through the mineral layer itself, via a combination of advection and diffusion.

A simplified approach to model the advective-diffusive transport of inorganic contaminants through composite liners was proposed by Katsumi *et al.* (2001), who identified an equivalent one-dimensional (1D) system for which analytical solutions to the contaminant breakthrough time and mass flux exist. This approach, which has since been implemented in a number of analytical studies that have dealt with the performance-based design of landfill lining systems, allows both steady-state (Dominijanni & Manassero 2021; Dominijanni *et al.* 2021; Foose 2010; Guarena *et al.* 2020) and transient-state contaminant transport analyses (Foose *et al.* 2001b; Kandris & Pantazidou 2012) to be carried out using typical spreadsheet applications and hand-held calculators, and the equivalence between the prescribed and alternative lining systems to be assessed on the basis of performance criteria (2) to (4), which are preferable over the advective travel time criterion (1) since diffusion is a significant, if not the dominant, transport mechanism through composite liners (Foose *et al.* 2002; Manassero & Shackelford 1994; Shackelford 2014). Furthermore, such an approach may be used as an effective tool to verify the results of more complex (fully 3D) and computationally rigorous numerical models.

Despite its simplicity and versatility, the Katsumi *et al.* (2001) approach is not devoid of drawbacks, the most serious of which can probably be ascribed to the way the equivalent 1D system is defined. Although, on the one hand, satisfaction of the mass conservation condition for the solvent phase is guaranteed with regard to the analytical or empirical model that is selected to calculate the leachate flow rate, on the other, the mass conservation condition for the solute phase is disregarded, and an error is therefore made in the predicted contaminant mass flux relative to the theoretically correct solution. With the aim of covering this modelling gap, a novel theoretical framework is outlined in the present paper, in which the 3D advective-diffusive transport of inorganic contaminants within the composite liner is conceptualised as a horizontal flow along the interface between the GM and the low-permeability mineral layer and then a vertical flow in the low-permeability mineral layer, in a similar way to the reference scheme that was considered by Rowe (1998) with a view to approximating the actual leachate flow network under imperfect contact conditions at the GM/CCL or GM/GCL interface. The error that can arise from the adoption of the Katsumi *et al.* (2001) approach is estimated on the basis of closed-form analytical solutions to the contaminant mass flow rate for the cases of pure advection and pure diffusion, assuming that steady-state conditions have been achieved for both the liquid and solute transport.

2 MODELLING THE ADVECTIVE-DIFFUSIVE TRANSPORT OF INORGANIC CONTAMINANTS THROUGH COMPOSITE LINERS

The containment performance of landfill composite liners is known to be affected by the areal density of wrinkles in the GM layer, whose formation is mostly controlled, during construction of the liner, by the thermal expansion of the GM upon heating by solar radiation, as well as by its placement and protection procedures (Chappel *et al.* 2012; Giroud & Morel 1992; Rowe 2005, 2012). Indeed, because of the greater hydraulic transmissivity of the gap beneath the wrinkles than that associated with the interfacial zone between the GM and the low-permeability mineral layer, contaminants preferentially migrate through holes that are located in correspondence to the wrinkles rather than through holes that occur in flat areas. The following theoretical framework has thus been developed only for the case of a damaged wrinkle, whose width, $2b_w$, is defined as the width of the zone where the GM is not in contact with the underlying mineral layer (Figure 1), as this is the one of the greatest concerns about the problem of assessing the ability of the selected composite liner to limit contaminant transport from the waste fill. Nonetheless, if the liquid and contaminant transport rates are not controlled by the size of the actual holes in the wrinkle, the case of a damaged wrinkle is perfectly analogous to the case of a cut, tear or defective seam of width $2b_w$ occurring in a flat area of the GM layer, so that the two types of defects can collectively be referred to as defects of uniform width. Moreover, if the

