

From the design of bottom landfill liner systems to the impact assessment of contaminants on underlying aquifers

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(Article begins on next page)

1 **FROM THE DESIGN OF BOTTOM LANDFILL LINER SYSTEMS TO THE IMPACT**  
2 **ASSESSMENT OF CONTAMINANTS ON UNDERLYING AQUIFERS**

3 by

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3  
4   **ABSTRACT:** The most recent advancements of the research activity that has been carried out at  
5 the Polytechnic University of Turin since the 90's are presented, with a focus on the design  
6 approaches which can be adopted for the optimisation of the engineered clay barriers that are used  
7 as a part of the composite liners of solid waste landfills. A particular attention is devoted to the  
8 characterisation of the geosynthetic clay liners (GCLs) in terms of their microstructural features and  
9 semipermeable properties, which affect both the liquid and contaminant transport and the swelling-  
10 shrinking behaviour upon a variation in the chemical and mechanical boundary conditions. In the  
11 first part of the paper, novel analytical solutions are derived in order to account for the influence of  
12 the chemico-osmotic counter-flow on the leakage rate through a lining system that consists of a  
13 geomembrane (GM) overlying a GCL, as well as for the effect of a variation in the GCL swelling  
14 pressure on the hydraulic transmissivity of the GM-GCL interface. In the second part of the paper, a  
15 steady-state analysis approach is proposed with the aim to include all the aforementioned  
16 phenomena in the assessment of the impact of contaminant migration through the landfill bottom  
17 liners on the groundwater quality, taking into account the presence of a natural attenuation layer  
18 (AL) between the GCL and the underlying aquifer.

19  
20   **Key Words:** bentonite fabric, chemico-osmosis, geomembrane, geosynthetic clay liner, interface  
21 transmissivity, swelling pressure.

## 23 INTRODUCTION

24 The performance-based design of landfill lining systems requires the impact of contaminant  
25 migration from the waste on groundwater quality to be assessed. The effectiveness of lining systems  
26 is indeed demonstrated through the verification that the risk for human health and the environment  
27 due to the contaminant migration is limited to an acceptable level. This risk is quantified through  
28 the calculation of the contaminant concentration in the aquifer beneath the landfill, which is  
29 expected to remain less than some prescribed level at a compliance point, which is often a  
30 monitoring well located down-gradient from the landfill [8].

31 In order to conduct an analysis of the contaminant transport through the lining system of a  
32 landfill, the vertical mass flux of the contaminant must be determined taking into account the  
33 properties of all the layers interposed between the waste and the aquifer, including not only the  
34 engineered barriers, but also the natural foundation or attenuation layer (AL). As the regulations in  
35 force in most of the countries prescribe the use of a composite liner that consists of a geomembrane  
36 (GM) overlying a mineral liner, the advective component of the contaminant mass flux is controlled  
37 by the leakage rate through the holes that are created during the installation of the geomembrane,  
38 and during any subsequent construction activities, such as the placement of materials on top of the  
39 geomembrane. With regard to this matter, it is not possible not to mention the fundamental  
40 contribution given by J.P. Giroud to the understanding of the leakage mechanisms that govern the  
41 water migration through composite liners, as well as the development of a rational approach for the  
42 calculation of the leakage rate [16-20, 42].

43 This study is focused on the use of the geosynthetic clay liners (GCLs) in place of the  
44 compacted clay liners (CCLs) as the mineral components of the composite liners. GCLs consist of a  
45 thin layer of bentonite (5-10 mm thick) sandwiched between two geotextiles. The term “bentonite”  
46 is commonly used to indicate a clay soil with a high content (e.g. > 60%) of montmorillonite, a  
47 mineral of the smectite group that is constituted by thin lamellae characterised by a high specific

48 surface (defined as the surface per unit weight) and a permanent negative electric charge. The  
49 montmorillonite lamellae may aggregate in packets (also called tactoids), within which several clay  
50 platelets are in parallel array. As a result, the degree of aggregation in the bentonite micro-fabric  
51 may be quantified through the average number of lamellae per tactoid,  $N_{l,AV}$ , which can vary from 1  
52 for a perfectly dispersed structure to values as high as 70-90 for highly aggregated structures [9].

53 As a consequence of the very high values of the specific surface which can be found in an  
54 ideal fully dispersed bentonite ( $\approx 780 \text{ m}^2/\text{g}$ ), the surface forces of electric nature are dominant over  
55 the mass forces (e.g. gravity) in these materials. The transport properties and the mechanical  
56 behaviour are therefore controlled by the electric interactions that occur at the micro-scale between  
57 the ions that are contained in the pore water and the clay particles. As a result of these interactions,  
58 bentonites may behave as semipermeable membranes, which are able to generate a water flux in  
59 response to a gradient in the chemical composition of the pore solution (chemico-osmosis).  
60 Moreover, bentonites may swell or shrink in response to changes in the chemical composition of the  
61 pore solution, as they are characterized by a macroscopic swelling pressure that is basically  
62 controlled by the solid skeleton fixed charge concentration of the clay particles [5, 26].

63 A theoretical approach for modelling the transport processes and the mechanical response of  
64 bentonites can be derived by upscaling the equations that govern the electric potential distribution,  
65 the water flow and the ion transport at the microscale. In such a theoretical approach the electric  
66 phenomena at the microscale are taken into account via a single parameter,  $\bar{c}'_{sk,0}$ , that represents the  
67 concentration of the solid skeleton electric charge [6, 7]. When this parameter is null, Terzaghi's  
68 equation for effective stress is recovered, as well as the standard advection-diffusion theory for  
69 solute transport; in all the other cases, the effective stress equation is modified to include the  
70 contribution of the swelling pressure, and the osmotic phenomena that characterize the behaviour of  
71 semipermeable membranes are incorporated in the water and solute flux equations [10].  $\bar{c}'_{sk,0}$  may  
72 be determined by fitting the experimental values of macroscopic parameters, such as the reflection

73 coefficient or the swell coefficient, which can be measured for different values of the salt  
74 concentration in the pore water or the bentonite void ratio [10, 12, 13, 31].

75 The changes in the solid skeleton electric charge, as well as in the hydraulic conductivity and  
76 the soil compressibility, which take place in response to the modifications of the bentonite fabric  
77 that are induced by large variations in the salt concentration of pore water or in the bentonite void  
78 ratio, are modelled through a Fabric Boundary Surface (FBS), whereby a fabric variable, such as  
79  $N_{LAV}$ , is related to the salt concentration,  $c_s$ , and the bentonite void ratio,  $e$  [11, 24, 28, 29]. The  
80 shape of the FBS is obtained by fitting the experimental data that are obtained through direct  
81 methods (e.g. transmission electron microscopy, X-ray diffraction analysis and nuclear magnetic  
82 resonance) or indirect methods (e.g. hydraulic conductivity test) for a specific bentonite [24].

83 As a result, starting from a limited number of laboratory tests, the mechanical behaviour and  
84 the transport properties of a bentonite under different conditions in terms of exposure to  
85 contaminants and applied external loads, is predicted through a theoretical model. From a practical  
86 standpoint this allows the barrier performances of GCLs to be simulated in a reliable way, taking  
87 into account the coupled hydro-chemo-mechanical behaviour of the bentonite.

88 In this study, an analytical solution for the calculation of the leakage rate through a composite  
89 liner that consists of a geomembrane overlying a geosynthetic clay liner is presented for the case of  
90 a hole that is located in correspondence of a wrinkle of the geomembrane. The solution  
91 contemplates the influence of the bentonite swelling on the determination of the hydraulic  
92 transmissivity at the interface between the geomembrane and the underlying geosynthetic clay liner,  
93 and the chemico-osmotic component of the water flow that is generated by the gradient in the solute  
94 concentration.

