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

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| 1 | FROM THE DESIGN OF BOTTOM LANDFILL LINER SYSTEMS TO THE IMPACT |
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| 2 | ASSESSMENT OF CONTAMINANTS ON UNDERLYING AQUIFERS |
| 3 | by |
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FROM THE DESIGN OF BOTTOM LANDFILL LINER SYSTEMS TO THE IMPACT ASSESSMENT OF CONTAMINANTS ON UNDERLYING AQUIFERS

3

4 ABSTRACT: The most recent advancements of the research activity that has been carried out at the Polytechnic University of Turin since the 90's are presented, with a focus on the design 5 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 geomembrane (GM) overlying a GCL, as well as for the effect of a variation in the GCL swelling 13 pressure on the hydraulic transmissivity of the GM-GCL interface. In the second part of the paper, a 14 steady-state analysis approach is proposed with the aim to include all the aforementioned 15 phenomena in the assessment of the impact of contaminant migration through the landfill bottom 16 17 liners on the groundwater quality, taking into account the presence of a natural attenuation layer (AL) between the GCL and the underlying aquifer. 18

19

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

23 INTRODUCTION

The performance-based design of landfill lining systems requires the impact of contaminant migration from the waste on groundwater quality to be assessed. The effectiveness of lining systems is indeed demonstrated through the verification that the risk for human health and the environment due to the contaminant migration is limited to an acceptable level. This risk is quantified through the calculation of the contaminant concentration in the aquifer beneath the landfill, which is expected to remain less than some prescribed level at a compliance point, which is often a 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 landfill, the vertical mass flux of the contaminant must be determined taking into account the 32 properties of all the layers interposed between the waste and the aquifer, including not only the 33 34 engineered barriers, but also the natural foundation or attenuation layer (AL). As the regulations in force in most of the countries prescribe the use of a composite liner that consists of a geomembrane 35 (GM) overlying a mineral liner, the advective component of the contaminant mass flux is controlled 36 by the leakage rate through the holes that are created during the installation of the geomembrane, 37 and during any subsequent construction activities, such as the placement of materials on top of the 38 geomembrane. With regard to this matter, it is not possible not to mention the fundamental 39 contribution given by J.P. Giroud to the understanding of the leakage mechanisms that govern the 40 water migration through composite liners, as well as the development of a rational approach for the 41 42 calculation of the leakage rate [16-20, 42].

This study is focused on the use of the geosynthetic clay liners (GCLs) in place of the compacted clay liners (CCLs) as the mineral components of the composite liners. GCLs consist of a thin layer of bentonite (5-10 mm thick) sandwiched between two geotextiles. The term "bentonite" is commonly used to indicate a clay soil with a high content (e.g. > 60%) of montmorillonite, a mineral of the smectite group that is constituted by thin lamellae characterised by a high specific surface (defined as the surface per unit weight) and a permanent negative electric charge. The montmorillonite lamellae may aggregate in packets (also called tactoids), within which several clay platelets are in parallel array. As a result, the degree of aggregation in the bentonite micro-fabric may be quantified through the average number of lamellae per tactoid, $N_{l,AV}$, which can vary from 1 for a perfectly dispersed structure to values as high as 70-90 for highly aggregated structures [9].

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

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

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

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

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

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

This solution is used to evaluate the vertical mass flux of the contaminant that is released in 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

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

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

problem of estimating the rate of contaminant transport through the bottom liners of waste disposalfacilities.

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, θ , up to a distance that is referred to as the half 128 width of the wetted area, ζ_w . Finally, the liquid migrates vertically through the mineral layer.