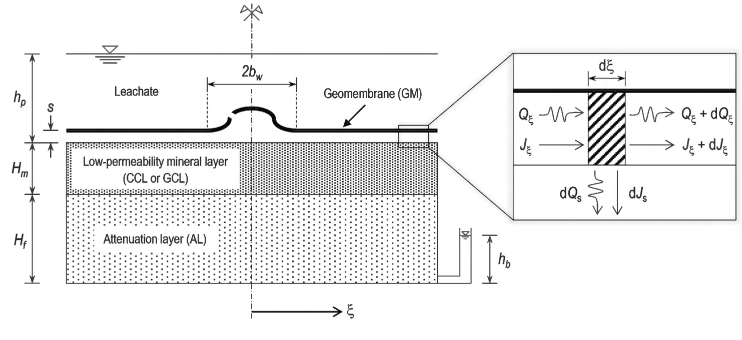

Figure 1. Reference scheme for the liquid and contaminant transport analyses through a composite liner with a defect of uniform width and infinite length in the GM layer and imperfect contact conditions between the GM and the low-permeability mineral layer (not to scale).

length of the defect, L_w, is much greater than its width (i.e. defect of uniform width and infinite length), the liquid and contaminant transport analyses can be treated as two-dimensional problems (Giroud & Touze-Foltz 2005; Touze-Foltz *et al.* 1999).

Provided the spacing between adjacent wrinkles is high enough for their mutual interactions to be neglected, Rowe's (1998) analytical solution to the steady-state hydraulic head profile, h, beneath the GM can be written in the following form:

$$h(\xi) = \begin{cases} h_p & \text{if } \xi \le b_w \\ \left(H_f + H_m - h_b + h_p\right) e^{-\alpha(\xi - b_w)} - \left(H_f + H_m - h_b\right) & \text{if } \xi > b_w \end{cases} \tag{1}$$

The α parameter that appears in Equation 1 is given by:

$$\alpha = \sqrt{\frac{k_s}{\left(H_f + H_m\right)\theta_h}} \tag{2}$$

where θ_h is the hydraulic transmissivity of the interfacial zone between the GM and the low-permeability mineral layer, and k_s is the equivalent hydraulic conductivity corresponding to the low-permeability mineral layer (saturated hydraulic conductivity k_m) and the attenuation layer (saturated hydraulic conductivity k_f):

$$k_s = \frac{H_f + H_m}{\frac{H_f}{k_f} + \frac{H_m}{k_m}} \tag{3}$$

The horizontal leachate flow rate in the transmissive layer, Q_ξ, at a distance $\xi > b_w$ from the longitudinal axis of the wrinkle, can be expressed as:

$$Q_\xi(\xi) = L_w i_s \frac{k_s}{\alpha} \mathrm{e}^{-\alpha(\xi - b_w)} \tag{4}$$

where i_s is the maximum mean hydraulic gradient through the low-permeability mineral layer and the attenuation layer:

$$i_s = 1 + \frac{h_p - h_b}{H_f + H_m} \tag{5}$$

The vertical leachate flow rate, $\mathrm{d}Q_s$, that infiltrates the strip of the mineral layer between the ξ and $\xi + \mathrm{d}\xi$ coordinates can be expressed as:

$$\mathrm{d}Q_s(\xi) = \begin{cases} L_w i_s k_s \mathrm{d}\xi & \text{if } \xi \le b_w \\ L_w i_s k_s e^{-\alpha(\xi - b_w)} \mathrm{d}\xi & \text{if } \xi > b_w \end{cases} \tag{6}$$

and the corresponding vertical volumetric leachate flux, q_s, at a distance ξ from the longitudinal axis of the wrinkle, is obtained directly as the ratio of $\mathrm{d}Q_s$ to $L_w\mathrm{d}\xi$:

$$q_s(\xi) = \begin{cases} i_s k_s & \text{if } \xi \le b_w \\ i_s k_s e^{-\alpha(\xi - b_w)} & \text{if } \xi > b_w \end{cases} \tag{7}$$