95 This solution is used to evaluate the vertical mass flux of the contaminant that is released in  
96 an aquifer beneath the landfill. The contaminant mass balance within the aquifer is used to calculate

97 the distribution of the contaminant concentration along the direction of the main component of  
98 groundwater flux. The risk for human health and the environment may then be determined based on  
99 the estimated value of the contaminant concentration [8].

100

## 101 **LEAKAGE RATE THROUGH GEOMEMBRANES OVERLYING GEOSYNTHETIC** 102 **CLAY LINERS**

103 The containment performance of composite liners that include a geomembrane over a low-  
104 permeability mineral layer is highly affected by the areal density of wrinkles in the geomembrane,  
105 whose formation is mostly controlled, during the liner construction, by the thermal expansion of the  
106 geomembrane upon heating by solar radiation, as well as by its placement and protection  
107 procedures. Apart from the case of volatile organic compounds, which are able to readily pass  
108 through intact polymer-based barriers via molecular diffusion [39], the vast majority of inorganic  
109 pollutants have been observed to migrate through the holes of geomembranes, and preferentially  
110 through holes that are located in correspondence of wrinkles rather than holes that occur in flat  
111 areas, as the transmissivity of the gap beneath the wrinkle is generally much higher than the  
112 transmissivity of the zone between the geomembrane and the underlying mineral layer [35, 36].

113 Among the different approaches that have been proposed with the aim to evaluate the rate of  
114 leachate flow through a defect in a geomembrane overlying a mineral layer [15, 20, 42], the general  
115 framework studied by Rowe [35] and Touze-Foltz et al. [43] for a circular hole in a flat  
116 geomembrane and for a damaged wrinkle is here adopted in order to extend the existing analytical  
117 solutions to the case of clay layers with a high content of smectite minerals, such as the  
118 geosynthetic clay liners, which are able to exhibit semipermeable membrane behaviour when  
119 permeated with diluted solutions. Such an extension is carried out only for the case of a damaged  
120 wrinkle (i.e. the “two-dimensional case”), as it is the one of greatest concern with respect to the

121 problem of estimating the rate of contaminant transport through the bottom liners of waste disposal  
122 facilities.

### 123 **Effect of the chemico-osmosis on the liquid flow through GM-GCL interfaces**

124 The idealised scenario considered hereafter is depicted in Figure 1. The liquid that has  
125 infiltrated through the geomembrane hole is assumed to spread horizontally and perpendicularly to  
126 the longitudinal axis of the wrinkle within the GM-GCL interface, which is hypothesised to be  
127 characterised by a uniform hydraulic transmissivity,  $\theta$ , up to a distance that is referred to as the half  
128 width of the wetted area,  $\zeta_w$ . Finally, the liquid migrates vertically through the mineral layer.

129 Under fully saturated conditions and assuming that the length of the damaged wrinkle,  $L_w$ , is  
130 much larger than its half width,  $b_w$ , the boundary effects at the ends of the wrinkle can be neglected  
131 and the horizontal liquid flow rate in the transmissive zone,  $Q_\xi$ , is given by:

$$132 \quad Q_\xi = -L_w \theta \frac{dh}{d\xi} \quad (1)$$

133 where  $h$  is the pressure head in the GM-GCL interface.

134 On the basis of the theoretical model developed by Dominijanni and Manassero [7], the  
135 vertical liquid flow rate,  $Q_s$ , which infiltrates into the strip of the geosynthetic clay liner between the  
136 coordinates  $\zeta$  and  $\zeta + d\xi$  can be regarded as the superposition of a Darcian component, which is  
137 driven by the gradient in hydraulic head, and a chemico-osmotic component, which is driven by the  
138 gradient in concentration of the inorganic contaminant across the semipermeable clay layer:

$$139 \quad dQ_s = k_g \frac{H_g + h - h_b}{H_g} L_w d\xi - 2RT \frac{k_g}{\gamma_w} \omega_g \frac{c_p - c_b}{H_g} L_w d\xi \quad (2)$$

140 where  $k_g$  is the hydraulic conductivity of the geosynthetic clay liner,  $H_g$  is the thickness of the  
141 geosynthetic clay liner,  $h_b$  is the pressure head at the bottom of the geosynthetic clay liner,  $R$  is the

142 universal gas constant ( $8.314 \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$ ),  $T$  is the absolute temperature,  $\gamma_w$  is the water unit weight  
 143 ( $\gamma_w = 9.81 \text{ kN/m}^3$ ),  $\omega_g$  is the reflection coefficient or chemico-osmotic efficiency coefficient,  $c_p$  is  
 144 the contaminant concentration in the leachate collection and removal system and  $c_b$  is the  
 145 contaminant concentration at the bottom of the geosynthetic clay liner.

146 The reflection coefficient quantifies the ability of the geosynthetic clay liner to act as a  
 147 selectively permeable membrane, and usually varies from zero for non-semipermeable porous  
 148 media to unity for "ideal" semipermeable porous media, whose conductive pores cannot be accessed  
 149 by the negatively charged ion species (i.e. the anions that result from the dissociation of the  
 150 contaminant in solution). When the contaminant of interest consists of a 1:1 electrolyte, a closed-  
 151 form expression of the reflection coefficient can be provided [12]:

$$152 \quad \omega_g = 1 + \frac{\bar{c}'_{sk,0}}{2e(c_p - c_b)} \left[ Z_2 - Z_1 - (2t_1 - 1) \ln \left( \frac{Z_2 + 2t_1 - 1}{Z_1 + 2t_1 - 1} \right) \right] \quad (3)$$

153 where  $\bar{c}'_{sk,0}$  is the solid charge coefficient,  $e$  is the void ratio of the bentonite component of the  
 154 geosynthetic clay liner and the dimensionless parameters  $Z_1$ ,  $Z_2$  and  $t_1$  are given by:

$$155 \quad Z_1 = \sqrt{1 + \left( \frac{2c_p e}{\bar{c}'_{sk,0}} \right)^2} \quad (4)$$

$$156 \quad Z_2 = \sqrt{1 + \left( \frac{2c_b e}{\bar{c}'_{sk,0}} \right)^2} \quad (5)$$

$$157 \quad t_1 = \frac{D_{1,0}}{D_{1,0} + D_{2,0}} \quad (6)$$

158 being  $D_{1,0}$  and  $D_{2,0}$  the free-solution or aqueous-phase diffusion coefficients of the cation and the  
 159 anion, respectively.

160 The following equation correlates the solid charge coefficient with the bentonite cation  
 161 exchange capacity, CEC, which should be measured by means of experimental procedures that  
 162 allow a complete dispersion of the bentonite unit layers, or montmorillonite lamellae, to be achieved  
 163 [13]:

$$164 \quad \bar{c}_{sk,0} = \frac{1 - f_{Stern}}{N_{l,AV}} \cdot CEC \cdot \rho_{sk} \cdot \frac{e}{e_m} \quad (7)$$

165 where  $f_{Stern}$  is the fraction of the adsorbed cations that are immobilised in the so-called Stern layer  
 166 ( $f_{Stern} \approx 0.85$ ), as opposed to the adsorbed cations that are delocalised in the diffuse-ion swarm  
 167 surrounding the bentonite particle or tactoid [40],  $\rho_{sk}$  is the solid-phase density ( $\rho_{sk} \approx 2.65 \text{ kg/dm}^3$ ),  
 168  $N_{l,AV}$  is the average number of montmorillonite lamellae that form the tactoid and  $e_m$  is the micro-  
 169 void ratio which, according to a simplified dual-porosity scheme of the bentonite fabric wherein the  
 170 tactoid consists of a parallel stacking of montmorillonite lamellae [32, 41], represents the portion of  
 171 the void ratio comprising the inter-tactoid conductive pores [24]:

$$172 \quad e_m = e - b_n \rho_{sk} CEC \frac{F}{\sigma} \left( \frac{N_l - 1 + d_d}{N_l} \right) \quad (8)$$

173 being  $b_n$  the average half distance between the montmorillonite lamellae in the tactoid ( $b_n \approx 0.45$   
 174 nm),  $d_d$  the ratio of the Stern layer thickness to the half inter-lamellar distance ( $d_d \approx 4$ ),  $F$  the  
 175 Faraday constant ( $F = 96487 \text{ C/mol}$ ) and  $\sigma$  the surface density of the solid skeleton electric charge  
 176 ( $\sigma = 0.114 \text{ C/m}^2$ ).

