EFFECT OF BENTONITE MIGRATION IN GEOSYNTHETIC CLAY LINERS ON CONTAMINANT TRANSPORT

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ABSTRACT: Since the introduction of geosynthetic clay liners (GCLs) to waste containment facilities, one of the major concerns about their use has been the hydraulic equivalency to a compacted clay liner as required by regulations. Laboratory test results and more recently field observations show that the thickness, or mass per unit area, of hydrated bentonite in a GCL can decrease under normal stress, especially around zones of stress concentration or nonuniform stresses, such as a rock or roughness in the subgrade, a leachate sump, or wrinkles in an overlying geomembrane. This paper describes the effect of bentonite migration on the hydraulic equivalence between a CCL and GCL and the contaminant transport through a thinned GCL. Finally, the paper presents suggestions for protecting hydrated bentonite from stress concentrations and reducing contaminant transport through a GCL.

1 INTRODUCTION

In recent years, geosynthetic clay liners (GCLs) are increasingly being selected to replace compacted clay liners (CCLs) in composite liner and cover systems for waste containment facilities. Some of the advantages of GCLs over CCLs from Daniel (1991) are: (1) usually lower and more predictable cost, (2) prefabricated/manufactured quality, (3) easier and faster construction, (4) reduced need for field hydraulic conductivity testing, (5) availability of the range of engineering properties, (6) more resistance to the effects of wetting/drying and freeze/thaw cycles, (7) increased airspace resulting from smaller thickness, and (8) easier repair during and after installation. Some of the disadvantages of GCLs versus CCLs include: (1) a potential for lower internal and interface shear strength (Eid and Stark 1997; Gilbert et al. 1996), (2) a possible large post-peak shear strength loss in reinforced GCLs (Stark and Eid 1997), (3) lower puncture resistance (Daniel 1991), (4) smaller leachate attenuation capacity (Daniel

1991), (5) shorter breakthrough time depending on the contaminant (Daniel 1991) as discussed herein, and (6) possibly higher long-term flux because of a reduction in hydrated bentonite thickness under the applied normal stress (Anderson and Allen 1995; Anderson 1996). Koerner and Daniel (1995) conclude that GCLs are hydraulically equivalent to CCLs if puncture and bentonite thinning do not occur.

The laboratory observations of bentonite migration have been performed in many literatures (Fox et al., 1996; Fox et al., 2000; Gilbert et al., 1996; Koerner and Narejo, 1995; and Peggs and Olsta, 1998). Anderson and Allen (1995) and Anderson (1996) show that the thickness of a hydrated GCL can be reduced significantly in the vicinity of a geomembrane wrinkle. The amount of bentonite that migrates might decrease so the difference in thickness is less than 7 mm to 2 mm after thinning as observed by Anderson and Allen (1995).

Field experiences with GCLs that confirm laboratory observations of bentonite migration are starting to appear in the literature. For example, Peggs and Olsta (1998) shows that hydrated bentonite can migrate in the field even under relatively low normal stresses, which is in agreement with the extremely compressible nature of hydrated bentonite.

2 CONTAMINANT TRANSPORT THROUGH A GCL

2.1 Steady Water Flux

The equation describing one-dimensional steady water flux (V), i.e., volume of water flowing across a unit area in a unit time, through a GCL (V_{GCL}) or a CCL (V_{CCL}) is:

$$V = K\left[\frac{H + L}{L}\right] \qquad (1)$$

where V is the water flux [$m^3/s/m^2$], K is the saturated hydraulic conductivity [m/s], H is the depth of liquid ponded above layer [m], and L is the thickness of the layer or liner [m].

For this study, it is assumed that Equation (1) applies to flux through a CCL or GCL and not a composite liner system. Equation (1) is also only applicable to flow through the bentonite component of the GCL. If the GCL contains a geomembrane, the water flux will be controlled by the water vapor diffusion through the geomembrane component and not the bentonite in the GCL.