Finally, the leachate flow rate, Q_s, that infiltrates the low-permeability mineral layer at a distance ξ from the longitudinal axis of the wrinkle is given by:

$$Q_s(\xi) = 2 b_w L_w i_s k_s \left\{ 1 + \frac{1}{\alpha b_w} \left[1 - \mathrm{e}^{-\alpha(\xi - b_w)} \right] \right\} \tag{8}$$

which yields the total leachate flow rate through the damaged wrinkle, Q, if ξ tends to infinity:

$$Q = 2 b_w L_w i_s k_s \left(1 + \frac{1}{\alpha b_w} \right) \tag{9}$$

2.1 *Katsumi* et al. *(2001) equivalent 1D system*

The approach that was proposed by Katsumi *et al.* (2001), with the aim of providing a simple calculation tool to analyse the transport of inorganic contaminants through composite liners when the leachate flow is at steady state, consists in computing an equivalent area, A_e, which conducts the same (total) leachate flow rate as the considered defect for the same hydraulic head drop across the composite liner, thereby ensuring that the mass conservation condition for the solvent phase is satisfied:

$$A_e = \frac{Q}{k_s i_s} \tag{10}$$

The equivalent area that is computed according to Equation 10 is here observed to correspond to the definition of the wetted area originally provided by Giroud *et al.* (1992, 1997). Furthermore, if Rowe's (1998) conceptual model is adopted to assess the leachate flow rate, the following expression results from substitution of Equation 9 in Equation 10:

$$A_e = 2b_w L_w \left(1 + \frac{1}{\alpha b_w}\right) \tag{11}$$

and the contaminant mass flow rate through the damaged wrinkle, J_{app}, which approximates the theoretically correct one, can then be obtained from the contaminant mass flux, j_s, which in turn is calculated according to the existing analytical solutions to the partial differential equation that governs the 1D solute transport through multi-layered barriers via advection, diffusion, sorption and degradation:

$$J_{app} = A_e j_s \tag{12}$$

When the contaminant transport is dominated by advection, and steady-state conditions are achieved for both the liquid and the solute transport, the following expression of Equation 12 holds true:

$$J_{app} = 2b_w L_w k_s i_s c_p \left(1 + \frac{1}{\alpha b_w}\right) \tag{13}$$

where c_p is the contaminant concentration in the leachate drainage layer, which is located directly above the GM layer.

If the diffusive component of contaminant transport prevails over the advective one, Equation 12 assumes the following form:

$$J_{app} = 2b_w L_w \Lambda (c_p - c_b) \left(1 + \frac{1}{\alpha b_w}\right) \tag{14}$$

where c_b is the contaminant concentration at the bottom of the composite liner, and Λ is the equivalent diffusivity (Manassero & Shackelford 1994; Manassero *et al.* 2000):

$$\Lambda = \frac{1}{\frac{H_f}{n_f D_f^*} + \frac{H_m}{n_m D_m^*}} \tag{15}$$

being n_m and n_f the porosities of the low-permeability mineral layer and the attenuation layer, respectively, and $D_m{}^*$ and $D_f{}^*$ the effective diffusion coefficients of the low-permeability mineral layer and the attenuation layer, respectively, which are obtained as the product of the apparent tortuosity factor (< 1) and the free-solution diffusion coefficient of the contaminant, $D_{s,0}$.

2.2 *Novel theoretical framework*

The theoretical framework outlined in this section should be interpreted as an attempt to overcome the limitations encountered in the Katsumi *et al.* (2001) approach, and to investigate the extent to which this latter approach approximates the actual transport mechanisms of inorganic contaminants through landfill composite liners with defects in the GM layer.