177 The pressure head profile in the GM-GCL interface can be determined by accounting for the  
 178 following mass conservation equation:

$$179 \quad dQ_s + \frac{dQ_\xi}{d\xi} d\xi = 0 \quad (9)$$

180 Substitution of Equations 1 and 2 into Equation 9 leads to a second order linear non-  
 181 homogeneous differential equation with constant coefficients, which can be solved in conjunction  
 182 with the following boundary conditions [43]:

$$183 \quad \begin{cases} h(\xi = b_w) = h_p \\ h(\xi = \xi_w) = 0 \\ \frac{dh}{d\xi}(\xi = \xi_w) = 0 \end{cases} \quad (10)$$

184 The pressure head profile in the GM-GCL interface, the half width of the wetted area and the  
 185 vertical liquid flow rate infiltrating into the composite liner for a single damaged wrinkle are then  
 186 given by:

$$187 \quad h = 2G \sinh^2 \left[ \alpha \left( \frac{\xi_w - \xi}{2} \right) \right] \quad (11)$$

$$188 \quad \xi_w = b_w + \frac{1}{\alpha} \cosh^{-1} \left( 1 + \frac{h_p}{G} \right) \quad (12)$$

$$189 \quad Q_s = 2 \frac{k_g}{H_g} L_w \int_0^{\xi_w} (h + G) d\xi = 2 \frac{k_g}{H_g} L_w b_w G \left\{ 1 + \frac{h_p}{G} + \frac{1}{b_w \alpha} \sinh \left[ \alpha (\xi_w - b_w) \right] \right\} \quad (13)$$

190 where the parameters  $G$  and  $\alpha$  are expressed as follows:

$$191 \quad G = H_g - h_b - h_\pi \quad (14)$$

$$192 \quad \alpha = \sqrt{\frac{k_g}{H_g \theta}} \quad (15)$$

193 The term  $h_\pi$  in Equation 14 is referred to as the osmotic head and depends on the  
194 semipermeable properties of the geosynthetic clay liner, as well as on the difference in contaminant  
195 concentration between the GCL boundaries:

$$196 \quad h_\pi = 2RT \frac{\omega_g}{\gamma_w} (c_p - c_b) \quad (16)$$

197 The derived analytical expressions for  $h$ ,  $\xi_w$  and  $Q_s$  are valid if  $G > 0$  (i.e.  $h_\pi < H_g - h_b$ ); at the  
198 limit  $G \rightarrow 0^+$ , the half width of the wetted area tends to infinity. As the thickness of geosynthetic  
199 clay liners can be assumed, as a first approximation, equal to 0.01 m and the osmotic head can  
200 easily reach values of the order of 0.1 m, the proposed theoretical model results to be of practical  
201 utility for the design of composite liners when the pressure head at the bottom of the geosynthetic  
202 clay liner assumes negative values (i.e.  $h_b < 0$ ), that is, when a matric suction builds up without a  
203 change in the saturation degree. Finally, it is stressed that the derived analytical solution is valid if  
204 the spacing between two adjacent wrinkles in the geomembrane,  $l_w$ , is large enough to avoid any  
205 mutual interaction, and therefore it should be verified that the condition  $\xi_w < 0.5 l_w$  is satisfied.

206 As exemplified in Figures 2 and 3 for a set of representative values of the parameters  $b_w$ ,  $h_p$ ,  
207  $H_g$  and  $h_b$  [37], an increase in the osmotic head produces an increase in the half width of the wetted  
208 area and a decrease in the liquid flow rate through a single damaged wrinkle, thus highlighting the  
209 improvement in the containment performance of the composite liner due to the GCL membrane  
210 behaviour. In addition to the advantages that arise from the chemico-osmotic counter-flow, also the  
211 hydraulic transmissivity of the GM-GCL interface significantly influences the resulting leachate  
212 flow rate through the composite liner [30, 35], as a variation in the  $\theta$  parameter affects the value  
213 that is assumed by the  $\alpha$  parameter; the latter remark has therefore stimulated further investigation  
214 on the relationship that exists between the bentonite osmotic properties and the GM-GCL interface  
215 transmissivity.

## 216 **Effect of the bentonite swelling behaviour on the GM-GCL interface transmissivity**

217 Although a number of studies have focused on the experimental assessment of the GM-GCL  
218 interface transmissivity by addressing the issue of the influence that is exerted, for instance, by the  
219 vertical confining stress, the bentonite gradation (powdered and granular), the cover geotextile  
220 fabric (woven and non-woven), the hydraulic head and the GCL prehydration, few of them have  
221 investigated the effect that is related to the physico-chemical interactions which occur between the  
222 bentonite component of the geosynthetic clay liner and the permeating solution: such pore-scale  
223 interactions, which are responsible for the semipermeable membrane behaviour, also affect the  
224 mechanical behaviour of bentonites and, in particular, the swelling-shrinking response upon a  
225 variation in the chemical composition of the permeant [31]. As discussed by AbdelRazek and Rowe  
226 [1], exposure of the geosynthetic clay liner to solutions with high ionic strength can alter the  
227 swelling ability of the bentonite and, consequently, its ability to conform to the irregularities at the  
228 interface between the geomembrane and the GCL cover geotextile, with an increase in the hydraulic  
229 transmissivity compared to permeation with deionised water.

230 On the basis of the same modelling assumptions that were adopted by Dominijanni and  
231 Manassero [7] to simulate the coupled flows of solvent and solutes through electrically charged  
232 porous media, it is possible to provide a closed-form expression of the chemico-osmotic swelling  
233 pressure,  $u_{sw}$ , when the inorganic contaminant of interest consists of a 1:1 electrolyte [12]:

$$234 \quad u_{sw} = 2RTc_{avg} \left[ \sqrt{\left( \frac{\bar{c}_{sk,0}}{2ec_{avg}} \right)^2 + 1} - 1 \right] \quad (17)$$

235 where  $c_{avg}$  can be assumed equal to the arithmetic mean of the values of the contaminant  
236 concentration at the GCL boundaries:

$$237 \quad c_{avg} = \frac{c_p + c_b}{2} \quad (18)$$

238           Mendes et al. [30] were the first to carry out laboratory tests aimed at investigating how the  
239 GM-GCL interface transmissivity is affected by cation exchange phenomena, whereby sodium  
240 cations which initially represent the dominant ion species in the exchange complex of the bentonite  
241 are replaced by multivalent cations. Four different GCLs, which consisted of either sodium  
242 bentonite or calcium bentonite, were tested and the obtained results, in terms of measured liquid  
243 flow rate through the composite liner system, were interpreted by means of the analytical solution  
244 proposed by Touze-Foltz et al. [43] for a circular hole in a flat geomembrane (i.e. the “axi-  
245 symmetric case”). In spite of a variation in the GCL hydraulic conductivity up to three orders of  
246 magnitude, the composition of the exchange complex of the bentonite was not observed to  
247 significantly influence the GM-GCL interface transmissivity at steady-state conditions; however, it  
248 is not possible to draw conclusions about the impact of the chemistry of the pore solution on the  $\theta$   
249 parameter, as clean water was used as the permeant during the tests.