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

132
$$Q_{\xi} = -L_{w}\theta \frac{\mathrm{d}h}{\mathrm{d}\xi}$$
(1)

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

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

139
$$dQ_s = k_g \frac{H_g + h - h_b}{H_g} L_w d\xi - 2RT \frac{k_g}{\gamma_w} \omega_g \frac{c_p - c_b}{H_g} L_w d\xi$$
(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 universal gas constant (8.314 J·mol⁻¹·K⁻¹), *T* is the absolute temperature, γ_w is the water unit weight ($\gamma_w = 9.81 \text{ kN/m}^3$), ω_g is the reflection coefficient or chemico-osmotic efficiency coefficient, c_p is the contaminant concentration in the leachate collection and removal system and c_b is the contaminant concentration at the bottom of the geosynthetic clay liner.

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

152
$$\omega_{g} = 1 + \frac{\overline{c}_{sk,0}}{2e(c_{p} - c_{b})} \left[Z_{2} - Z_{1} - (2t_{1} - 1) \ln\left(\frac{Z_{2} + 2t_{1} - 1}{Z_{1} + 2t_{1} - 1}\right) \right]$$
(3)

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

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

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

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

being $D_{1,0}$ and $D_{2,0}$ the free-solution or aqueous-phase diffusion coefficients of the cation and the 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
$$\overline{c}'_{sk,0} = \frac{1 - f_{Stern}}{N_{l,AV}} \cdot \text{CEC} \cdot \rho_{sk} \cdot \frac{e}{e_m}$$
(7)

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

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

being b_n the average half distance between the montmorillonite lamellae in the tactoid ($b_n \approx 0.45$ nm), d_d the ratio of the Stern layer thickness to the half inter-lamellar distance ($d_d \approx 4$), F the Faraday constant (F = 96487 C/mol) and σ the surface density of the solid skeleton electric charge ($\sigma = 0.114$ C/m²).

177 The pressure head profile in the GM-GCL interface can be determined by accounting for the178 following mass conservation equation:

179
$$dQ_s + \frac{dQ_{\xi}}{d\xi} d\xi = 0$$
(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]:

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

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

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

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

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

190 where the parameters G and α are expressed as follows:

$$191 \qquad G = H_g - h_b - h_\pi \tag{14}$$

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

193 The term h_{π} 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
$$h_{\pi} = 2RT \frac{\omega_g}{\gamma_w} \left(c_p - c_b \right)$$
(16)

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

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

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

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

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

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

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

$$c_{avg} = \frac{c_p + c_b}{2} \tag{18}$$

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

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

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

spread horizontally at the GM-GCL interface rather than vertically through the GCL: as a difference 263 from the aforementioned studies, the estimation of the θ parameter is the result of a direct 264 measurement, and not of an interpretation that, necessarily, involves a number of modelling 265 hypotheses. The reported trends in the steady-state values of the interface transmissivity versus the 266 ionic strength of the permeant are consistent with the available experimental evidences on the 267 osmotic swelling of clay soils [4, 12, 33], as permeation with both the synthetic leachate and the 268 269 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] did not provide sufficient data concerning the tested GCL (e.g. the GCL hydraulic conductivity) for 273 a direct or indirect evaluation of the fundamental fabric parameter (i.e. the average number of 274 lamellae per tactoid, $N_{l,AV}$), which accounts for the arrangement of the bentonite unit layers at the 275 276 microscale and influences the effective electric charge concentration of the solid phase [24].

AbdelRazek and Rowe [2] carried out additional tests series by means of the same testing 277 apparatus described by AbdelRazek and Rowe [1], with the aim to investigate the effect determined 278 279 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 reference to the polymer-enhanced GCL that was tested in contact with a smooth 2 mm-thick 281 LLDPE GM, two permeants were used, namely reverse osmosis water ($I \le 3.29$ mM) and a saline 282 solution with varying ionic strength (I = 440 - 2200 - 4400 mM), at two different confining stress 283 levels ($\sigma_v = 10 - 150$ kPa). Upon termination of the interface transmissivity tests, the GCL hydraulic 284 conductivity was measured in a flexible wall permeameter and a weak dependence of k_g on the 285 286 brine concentration emerged from the tests results, which are listed in Table 1. Such results are here