Satisfaction of the mass conservation condition for the solute phase is guaranteed under steady-state conditions, with reference to the control volume in the interfacial zone between the GM and the low-permeability mineral layer (Figure 1), if the following relationship is verified:

$$\mathrm{d}J_s(\xi) + \frac{\mathrm{d}J_\xi(\xi)}{\mathrm{d}\xi}\mathrm{d}\xi = 0 \tag{16}$$

The vertical contaminant mass flow rate, $\mathrm{d}J_s$, that infiltrates the strip of the mineral layer between the ξ and $\xi + \mathrm{d}\xi$ coordinates can be expressed as:

$$\mathrm{d}J_s(\xi) = q_s \frac{c e^{\frac{q_s}{\Lambda}} - c_b}{e^{\frac{q_s}{\Lambda}} - 1} L_w \mathrm{d}\xi \tag{17}$$

or, substituting Equation 7 in Equation 17, in the following alternative form:

$$\mathrm{d}J_s(\xi) = \begin{cases} i_s k_s \dfrac{c_p e^{\frac{i_s k_s}{\Lambda}} - c_b}{e^{\frac{i_s k_s}{\Lambda}} - 1} L_w \mathrm{d}\xi & \text{if } \xi \leq b_w \\ i_s k_s e^{-\alpha(\xi - b_w)} \dfrac{c e^{\frac{i_s k_s}{\Lambda} e^{-\alpha(\xi - b_w)}} - c_b}{e^{\frac{i_s k_s}{\Lambda} e^{-\alpha(\xi - b_w)}} - 1} L_w \mathrm{d}\xi & \text{if } \xi > b_w \end{cases} \tag{18}$$

where c is the contaminant concentration beneath the GM.

The horizontal contaminant mass flow rate in the transmissive layer, J_ξ, at a distance $\xi > b_w$ from the longitudinal axis of the wrinkle, can be expressed as:

$$J_\xi(\xi) = Q_\xi c - L_w \theta_d \frac{\mathrm{d}c}{\mathrm{d}\xi} \tag{19}$$

or, substituting Equation 4 in Equation 19, in the following alternative form:

$$J_\xi(\xi) = L_w i_s \frac{k_s}{\alpha} c e^{-\alpha(\xi - b_w)} - L_w \theta_d \frac{\mathrm{d}c}{\mathrm{d}\xi} \tag{20}$$

where θ_d is the diffusive transmissivity of the GM/CCL or GM/GCL interface.

Substituting Equations 18 and 20 in Equation 16 and collecting terms yields the following homogeneous, second-order, linear ordinary differential equation with non-constant coefficients:

$$\frac{\mathrm{d}^2 c}{\mathrm{d}\xi^2} - \frac{i_s k_s}{\theta_d \alpha} e^{-\alpha(\xi - b_w)} \frac{\mathrm{d}c}{\mathrm{d}\xi} - \frac{i_s k_s}{\theta_d} \left[\frac{e^{-\alpha(\xi - b_w)}}{e^{\frac{i_s k_s}{\Lambda} e^{-\alpha(\xi - b_w)}} - 1} \right] (c - c_b) = 0 \tag{21}$$

which has to be solved for $b_w \leq \xi < +\infty$ in conjunction with the following set of boundary conditions:

$$\begin{cases} c(b_w) = c_p \\ \lim\limits_{\xi \to +\infty} \dfrac{\mathrm{d}c}{\mathrm{d}\xi}(\xi) = 0 \end{cases} \tag{22}$$

Once the steady-state contaminant concentration profile beneath the GM has been determined, either analytically or numerically, the contaminant mass flow rate, J_s, that infiltrates the low-permeability mineral layer at a distance ξ from the longitudinal axis of the wrinkle is given by:

$$J_s(\xi) = 2 b_w L_w i_s k_s c_p \left\{ \frac{\mathrm{e}^{\frac{i_s k_s}{\Lambda}} - \frac{c_b}{c_p}}{\mathrm{e}^{\frac{i_s k_s}{\Lambda}} - 1} + \frac{1}{\alpha b_w} \left[1 - \frac{c(\xi)}{c_p} \mathrm{e}^{-\alpha(\xi - b_w)} \right] - \frac{\theta_d}{b_w i_s k_s c_p} \left[\frac{\mathrm{d}c}{\mathrm{d}\xi}(b_w) - \frac{\mathrm{d}c}{\mathrm{d}\xi}(\xi) \right] \right\} \tag{23}$$