250           Rowe and Abdelatty [38] carried out a series of laboratory tests on a composite liner system  
251 by circulating both reverse osmosis water and a 0.14 M NaCl solution, which resulted in an increase  
252 in the GCL hydraulic conductivity by about an order of magnitude and in an almost unchanged  
253 liquid flow rate. On the basis of a numerical interpretation of the aforementioned results, it was  
254 concluded that the GM-GCL transmissivity had to experience a twofold decrease as a consequence  
255 of the physico-chemical interactions between the geosynthetic clay liner and the salt solution.

256           Among the tests series that were performed by AbdelRazek and Rowe [1] with the aim to  
257 investigate the effect of a number of variables on the GM-GCL interface transmissivity, two of  
258 them focused on the measurement of the  $\theta$  parameter upon permeation of a coated needle-punched  
259 GCL, placed in contact with a smooth 1.5 mm-thick HDPE GM, by reverse osmosis water ( $I < 3.29$   
260 mM), a synthetic MSW landfill leachate ( $I = 159.5$  mM) and a saline solution ( $I = 4400$  mM), being  
261  $I$  the ionic strength of the permeant, under vertical confining stresses ranging between 10 and 150  
262 kPa. All tests were carried out with an novel experimental apparatus, which forces the liquid to

263 spread horizontally at the GM-GCL interface rather than vertically through the GCL: as a difference  
264 from the aforementioned studies, the estimation of the  $\theta$  parameter is the result of a direct  
265 measurement, and not of an interpretation that, necessarily, involves a number of modelling  
266 hypotheses. The reported trends in the steady-state values of the interface transmissivity versus the  
267 ionic strength of the permeant are consistent with the available experimental evidences on the  
268 osmotic swelling of clay soils [4, 12, 33], as permeation with both the synthetic leachate and the  
269 saline solution was detrimental with respect to the bentonite swelling potential and, consequently, to  
270 the GM-GCL interface transmissivity, which increased up to four orders of magnitude at the lowest  
271 confining stress compared to permeation with reverse osmosis water. Nevertheless, further analysis  
272 of these experimental results through Equation 17 is not possible, since AbdelRazek and Rowe [1]  
273 did not provide sufficient data concerning the tested GCL (e.g. the GCL hydraulic conductivity) for  
274 a direct or indirect evaluation of the fundamental fabric parameter (i.e. the average number of  
275 lamellae per tactoid,  $N_{LAV}$ ), which accounts for the arrangement of the bentonite unit layers at the  
276 microscale and influences the effective electric charge concentration of the solid phase [24].

277         AbdelRazek and Rowe [2] carried out additional tests series by means of the same testing  
278 apparatus described by AbdelRazek and Rowe [1], with the aim to investigate the effect determined  
279 by the permeation of an untreated and a polymer-enhanced GCL (without smooth and indented  
280 coating or lamination) with a saline solution on the GM-GCL interface transmissivity. With  
281 reference to the polymer-enhanced GCL that was tested in contact with a smooth 2 mm-thick  
282 LLDPE GM, two permeants were used, namely reverse osmosis water ( $I < 3.29$  mM) and a saline  
283 solution with varying ionic strength ( $I = 440 - 2200 - 4400$  mM), at two different confining stress  
284 levels ( $\sigma_v = 10 - 150$  kPa). Upon termination of the interface transmissivity tests, the GCL hydraulic  
285 conductivity was measured in a flexible wall permeameter and a weak dependence of  $k_g$  on the  
286 brine concentration emerged from the tests results, which are listed in Table 1. Such results are here

287 interpreted through the modified Kozeny-Carman equation, which relates the GCL hydraulic  
 288 conductivity to the average number of lamellae per tactoid [29]:

$$289 \quad k_g = \frac{\tau_m \gamma_w}{3 \mu_e} \frac{e_m^3}{(1+e_m)} \left( \frac{\sigma}{F \rho_{sk} \text{CEC}} \right)^2 N_{l,AV}^2 \quad (19)$$

290 where  $\tau_m$  is the matrix tortuosity factor, which accounts for the tortuous nature of the actual flow  
 291 paths within the bentonite pores ( $\tau_m \approx 0.2$ ), and  $\mu_e$  is the electro-viscous coefficient that, as a first  
 292 approximation, can be assumed equal to the viscous coefficient of water ( $\mu_e \approx 1$  mPa·s). The CEC  
 293 of the tested GCL was measured to be 83 meq/100g.

294 The calculated values of the  $N_{l,AV}$  parameter, which are listed in Table 1, allow the influence  
 295 of the ionic strength of the permeant on the clay fabric to be appreciated, whose aggregation state  
 296 did not significantly change from one to another test, thus demonstrating the effectiveness of the  
 297 polymer enhancement in maintaining a dispersed microstructure of the bentonite. The calculated  
 298  $N_{l,AV}$  values are also plotted in Figure 4 as a function of the micro-void ratio, together with the iso-  
 299 concentration curves (i.e. curves of equal ionic strength of the permeant) of the Fabric Boundary  
 300 Surface, as was calibrated by Manassero [24] on the basis of the results of the hydraulic  
 301 conductivity tests performed by Petrov and Rowe [34] on an untreated needle-punched GCL  
 302 (without polymer addition). The phenomenological equation of the Fabric Boundary Surface is  
 303 given as follows:

$$304 \quad N_{l,AV} = N_{l,AV0} + \frac{\alpha}{e_m} \left( \frac{c_{avg}}{c_0} + 1 \right) + \beta e_m \left[ 1 - \exp \left( - \frac{c_{avg}}{c_0} \right) \right] \quad (20)$$

305 where  $c_0$  is the reference concentration ( $c_0 = 1$  M) and  $N_{l,AV0}$  is the ideal average minimum number  
 306 of lamellae per tactoid when  $c_{avg} = 0$  and  $e_m \rightarrow \infty$ . The dimensionless coefficients  $\alpha$ ,  $\beta$  and  $N_{l,AV0}$   
 307 have to be regarded as material-dependent parameters and, therefore, should be adjusted on a given  
 308 set of data pertaining to a specific bentonite ( $N_{l,AV0} = 1.56$ ,  $\alpha = 8.82$  and  $\beta = 10.01$  for the GCL

309 tested by Petrov and Rowe [34]). When the permeating solution consists of a mixture of ion species,  
310 as in the case of the tests series carried out by AbdelRazek and Rowe [2], the average contaminant  
311 concentration across the GCL (see Equation 18) can be set equal to the ionic strength.

312 Figure 4 draws attention to the different behaviours of the modified GCL tested by  
313 AbdelRazek and Rowe [2] and the untreated GCL tested by Petrov and Rowe [34]. Indeed, whilst  
314 the bentonite aggregation state does not appreciably change upon permeation with diluted solutions,  
315 the difference in  $N_{l,AV}$  between the two GCL types becomes more and more pronounced as the ionic  
316 strength increases: such bentonite flocculation phenomena for the untreated GCL led to an increase  
317 in the measured hydraulic conductivity up to three orders of magnitude moving from a 10 mM to a  
318 2000 mM NaCl solution.