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

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

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

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

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

where c_0 is the reference concentration ($c_0 = 1$ M) and $N_{l,AV0}$ is the ideal average minimum number of lamellae per tactoid when $c_{avg} = 0$ and $e_m \rightarrow \infty$. The dimensionless coefficients α , β and $N_{l,AV0}$ have to be regarded as material-dependent parameters and, therefore, should be adjusted on a given set of data pertaining to a specific bentonite ($N_{l,AV0} = 1.56$, $\alpha = 8.82$ and $\beta = 10.01$ for the GCL tested by Petrov and Rowe [34]). When the permeating solution consists of a mixture of ion species,
as in the case of the tests series carried out by AbdelRazek and Rowe [2], the average contaminant
concentration across the GCL (see Equation 18) can be set equal to the ionic strength.

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

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

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

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

$$\log_{10}\theta = -9.553 - 0.04121 \cdot u_{sw} \tag{21}$$

347 where
$$\theta$$
 and u_{sw} are expressed in m²/s and kPa, respectively.

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

353

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

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

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

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

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

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

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

$$q_c = n_w Q_s \tag{23}$$

being n_w the number of damaged wrinkles per unit area.

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

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

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

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

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

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

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

being D_g^* and D_a^* the effective diffusion coefficients of the contaminant in the GCL and the AL, respectively, which are calculated as the product of the matrix tortuosity factor and the free-solution diffusion coefficient of the contaminant [25], n_g and n_a the porosities of the GCL and the AL, 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
$$H_{aq} \frac{\mathrm{d}}{\mathrm{d}x} (q_x c_x) = \frac{q_c}{q_w} J_{s,a}$$
(29)

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

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

410 where the dimensionless χ parameter is given by:

411
$$\chi = \frac{\exp(P_{L,a})}{\exp(P_{L,a}) - 1}$$
(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
$$c_x = A \cdot c_b - B \cdot c_p \tag{32}$$

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

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

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

418 Hence, Equation 30 can be reformulated as follows:

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

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

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

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

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

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

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

429
$$RC = \frac{c_x - c_{x0}}{c_p - c_{x0}}$$
 (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 at the bottom of the GCL. Therefore, the condition of continuity in the volumetric liquid fluxthrough all the mineral layers of the system has to be imposed:

$$434 \qquad \frac{Q_s}{2L_w\xi_w} = k_a \frac{H_a + h_b - h_{aq}}{H_a}$$
(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.

Following a rearrangement of Equation 39, the pressure head at the bottom of the GCL resultsto be given by:

$$h_{b} = h_{aq} - H_{a} + \frac{H_{a}}{H_{g}} \frac{k_{g}}{k_{a}} \left\{ \frac{b_{w}}{\xi_{w}} \left(h_{p} + G \right) + \frac{G}{\xi_{w} \alpha} \sinh \left[\alpha \left(\xi_{w} - b_{w} \right) \right] \right\}$$

$$\tag{40}$$

Finally, the practical significance of the derived analytical solutions is clarified with the aid of 440 an example analysis. The composite liner system tested by AbdelRazek and Rowe [2] (smooth 2 441 442 mm-thick LLDPE GM + polymer-enhanced GCL) is considered for the example calculation: the fundamental fabric parameter of the GCL (i.e. the average number of lamellae per tactoid, N_{LAV}) is 443 set equal to 7.21, as detailed in the previous section of the paper, and the GM-GCL interface 444 transmissivity is hypothesised to vary according to Equation 21. The inorganic contaminant of 445 interest is supposed to be NaCl ($D_{Na,0} = 13.3 \cdot 10^{-10} \text{ m}^2/\text{s}$, $D_{Cl,0} = 20.3 \cdot 10^{-10} \text{ m}^2/\text{s}$, $D_{NaCl,0} = 16.1 \cdot 10^{-10}$ 446 m²/s), the height of the ponded leachate in the leachate collection and removal system, h_p , is set 447 equal to 0.5 m and the absolute temperature equal to 293.15 K. The aquifer beneath the landfill is 448 assumed to be characterised by a thickness $H_{aq} = 3$ m, a length $l_{aq} = 500$ m, a pressure head in 449 correspondence to the bottom of the attenuation layer $h_{aq} = 1$ m, a horizontal volumetric flux and a 450 contaminant concentration in the groundwater just upstream from the landfill $q_{x0} = 1.10^{-6}$ m/s (31.6 451 m/year) and $c_{x0} = 0$. The physical, hydraulic and transport parameters that are assigned to the 452 453 geomembrane and the mineral layers are listed in Table 3.