which yields the total contaminant mass flow rate through the damaged wrinkle, J, if ξ tends to infinity:

$$J = 2b_w L_w i_s k_s c_p \left[\frac{e^{\frac{i_s k_s}{\Lambda}} - \frac{c_b}{c_p}}{e^{\frac{i_s k_s}{\Lambda}} - 1} + \frac{1}{\alpha b_w} - \frac{\theta_d}{b_w i_s k_s c_p} \frac{\mathrm{d}c}{\mathrm{d}\xi}(b_w) \right] \tag{24}$$

2.2.1 *Closed-form analytical solution for the case of pure advection*

A first case of interest, for which a closed-form analytical solution to the total contaminant mass flow rate is easily obtained, is that of the advection that represents the main transport mechanism through the composite liner. Under such an assumption, Equations 21 and 22 reduce to a condition of constant solute concentration beneath the GM (i.e. $c = c_p$ for $b_w \leq \xi < +\infty$), and the total contaminant mass flow rate through the damaged wrinkle is then given by a relationship that is identical to Equation 13. Therefore, for the limiting case of purely advective transport, the Katsumi *et al.* (2001) approach leads to a prediction of the contaminant mass flow rate that can be regarded as the rigorous one from the mass conservation condition viewpoint, for both the solvent and the solute phases.

2.2.2 *Closed-form analytical solution for the case of pure diffusion*

When diffusion is the controlling mechanism of contaminant transport, as might be the case of composite liners that include mineral layers with very low hydraulic conductivity values (e.g. GCLs or bentonite-amended CCLs), the steady-state contaminant concentration profile beneath the GM assumes a form that is analogous to the hydraulic head profile given by Equation 1:

$$c(\xi) = \begin{cases} c_p & \text{if } \ \xi \leq b_w \\ (c_p - c_b) e^{-\beta(\xi - b_w)} + c_b & \text{if } \ \xi > b_w \end{cases} \tag{25}$$

where:

$$\beta = \sqrt{\frac{\Lambda}{\theta_d}} \tag{26}$$

The following expression can then be derived for the total contaminant mass flow rate through the damaged wrinkle:

$$J = 2b_w L_w \Lambda (c_p - c_b) \left(1 + \frac{1}{\beta b_w} \right) \tag{27}$$

Finally, the error that arises when the Katsumi *et al.* (2001) approach is used, relative to the theoretically correct solution for the limiting case of purely diffusive transport, is assessed by finding the ratio of Equation 27 to Equation 14:

$$\frac{J}{J_{app}} = \frac{1 + \frac{1}{\beta b_w}}{1 + \frac{1}{\alpha b_w}} \tag{28}$$

With the aim of quantifying the aforementioned error for a real pollutant containment scenario, the two landfill composite liners described by Dominijanni & Manassero (2021) have been considered herein, and cadmium (Cd^{2+}) has been selected to represent the inorganic leachate constituent of interest ($D_{s,0} = 7.17 \cdot 10^{-10}$ m^2/s). The first lining system consists of a 1.5 mm thick GM and a 1 m thick CCL, which overlies a 3 m thick AL. The second lining system consists of a 1.5 mm thick GM and a 1 cm thick GCL, which overlies a 4 m thick AL. Further details about the physical, hydraulic and transport parameters assigned to the two composite liners can be found in Dominijanni & Manassero (2021), while an assessment of the diffusive transmissivity, in the absence of experimental studies devoted to its measurement, can be obtained as follows:

$$\theta_d = D_{s,0} s \tag{29}$$

where s is the thickness of the GM/CCL or GM/GCL interface, which in turn can be related to θ_h, if Newton's viscosity law for the flow between two parallel plates applies to the transmissive layer (Giroud & Bonaparte 1989):

$$s = \sqrt[3]{\frac{12\theta_h \mu_w}{\gamma_w}} \tag{30}$$

being γ_w and μ_w the unit weight and viscosity of water, respectively.