319 In order to investigate the influence of the bentonite osmotic swelling on the GM-GCL  
320 interface transmissivity, a value of the swelling pressure has been calculated through Equation 17  
321 for each measured steady-state value of  $\theta$  (Table 2), adopting the arithmetic mean of the  $N_{l,AV}$  values  
322 listed in Table 1 (i.e.  $N_{l,AV} = 7.21$ ) and the ionic strength of the permeant in lieu of the 1:1  
323 electrolyte concentration. The first of the previous assumptions is acceptable for the considered  
324 GCL, as clay fabric modifications were substantially hindered by the polymer enhancement, with a  
325 narrow range of variation in the  $N_{l,AV}$  parameter ( $N_{l,AV} = 2.64 - 12.46$ ). As far as the second  
326 assumption is concerned, it is noted that the osmotic swelling-shrinking behaviour of bentonites is  
327 mostly controlled by the Debye length which, in turn, is inversely proportional to the square root of  
328 the ionic strength of the permeant [22]: in the simplest case of a single 1:1 electrolyte, the ionic  
329 strength equals the electrolyte concentration but, in the most general case, it allows the detrimental  
330 effect of the presence of multivalent cations to be taken into account when calculating the chemico-  
331 osmotic swelling pressure through Equation 17.

332 Consistently to the diffuse double layer theory, the swelling pressure is found to be relevant  
333 only in case of permeation with reverse osmosis water, being almost completely annulled in case of

334 permeation with highly concentrated saline solutions. With respect to the latter case, as observed by  
335 AbdelRazek and Rowe [2], there is no clear trend between the interface transmissivity and the  
336 vertical confining stress, thus suggesting that the variability in GCL specimens and GM-GCL  
337 contact conditions dominated the measured liquid flow and did not allow the influence of the stress  
338 level to be appreciated. On the contrary, when the GCL is permeated by reverse osmosis water, the  
339 increase in the swelling pressure resulting from a decrease in the bentonite void ratio, which in turn  
340 is related to a change in the vertical confining stress, seems to correlate well with the reduction in  
341 the interface transmissivity and, on the basis of such a remark, an attempt has been made in order to  
342 define a first tentative empirically-based relationship between the GM-GCL interface transmissivity  
343 and the bentonite swelling pressure for the composite liner system which was tested by AbdelRazek  
344 and Rowe [2], as illustrated in Figure 5. In particular, the curve that interpolates the two available  
345 experimental data measured with reverse osmosis water is given by:

$$346 \log_{10} \theta = -9.553 - 0.04121 \cdot u_{sw} \quad (21)$$

347 where  $\theta$  and  $u_{sw}$  are expressed in  $m^2/s$  and kPa, respectively.

348 Further research is warranted in order to investigate the influence of a variation in the stress  
349 level on the interface transmissivity, especially when the swelling pressure is annulled as a  
350 consequence of permeation with highly concentrated solutions. Moreover, the derived empirical  
351 equation should be considered valid only in case of monotonic loadings, for which a unique  $\sigma_v - e$   
352 relationship may exist, thus excluding any preconsolidation effect.

353

## 354 **IMPACT OF CONTAMINANT MIGRATION THROUGH LANDFILL BOTTOM LINERS** 355 **ON THE GROUNDWATER QUALITY**

356 The idealised scenario which is considered for the evaluation of the effectiveness of landfill  
357 bottom liners in limiting the migration of inorganic contaminants from the waste fill is depicted in  
358 Figure 6. It is assumed that the pollutant of interest, which consists of an electrolyte completely  
359 dissolved in water, migrates vertically from the leachate collection and removal system towards the  
360 underlying aquifer through the composite liner, which is constituted by a geomembrane (GM)  
361 overlying a geosynthetic clay liner (GCL). A natural attenuation layer (AL), which is characterised  
362 by a higher hydraulic conductivity than the engineered clay barrier, is interposed between the  
363 aquifer and the composite liner: such a low-permeability foundation layer is meant to reduce the  
364 concentration gradient along the contaminant migration path and, as a result, the rate of diffusive  
365 transport from the waste fill [39]. When the pollutant reaches the aquifer, which is hypothesised to  
366 be sufficiently thin in order to neglect the vertical distribution of the contaminant concentration in  
367 the groundwater, advection becomes the main transport mechanism in the horizontal direction  
368 compared to longitudinal hydrodynamic dispersion.

369 The analytical solution that is presented hereafter is developed under the assumptions of  
370 steady-state conditions and constant source concentration in the waste leachate, as done for instance  
371 by Guyonnet et al. [21] and Foose [14]. In particular, with respect to the already available steady-  
372 state analysis approach proposed by Dominijanni and Manassero [8] to model the impact of  
373 contaminant migration from the waste fill on the groundwater quality, this paper aims to extend  
374 such an analysis tool in order to account for the bentonite semipermeable properties, which are  
375 responsible for the improvement of the GCL containment performance as a result of three processes  
376 that reduce the pollutant mass flux, namely hyperfiltration, chemico-osmotic counter-advection and  
377 restricted diffusion [23].

378 First of all, under the hypothesis of thin aquifer (i.e. aquifer thickness,  $H_{aq}$ , of the order of few  
379 meters), solving the balance equation for the volumetric liquid flux inside the aquifer yields the

380 following linear relationship between the horizontal groundwater flux,  $q_x$ , and the horizontal  
 381 distance beneath the landfill in the direction of the groundwater flow,  $x$  [8]:

$$382 \quad q_x = q_{x0} + \frac{q_c}{H_{aq}} x \quad (22)$$

383 where  $q_{x0}$  is the groundwater flux just upstream from the landfill and  $q_c$  is the vertical leachate flux  
 384 through the composite liner, which is given by:

$$385 \quad q_c = n_w Q_s \quad (23)$$

386 being  $n_w$  the number of damaged wrinkles per unit area.

387 The expressions of the contaminant mass fluxes that cross the geosynthetic clay liner,  $J_{s,g}$ , and  
 388 the attenuation layer,  $J_{s,a}$ , in correspondence to the wetted surface of the barrier have to take into  
 389 account both the advective and the diffusive transport mechanisms and, in the specific case of the  
 390 GCL, the effect which is related to the semipermeable membrane behaviour [24, 27]:

$$391 \quad J_{s,g} = (1 - \omega_g) q_w \frac{c_p \exp(P_{L,g}) - c_b}{\exp(P_{L,g}) - 1} \quad (24)$$

$$392 \quad J_{s,a} = q_w \frac{c_b \exp(P_{L,a}) - c_x}{\exp(P_{L,a}) - 1} \quad (25)$$

393 where  $c_x$  is the pollutant concentration in the aquifer beneath the landfill,  $P_{L,g}$  and  $P_{L,a}$  are the Peclet  
 394 numbers of the GCL and the AL, respectively, and  $q_w$  is the vertical leachate flux that occurs in  
 395 correspondence to the wetted surface of the barrier:

$$396 \quad P_{L,g} = \frac{q_w H_g}{n_g D_g^*} \quad (26)$$

$$397 \quad P_{L,a} = \frac{q_w H_a}{n_a D_a^*} \quad (27)$$

398 
$$q_w = \frac{Q_s}{2L_w \xi_w} \quad (28)$$

399 being  $D_g^*$  and  $D_a^*$  the effective diffusion coefficients of the contaminant in the GCL and the AL,  
 400 respectively, which are calculated as the product of the matrix tortuosity factor and the free-solution  
 401 diffusion coefficient of the contaminant [25],  $n_g$  and  $n_a$  the porosities of the GCL and the AL,  
 402 respectively, and  $H_a$  the thickness of the AL.