Koerner and Daniel (1995) suggest that hydraulic equivalency between a CCL and GCL for steady water flux can be expressed as:

$$V_{GCL} = V_{CCL} \qquad (2)$$

which can be used to solve Equation (1) for the required hydraulic conductivity of the GCL, K_{GCL}, using:

$$K_{GCL} = K_{CCL}\left[\frac{L_{GCL}}{L_{CCL}}\right]\left[\frac{H + L_{CCL}}{H + L_{GCL}}\right] \qquad (3)$$

This expression is used to estimate the value of K_{GCL} required for equivalency for various values of CCL thickness, i.e., L_{CCL}. To satisfy the RCRA Subtitle D regulation (40 CFR 258) for municipal solid waste landfills and Subtitle C regulation (40 CFR 264 and 265) for hazardous waste landfills, this analysis assumes a regulatory CCL thickness of 0.9 m, a saturated hydraulic conductivity of the CCL, K_{CCL}, of 1×10^{-9} m/s, and a maximum depth of liquid ponded above the liner of 0.3 m. The thickness of the GCL, L_{GCL}, is varied from the manufactured thickness of 7 mm to 2 mm, which was observed in the tests reported by Anderson (1996) to estimate the required saturated GCL hydraulic conductivity, K_{GCL}, to achieve hydraulic equivalence for various CCL thicknesses. Figure 1 shows that for a 0.6 m and 0.9 m thick CCL with a hydraulic conductivity of 1×10^{-9} m/s and a pond depth of 0.3 m, the required GCL hydraulic conductivity for equivalency ranges from about 3.42 to 3.04×10^{-11} m/s, respectively, for an unthinned GCL (i.e., L_{GCL} = 7 mm). If the GCL thins to 2 mm the required GCL hydraulic conductivity for equivalency ranges from about 0.99 to 0.88×10^{-11} m/s for a 0.6 m and 0.9 m thick CCL, respectively. Therefore, the GCL hydraulic conductivity must be approximately 3.45 times lower if the GCL thickness decreases from the manufactured thickness of 7 mm to 2 mm to maintain equivalency with a 0.6 m and 0.9 m thick CCL. A hydraulic conductivity of less than 1×10^{-11} m/s is probably achievable with existing GCLs (Gleason et al. 1997). Therefore, bentonite migration does not seem to preclude equivalency between a GCL and a CCL in terms of steady water flux.

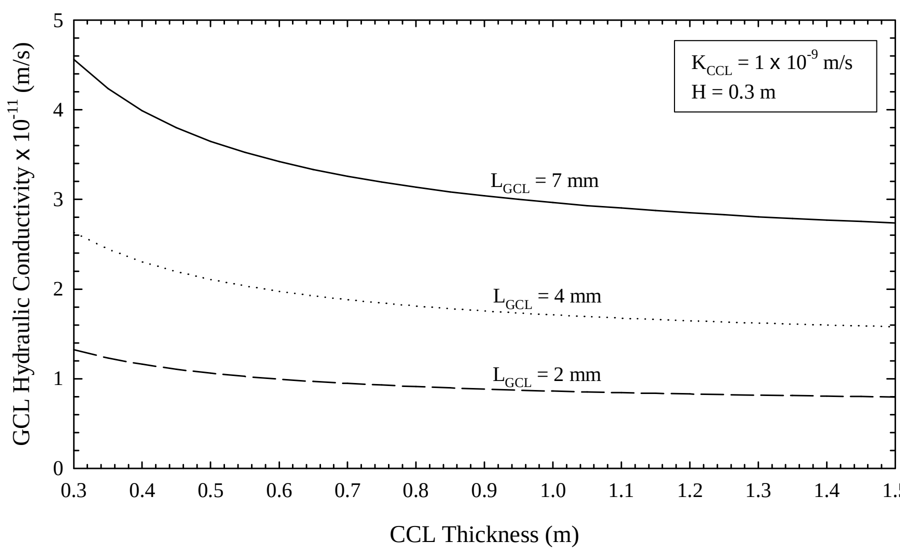

Figure 1. Effect of hydrated bentonite thickness on required K_{GCL} base on steady water flux equivalence.