The use of Equation 28 leads to a calculated error, J/J_{app}, equal to 0.022 for the composite liner that comprises the CCL, and 0.763 for the composite liner that comprises the GCL, as illustrated in Figure 2. Therefore, the Katsumi *et al.* (2001) approach overestimates the contaminant mass flow rate for both the considered lining systems, with an error that is greater in the case of the GM + CCL + AL composite liner than in the case of the GM + GCL + AL composite liner. Such an overestimation can be expected, considering the values of the decay constant, β, for the solute concentration profile beneath the GM (Equation 25), which are greater than the corresponding values of the decay constant, α, for the hydraulic head profile (Equation 1) and, thus, cause the footprint of the low-permeability mineral layer, over which contaminant diffusion takes place, to be smaller than the equivalent area that is given by Equation 11.

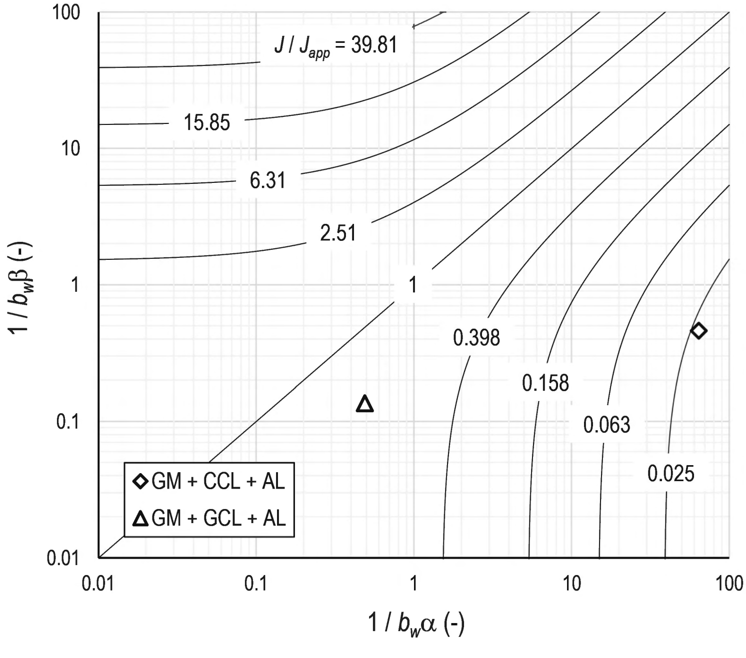

Figure 2. Iso-value curves of the error associated with the use of the Katsumi *et al.* (2001) approach, which is defined as the ratio of the theoretically correct contaminant mass flow rate, J, to the approximate one, J_{app}, under the hypothesis that diffusion is the controlling transport mechanism. The open symbols refer to the landfill composite liners considered by Dominijanni & Manassero (2021).

3 CONCLUSIONS

An original theoretical framework has been developed to calculate the steady-state mass flow rate of inorganic contaminants through landfill composite liners, which are made up of a GM overlying a low-permeability mineral layer, under the restrictive hypotheses that the transport of both the liquid and the solute only occurs through GM defects of uniform width and infinite length (e.g. holed wrinkles and defective seams), and that all the soil layers maintain fully-saturated conditions, even when negative pore-water pressures build up. The migration pathway within the lining system has been conceptualised as a horizontal flow along the interfacial zone between the GM and the underlying mineral layer, and then as a vertical flow in the mineral layer itself, as in the reference scheme considered by Rowe (1998) for the calculation of the leachate flow rate. Closed-form analytical solutions to the contaminant mass flow rate have been derived for two specific cases, namely pure advection and pure diffusion, with the aim of quantifying the error associated with the use of the simplified calculation approach that was proposed by Katsumi *et al.* (2001). In the case of purely advective transport, the latter approach has been proven to be consistent with the mass conservation condition for both the solvent and the solute phases, while satisfaction of the mass conservation condition for the solute phase is no longer guaranteed when diffusion represents the main transport mechanism, leading to an overestimation of the contaminant mass flow rate if the composite liners described by Dominijanni & Manassero (2021) are considered.