403 The balance equation for the contaminant mass flux inside the aquifer can be expressed as  
 404 follows:

405 
$$H_{aq} \frac{d}{dx}(q_x c_x) = \frac{q_c}{q_w} J_{s,a} \quad (29)$$

406 Neglecting the variation in the leachate volumetric flux with respect to the  $x$  coordinate,  
 407 substitution of Equation 25 into Equation 29 yields the following first order linear differential  
 408 equation:

409 
$$\frac{dc_x}{dx} + \chi \frac{q_c}{q_{x0} H_{aq} + q_c x} c_x = \chi \frac{q_c}{q_{x0} H_{aq} + q_c x} c_b \quad (30)$$

410 where the dimensionless  $\chi$  parameter is given by:

411 
$$\chi = \frac{\exp(P_{L,a})}{\exp(P_{L,a}) - 1} \quad (31)$$

412 The relationship that exists between  $c_x$  and  $c_b$  stems from the condition of continuity in the  
 413 contaminant mass flux through all the mineral layers of the system (i.e.  $J_{s,g} = J_{s,a}$ ):

414 
$$c_x = A \cdot c_b - B \cdot c_p \quad (32)$$

415 where the dimensionless  $A$  and  $B$  parameters are given by:

$$416 \quad A = (1 - \omega_g) \frac{\exp(P_{L,a}) - 1}{\exp(P_{L,g}) - 1} + \exp(P_{L,a}) \quad (33)$$

$$417 \quad B = (1 - \omega_g) \frac{\exp(P_{L,a}) - 1}{\exp(P_{L,g}) - 1} \exp(P_{L,g}) \quad (34)$$

418 Hence, Equation 30 can be reformulated as follows:

$$419 \quad \frac{dc_x}{dx} + \left(1 - \frac{1}{A}\right) \chi \frac{q_c}{q_{x0}H_{aq} + q_c x} c_x = \frac{B}{A} \chi \frac{q_c}{q_{x0}H_{aq} + q_c x} c_p \quad (35)$$

420 Equation 35 is solved in conjunction with the following boundary condition:

$$421 \quad c_x(x=0) = c_{x0} \quad (36)$$

422 where  $c_{x0}$  is the contaminant concentration in the groundwater just upstream from the landfill.

423 The relationship which defines the distribution of the contaminant concentration beneath the  
 424 landfill can be derived under the hypothesis that the variation in the reflection coefficient with  
 425 respect to the  $x$  coordinate is negligible:

$$426 \quad RC = \frac{c_p \frac{B}{A-1} - c_{x0}}{c_p - c_{x0}} \left[ 1 - \left( \frac{q_{x0}H_{aq}}{q_{x0}H_{aq} + q_c x} \right)^{\chi \frac{\chi}{A}} \right] \quad (37)$$

427 where the parameters  $A$ ,  $B$ ,  $\chi$  and  $q_c$  are calculated at  $x = 0$  and  $RC$  is the relative contaminant  
 428 concentration:

$$429 \quad RC = \frac{c_x - c_{x0}}{c_p - c_{x0}} \quad (38)$$

430 The use of Equation 37 requires the leachate flow rate,  $Q_s$ , in correspondence to a single  
 431 damaged wrinkle to be calculated though Equation 13 which, in turn, depends on the pressure head

432 at the bottom of the GCL. Therefore, the condition of continuity in the volumetric liquid flux  
 433 through all the mineral layers of the system has to be imposed:

$$434 \quad \frac{Q_s}{2L_w \xi_w} = k_a \frac{H_a + h_b - h_{aq}}{H_a} \quad (39)$$

435 where  $k_a$  is the hydraulic conductivity of the AL and  $h_{aq}$  is the pressure head at the bottom of the  
 436 AL.

437 Following a rearrangement of Equation 39, the pressure head at the bottom of the GCL results  
 438 to be given by:

$$439 \quad h_b = h_{aq} - H_a + \frac{H_a}{H_g} \frac{k_g}{k_a} \left\{ \frac{b_w}{\xi_w} (h_p + G) + \frac{G}{\xi_w \alpha} \sinh[\alpha(\xi_w - b_w)] \right\} \quad (40)$$

440 Finally, the practical significance of the derived analytical solutions is clarified with the aid of  
 441 an example analysis. The composite liner system tested by AbdelRazek and Rowe [2] (smooth 2  
 442 mm-thick LLDPE GM + polymer-enhanced GCL) is considered for the example calculation: the  
 443 fundamental fabric parameter of the GCL (i.e. the average number of lamellae per tactoid,  $N_{L,AV}$ ) is  
 444 set equal to 7.21, as detailed in the previous section of the paper, and the GM-GCL interface  
 445 transmissivity is hypothesised to vary according to Equation 21. The inorganic contaminant of  
 446 interest is supposed to be NaCl ( $D_{Na,0} = 13.3 \cdot 10^{-10}$  m<sup>2</sup>/s,  $D_{Cl,0} = 20.3 \cdot 10^{-10}$  m<sup>2</sup>/s,  $D_{NaCl,0} = 16.1 \cdot 10^{-10}$   
 447 m<sup>2</sup>/s), the height of the ponded leachate in the leachate collection and removal system,  $h_p$ , is set  
 448 equal to 0.5 m and the absolute temperature equal to 293.15 K. The aquifer beneath the landfill is  
 449 assumed to be characterised by a thickness  $H_{aq} = 3$  m, a length  $l_{aq} = 500$  m, a pressure head in  
 450 correspondence to the bottom of the attenuation layer  $h_{aq} = 1$  m, a horizontal volumetric flux and a  
 451 contaminant concentration in the groundwater just upstream from the landfill  $q_{x0} = 1 \cdot 10^{-6}$  m/s (31.6  
 452 m/year) and  $c_{x0} = 0$ . The physical, hydraulic and transport parameters that are assigned to the  
 453 geomembrane and the mineral layers are listed in Table 3.

454 The calculation results, which are reported in Figure 7 in terms of the relative contaminant  
455 concentration in the groundwater just downstream from the landfill, refer to two different values of  
456 the bentonite void ratio (i.e.  $e = 3.33 - 4.27$ ) that are obtained as mean values of the void ratios  
457 measured by AbdelRazek and Rowe [2] for each of the two considered stress levels (i.e.  $\sigma_v = 10 -$   
458  $150$  kPa). The height of the GCL is then determined as follows [34]:

$$459 \quad H_g = \frac{m}{\rho_{sk}(1+w)}(1+e) \quad (41)$$

460 where  $m$  is the mass of bentonite per unit area in the GCL ( $m = 5300$  g/m<sup>2</sup>) and  $w$  is the initial water  
461 content of the bentonite ( $w = 11\%$ ).

462 In addition to the beneficial effect of a decrease in the bentonite void ratio, which is induced  
463 by an increase in the vertical load acting on the landfill bottom liner, it is shown that the  
464 contribution of the osmotic phenomena in the geosynthetic clay liner can lead to a relevant  
465 improvement in the containment performance of the considered barrier compared to the case of  
466 absence of membrane behaviour, especially at low concentration of the contaminant in the waste  
467 leachate. As a result, neglecting such a contribution can lead to an overestimation of the impact of  
468 contaminant migration on the groundwater quality.

469

## 470 CONCLUSIONS

471 The bentonite semipermeable properties can affect the leakage rate through landfill composite  
472 liners that consist of a GM over a GCL, as a consequence of the chemico-osmotic counter-flow that  
473 is generated in response to a gradient in the contaminant concentration. The existing analytical  
474 solutions, which refer to the case of a single damaged wrinkle of infinite length in the GM layer,  
475 have been extended in order to account for the aforementioned osmotic phenomena, thus  
476 highlighting the reduction in the liquid flow rate and the widening of the wetted area of the barrier

477 that are determined by an increase in the osmotic head. Such an extension is limited in terms of the  
478 maximum value that can be assumed by the osmotic head, and further research is warranted in order  
479 to investigate the effect of a larger chemico-osmotic counter-flow, until the limiting case of an  
480 inversion in the direction of the overall liquid flow.