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

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

460 where *m* is the mass of bentonite per unit area in the GCL ($m = 5300 \text{ g/m}^2$) and *w* is the initial water 461 content of the bentonite (w = 11%).

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

469

470 CONCLUSIONS

The bentonite semipermeable properties can affect the leakage rate through landfill composite liners that consist of a GM over a GCL, as a consequence of the chemico-osmotic counter-flow that is generated in response to a gradient in the contaminant concentration. The existing analytical solutions, which refer to the case of a single damaged wrinkle of infinite length in the GM layer, have been extended in order to account for the aforementioned osmotic phenomena, thus highlighting the reduction in the liquid flow rate and the widening of the wetted area of the barrier that are determined by an increase in the osmotic head. Such an extension is limited in terms of the maximum value that can be assumed by the osmotic head, and further research is warranted in order to investigate the effect of a larger chemico-osmotic counter-flow, until the limiting case of an inversion in the direction of the overall liquid flow.

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

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

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

503

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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 | 3.10-11 | 128 | 3.39 | 6.94 |
| GCg1m-SA2-150 ^a | 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 ^a | < 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% ^a | 440 | $4 \cdot 10^{-11}$ | 115 | 3.05 | 9.25 |
| GCg1m-SZ-150-RO ^a | < 3.29 | 1.5.10-11 | 139 | 3.68 | 4.63 |

^a 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.

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

| Test ID | Ionic strength | Vertical stress | Steady-state interface transmissivity | Water content | Void ratio | Swelling pressure |
|-------------------------|-------------------|--------------------|---|---------------|---------------|-------------------|
| | [mM] | [kPa] | [m ² /s] | [%] | [-] | [kPa] |
| GCg1m-SJ1-BxV20-10-RO | 3 | 10 | 4.9·10 ⁻¹¹ | 187 | 4.96 | 18.37 |
| GCg1m-SL1-BxV20-150-RO | 3 | 150 | 1.3.10-11 | 139 | 3.68 | 32.36 |
| GCg1m-SA1-BxV20-10 | 4400 | 10 | 3.3.10-10 | 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 | 9.5.10-11 | 137 | 3.63 | 0.05 |
| GCg1m-SQ1-BxV20-150-50% | 2200 | 150 | 5.3.10-10 | 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 | 3.6.10-11 | 121 | 3.21 | 0.71 |

11 to the arithmetic mean of the values reported in Table 1 ($N_{l,AV} = 7.21$).

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

| Poromotor | Mineral layers | | | |
|-----------------------------------|-----------------|-------------------|--|--|
| 1 al ameter | GCL | AL | | |
| Thickness, H (m) | 0.0078 - 0.0095 | 2 | | |
| Hydraulic conductivity, k (m/s) | Equation 19 | $1 \cdot 10^{-7}$ | | |
| Void ratio, <i>e</i> | 3.33 - 4.27 | 0.43 | | |
| Matrix tortuosity, τ_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 | |



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



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



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



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



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





- 27 Figure 6 Reference scheme for the water volumetric balance and the contaminant mass balance
- within a thin aquifer beneath the landfill (modified from Dominijanni and Manassero [8]).
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Figure 7 Effectiveness of the composite liner tested by AbdelRazek and Rowe [2] in limiting the contaminant migration from the landfill towards the underlying aquifer, taking into account the improvement in the containment performance due to the semipermeable membrane behaviour of the GCL.