Further research is recommended on the aspects dealt with in the present paper. From a theoretical viewpoint, the possible existence of an analytical expression for the solute concentration profile beneath the GM should be investigated, also considering different defect types (e.g. circular holes in a flat GM), boundary conditions (e.g. parallel interacting damaged wrinkles) and transport properties of the soil layers (e.g. change in the degree of saturation for positive suction heads) from the working hypotheses of this study. Furthermore, the ability of the assumed migration pathway to represent the actual 3D advective-diffusive transport in composite liners should be verified with the aid of computationally rigorous numerical models. From an experimental viewpoint, the development of a laboratory apparatus, which allows the newly introduced θ_d parameter (i.e. the diffusive transmissivity of the GM/CCL or GM/GCL interface) to be measured, is of the utmost importance.

REFERENCES

Bannour, H., Goblet, P., Mendes, M. & Touze-Foltz, N. 2016. Numerical Study of Advective Flow Through Composite Liners. *Environmental Geotechnics* 3(6): 379–385.

Cartaud, F., Goblet, P. & Touze-Foltz, N. 2005a. Numerical Simulation of the Flow in the Interface of a Composite Bottom Liner. *Geotextiles and Geomembranes* 23(6): 513–533.

Cartaud, F., Goblet, P. & Touze-Foltz, N. 2005b. Numerical Study of Advective Flow Through Composite Liners. *Geosynthetics International* 12(6): 299–309.

Chappel, M.J., Brachman, R.W.I., Take, W.A. & Rowe, R.K. 2012. Large-scale Quantification of Wrinkles in a Smooth Black HDPE Geomembrane. *Journal of Geotechnical and Geoenvironmental Engineering* 138(6): 671–679.

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. 2021. Risk Assessment Procedure for the Performance-Based Design of Landfill Lining Systems and Cutoff Walls. *Japanese Geotechnical Society Special Publication* 9(5): 199–204.

Foose, G.J. 2002. Transit-time Design for Diffusion Through Composite Liners. *Journal of Geotechnical and Geoenvironmental Engineering* 128(7): 590–601.

Foose, G.J. 2010. A Steady-state Approach for Evaluating the Impact of Solute Transport Through Composite Liners on Groundwater Quality. *Waste Management* 30(8–9): 1577–1586.

Foose, G.J., Benson, C.H. & Edil, T.B. 2001a. Predicting Leakage through Composite Landfill Liners. *Journal of Geotechnical and Geoenvironmental Engineering* 127(6): 510–520.

Foose, G.J., Benson, C.H. & Edil, T.B. 2001b. Analytical Equations for Predicting Concentration and Mass Flux From Composite Liners. *Geosynthetics International* 8(6): 551–575.

Foose, G.J., Benson, C.H. & Edil, T.B. 2002. Comparison of Solute Transport in Three Composite Liners. *Journal of Geotechnical and Geoenvironmental Engineering* 128(5): 391–403.

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.

Giroud, J.P. & Bonaparte, R. 1989. Leakage Through Liners Constructed with Geomembranes - Part II. Composite liners. *Geotextiles and Geomembranes* 8(2): 71–111.

Giroud, J.P. & Morel, N. 1992. Analysis of Geomembrane Wrinkles. *Geotextiles and Geomembranes* 11(3): 255–276.

Giroud, J.P. & Touze-Foltz, N. 2005. Equations for Calculating the Rate of Liquid Flow Through Geomembrane Defects of Uniform Width and Finite or Infinite Length. *Geosynthetics International* 12(4): 191–204.

Giroud, J.P., Badu-Tweneboah, K. & Bonaparte, R. 1992. Rate of Leakage Through a Composite Liner Due to Geomembrane Defects. *Geotextiles and Geomembranes* 11(1): 1–28.