481 Furthermore, the influence of the physico-chemical interactions that take place in the  
482 bentonite pores on the hydraulic transmissivity of the GM-GCL interface has been explored. The  
483 results of the laboratory tests performed by AbdelRazek and Rowe [2] have been interpreted in light  
484 of a constitutive model that allows the swelling-shrinking behaviour of active clays to be accounted  
485 for, showing that the ability of the bentonite to swell and conform to the irregularities of the GM-  
486 GCL interface, upon permeation with diluted solutions, is effective to maintain a low hydraulic  
487 transmissivity. A first tentative empirical equation, valid for the tested composite liner system, has  
488 been proposed in order to relate the interface transmissivity to the bentonite swelling pressure.

489 Finally, a novel analytical solution has been developed for the evaluation of the distribution of  
490 the contaminant concentration within an aquifer that underlies a waste disposal facility, including  
491 the influence of the semipermeable properties of the mineral layer, which is supposed to consists of  
492 a GCL, on the transport rate of inorganic pollutants through the landfill composite liner. The  
493 derivation of such an analytical solution is possible under the assumption that the variation in the  
494 vertical leachate flux coming from the landfill, as well as in the GCL reflection coefficient, with  
495 respect to the horizontal distance is negligible: this assumption is certainly acceptable when  
496 diffusion represents the main transport mechanism of contaminants through the landfill liner, as in  
497 the case of the low-permeability GCLs, and the groundwater seepage velocity is sufficiently high.  
498 The proposed analysis approach considers steady-state conditions and a constant source  
499 concentration in the leachate collection and removal system and, therefore, it represents a useful  
500 tool for a preliminary evaluation of the risk related to a given contaminant concentration in the

501 waste leachate, similarly to a tier-2 risk assessment of the ASTM RBCA standard [3] for a polluted  
502 site.

503

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1 **Table 1** Interpretation of the results of the hydraulic conductivity tests performed by AbdelRazek  
2 and Rowe [2] on a polymer-enhanced GCL. Note: the void ratio has been calculated, under the  
3 hypothesis of complete saturation, adopting a specific gravity of the bentonite  $G_s = 2.65$  [12].

Test ID	Ionic strength	Hydraulic conductivity	Water content	Void ratio	Average number of lamellae per tactoid
	[mM]	[m/s]	[%]	[-]	[-]
GCg1m-SA2-10	4400	$2 \cdot 10^{-10}$	153	4.05	12.46
GCg1m-SB1-10	4400	$2 \cdot 10^{-10}$	159	4.21	11.81
GCg1m-SD1-150	4400	$2 \cdot 10^{-11}$	125	3.31	6.08
GCg1m-SE1-150	4400	$4 \cdot 10^{-11}$	125	3.31	8.13
GCg1m-SE2-150	4400	$3 \cdot 10^{-11}$	128	3.39	6.94
GCg1m-SA2-150 <sup>a</sup>	4400	$2 \cdot 10^{-11}$	137	3.63	5.31
GCg1m-SP1-10-10%	440	$1 \cdot 10^{-10}$	135	3.58	10.85
GCg1m-SZ-10-RO <sup>a</sup>	< 3.29	$1 \cdot 10^{-11}$	187	4.96	2.64
GCg1m-SQ1-150-50%	2200	$1 \cdot 10^{-11}$	125	3.31	4.64
GCg1m-SR2-150-10%	440	$5 \cdot 10^{-12}$	121	3.21	3.80
GCg1m-SP1-150-10% <sup>a</sup>	440	$4 \cdot 10^{-11}$	115	3.05	9.25
GCg1m-SZ-150-RO <sup>a</sup>	< 3.29	$1.5 \cdot 10^{-11}$	139	3.68	4.63

4 <sup>a</sup> As the water content was not indicated for these GCL specimens, it was estimated on the basis of the values  
5 reported for similar specimens tested under the same vertical stress and ionic strength of the permeant.

6

7

8 **Table 2** Interpretation of the results of the interface transmissivity tests performed by AbdelRazek  
9 and Rowe [2] on a composite liner system, which consists of a smooth LLDPE GM overlying a  
10 polymer-enhanced GCL. Note: the average number of lamellae per tactoid has been assumed equal  
11 to the arithmetic mean of the values reported in Table 1 ( $N_{l,AV} = 7.21$ ).

Test ID	Ionic strength	Vertical stress	Steady-state interface transmissivity	Water content	Void ratio	Swelling pressure
	[mM]	[kPa]	[m <sup>2</sup> /s]	[%]	[-]	[kPa]
GCg1m-SJ1-BxV20-10-RO	3	10	$4.9 \cdot 10^{-11}$	187	4.96	18.37
GCg1m-SL1-BxV20-150-RO	3	150	$1.3 \cdot 10^{-11}$	139	3.68	32.36
GCg1m-SA1-BxV20-10	4400	10	$3.3 \cdot 10^{-10}$	169	4.48	0.03
GCg1m-SA2-BxV20-10	4400	10	$1.7 \cdot 10^{-10}$	153	4.05	0.04
GCg1m-SP1-BxV20-10-10%	440	10	$2.1 \cdot 10^{-10}$	135	3.58	0.51
GCg1m-SD1-BxV20-150	4400	150	$2 \cdot 10^{-10}$	125	3.31	0.06
GCg1m-SD2-BxV20-150	4400	150	$9.5 \cdot 10^{-11}$	137	3.63	0.05
GCg1m-SQ1-BxV20-150-50%	2200	150	$5.3 \cdot 10^{-10}$	125	3.31	0.13
GCg1m-SQ2-BxV20-150-50%	2200	150	$3.3 \cdot 10^{-10}$	115	3.05	0.17
GCg1m-SO1-BxV20-150-50%	2200	150	$1 \cdot 10^{-10}$	128	3.39	0.12
GCg1m-SP2-BxV20-150-10%	440	150	$1.7 \cdot 10^{-11}$	115	3.05	0.84
GCg1m-SR2-BxV20-150-10%	440	150	$3.6 \cdot 10^{-11}$	121	3.21	0.71

12

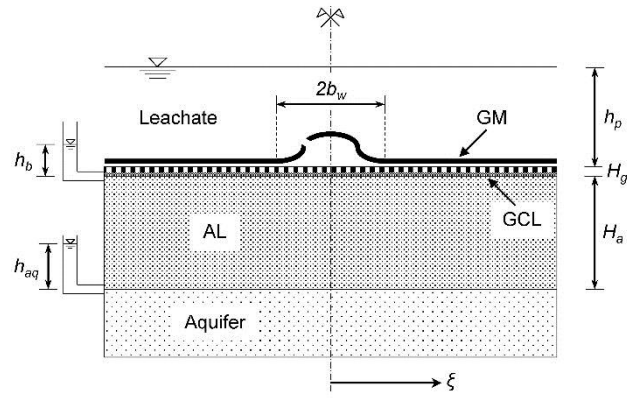
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14 **Table 3** Physical, hydraulic and transport parameters of the geomembrane and the mineral layers of  
 15 the example landfill bottom liner.