Giroud, J.P., Rad, N.S. & McKelvey, J.A. 1997. Evaluation of the Surface Area of a GCL Hydrated by Leachate Migrating Through Geomembrane Defects. *Geosynthetics International* 4(3–4): 433–462.

Guarena, N., Dominijanni, A. & Manassero, M. 2020. From the Design of Bottom Landfill Liner Systems to the Impact Assessment of Contaminants on Underlying Aquifers. *Innovative Infrastructure Solutions* 5: 2.

Kandris, K. & Pantazidou, M. 2012. Landfill Base Liners: Assessment of Material Equivalency and Impact to Groundwater. *Geotechnical and Geological Engineering* 30(1): 27–44.

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

Manassero, M. & Shackelford, C.D. 1994. The Role of Diffusion in Contaminant Migration Through Soil Barriers. *Rivista Italiana di Geotecnica* 28(1): 5–31.

Manassero, M., Benson, C.H. & Bouazza, A. 2000. Solid Waste Containment Systems. In *Proc. GeoEng2000: An International Conference on Geotechnical & Geological Engineering, Melbourne, 19-24 November 2000*. Lancaster: Technomic Publishing Company.

Rowe, R.K. 1998. Geosynthetics and the Minimization of Contaminant Migration Through Barrier Systems Beneath Solid Waste. In *Proc. 6th Int. Conf. on Geosynthetics, Atlanta, 25-29 March 1998*. Roseville: Industrial Fabrics Association International.

Rowe, R.K. 2005. Long-term Performance of Contaminant Barrier Systems. 45th Rankine Lecture. *Géotechnique* 55(9): 631–678.

Rowe, R.K. 2012. Short and Long-term Leakage Through Composite Liners. 7th Arthur Casagrande Lecture. *Canadian Geotechnical Journal* 49(2): 141–169.

Rowe, R.K. & Brachman, R.W.I. 2004. Assessment of Equivalence of Composite Liners. *Geosynthetics International* 11(4): 273–286.

Saidi, F., Touze-Foltz, N. & Goblet, P. 2006. 2D and 3D Numerical Modelling of Flow Through Composite Liners Involving Partially Saturated GCLs. *Geosynthetics International* 13(6): 265–276.

Saidi, F., Touze-Foltz, N. & Goblet, P. 2008. Numerical Modelling of Advective Flow Through Composite Liners in Case of Two Interacting Adjacent Square Defects in the Geomembrane. *Geotextiles and Geomembranes* 26(2): 196–204.

Shackelford, C.D. 1990. Transit-time Design of Earthen Barriers. *Engineering Geology* 29(1): 79–94.

Shackelford, C.D. 1993. Contaminant Transport. In D.E. Daniel (ed.), *Geotechnical Practice for Waste Disposal*: 33–65. London: Chapman & Hall.

Shackelford, C.D. 2014. The ISSMGE Kerry Rowe Lecture. The Role of Diffusion in Environmental Geotechnics. *Canadian Geotechnical Journal* 51(11): 1219–1242.

Touze-Foltz, N. & Giroud, J.P. 2003. Empirical Equations for Calculating the Rate of Liquid Flow Through Composite Liners Due to Geomembrane Defects. *Geosynthetics International* 10(6): 215–233.

Touze-Foltz, N. & Giroud, J.P. 2005. Empirical Equations for Calculating the Rate of Liquid Flow Through Composite Liners Due to Large Circular Defects in the Geomembrane. *Geosynthetics International* 12(4): 205–207.

Touze-Foltz, N., Rowe, R.K. & Duquennoi, C. 1999. Liquid Flow Through Composite Liners Due to Geomembrane Defects: Analytical Solutions for Axi-symmetric and Two-dimensional Problems. *Geosynthetics International* 6(6): 455–479.

Touze-Foltz, N., Rowe, R.K. & Navarro, N. 2001. Liquid Flow Through Composite Liners Due to Geomembrane Defects: Nonuniform Hydraulic Transmissivity at the Liner Interface. *Geosynthetics International* 8(1): 1–26.