Parameter	Mineral layers	
	GCL	AL
Thickness, $H$ (m)	0.0078 - 0.0095	2
Hydraulic conductivity, $k$ (m/s)	Equation 19	$1 \cdot 10^{-7}$
Void ratio, $e$	3.33 - 4.27	0.43
Matrix tortuosity, $\tau_m$	0.2	0.25
	Geomembrane	
Wrinkle length, $L_w$ (m)	200	
Wrinkle width, $2b_w$ (m)	0.2	
Number of wrinkles per hectare, $n_w$ (1/ha)	1	

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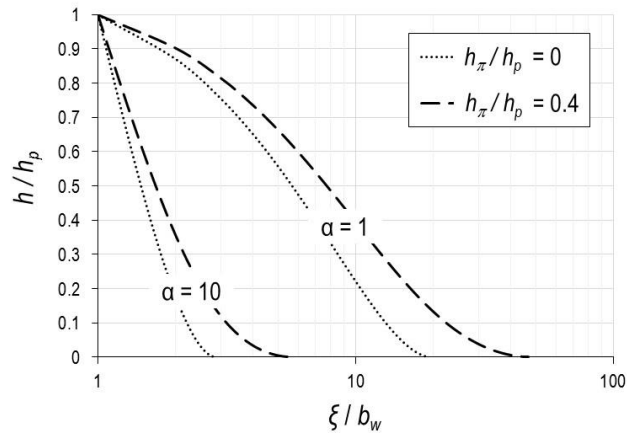
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2 **Figure 1** Reference scheme for the calculation of the leachate flow rate through a composite liner  
 3 which consists of a GM overlying a GCL.

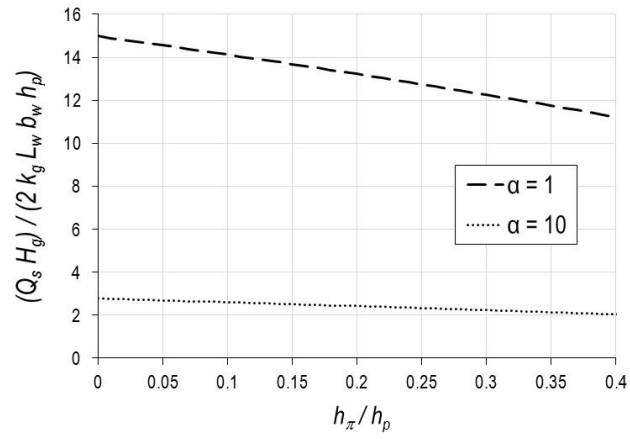
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6 **Figure 2** Influence of the GCL osmotic properties and of the  $\alpha$  parameter on the pressure head  
 7 distribution in the GM-GCL interface ( $b_w = 0.1$  m,  $h_p = 0.5$  m,  $H_g = 0.01$  m,  $h_b = -0.2$  m).

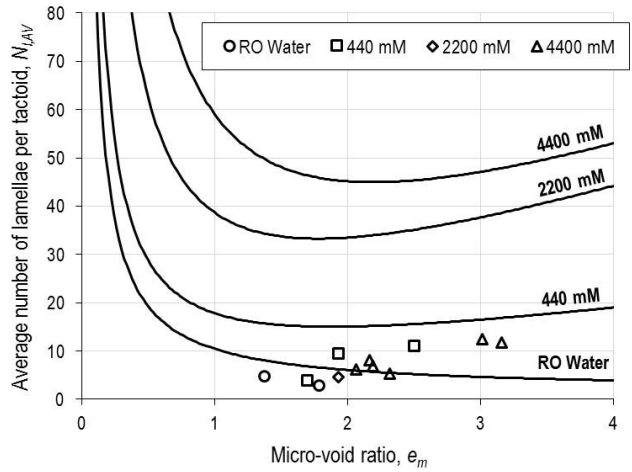
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10 **Figure 3** Influence of the GCL osmotic properties and of the  $\alpha$  parameter on the liquid flow rate  
 11 through a single damaged wrinkle ( $b_w = 0.1$  m,  $h_p = 0.5$  m,  $H_g = 0.01$  m,  $h_b = -0.2$  m).

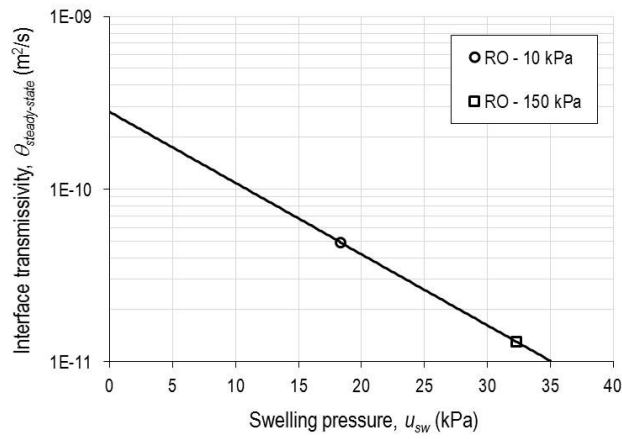
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14 **Figure 4** Comparison between the values of the average number of lamellae per tactoid, as obtained  
 15 through the interpretation of the results of the hydraulic conductivity tests that were performed by  
 16 AbdelRazek and Rowe [2] on a polymer-enhanced GCL (open symbols), and the iso-concentration  
 17 curves of the Fabric Boundary Surface, as calibrated on the results of the hydraulic conductivity  
 18 tests that were performed by Petrov and Rowe [34] on an untreated needle-punched GCL  
 19 (continuous lines).

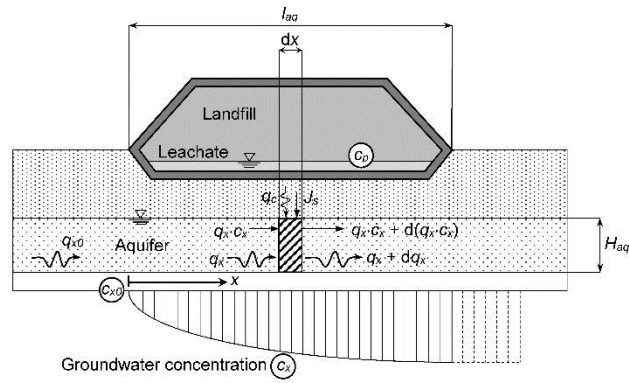
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22 **Figure 5** Steady-state values of the GM-GCL interface transmissivity measured by AbdelRazek and  
 23 Rowe [2] with reverse osmosis water as a function of the calculated swelling pressure (open  
 24 symbols), together with the interpolation curve (continuous line).

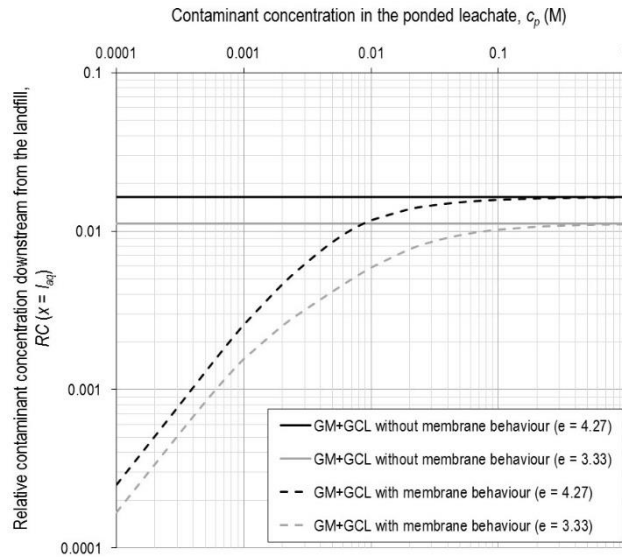
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27 **Figure 6** Reference scheme for the water volumetric balance and the contaminant mass balance  
 28 within a thin aquifer beneath the landfill (modified from Dominijanni and Manassero [8]).

29



30

31 **Figure 7** Effectiveness of the composite liner tested by AbdelRazek and Rowe [2] in limiting the  
 32 contaminant migration from the landfill towards the underlying aquifer, taking into account the  
 33 improvement in the containment performance due to the semipermeable membrane behaviour of the  
 34 GCL.

35