2.2 Steady Solute Flux

The equation governing one-dimensional steady solute flux, i.e., volume of solute flowing across a unit area in a unit time via advection, is:

$$J_A = C_{leachate}(K)\left[\frac{H+L}{L}\right] = C_{leactate}(V) \qquad (4)$$

where J_A is the advective mass flux [mg/s/m^2] and $C_{leachate}$ is the concentration of solute in the leachate [mg/m^3]. This equation is applicable to a CCL (Shakelford 1990) and thus is applied to a GCL.

The advective mass flux ratio, F_A, is the mass flux of solute through a GCL divided by the mass flux of solute through a CCL as shown below:

$$F_A = \frac{(J_A)_{GCL}}{(J_A)_{CCL}} = \frac{C_{leachate}(K_{GCL})\left[\frac{H+L_{GCL}}{L_{GCL}}\right]}{C_{leachate}(K_{CCL})\left[\frac{H+L_{CCL}}{L_{CCL}}\right]} = \frac{V_{GCL}}{V_{CCL}} \qquad (5)$$

Therefore, the advective mass flux ratio is identical to the water flux ratio, i.e., $\frac{V_{GCL}}{V_{CCL}}$. If equivalency is demonstrated in terms of steady water flux, equivalency is also demonstrated in terms of steady mass flux of solute via Equation (5). As described above and shown in Figure 1, a hydraulic conductivity of 0.99 to 0.88×10^{-11} m/s is required for a GCL that has thinned to 2 mm to be hydraulically equivalent to a 0.6 and 0.9 m thick CCL, respectively. This hydraulic conductivity is probably achievable with current bentonite (Gleason et al. 1997) and thus a thinned GCL should still be equivalent to a CCL with a saturated hydraulic conductivity of less than 10^{-9} m/s based on steady water flux and steady solute flux calculations. If the regulatory requirement is a saturated hydraulic conductivity for the CCL less than 1×10^{-9} m/s, equivalency probably will not be satisfied with a GCL having a hydrated bentonite thickness of 2 mm because bentonite hydraulic conductivity will not be much less than 1×10^{-11} m/s (Gleason et al. 1997).

2.3 Steady Diffusion

Shackelford (1990) concludes the governing equation for steady diffusive mass flux, J_D, through a CCL is:

$$J_D = D^{*}(n_e)\left[\frac{\Delta C}{L}\right] \qquad (6)$$

where J_D is the diffusive mass flux [mg/s/m^2], D^* is the effective diffusion coefficient [m^2/s], n_e is the effective porosity which equals the volume of voids conducting flow per unit total volume of soil, ΔC is the change in concentration or the concentration at point A minus the concentration at point B, and L is the thickness of the layer [m]. The effective diffusion coefficient, D^*, is less than the free-solution diffusion coefficient, D^0, due to the tortuosity of the porous medium, which is expressed as follows:

$$D^* = \tau D^0 \qquad (7)$$

where τ is the tortuosity factor ($\tau \leq 1$). Laboratory data show that a typical value of the tortuosity factor ranges from 0.01 to 0.6 for common geologic materials (Daniel and Shackelford 1988; Freeze and Cheery 1979; Johnson et al. 1989; Quigley et al. 1987; Rowe 1987; Shackelford 1989; Shackelford and Daniel 1991). Therefore, mass transport due to diffusion in porous materials is slower than mass transport due to diffusion in free or aqueous solutions. The free-solution diffusion coefficient, D^0, depends on the interactive forces between the molecules of solute and liquid and is mainly affected by the viscosity of the liquid. Theoretical and/or empirical expressions for D^0 are found in references such as Grathwohl (1998), Shackelford and Daniel (1991), and Wilke and Chang (1955).

The chemical compounds considered in the diffusion analysis presented herein are chloride (Cl^-) and trichloroethylene (TCE: C_2HCl_3). The free-solution diffusion coefficient (D^0) of chloride is 2.03×10^{-9} m^2/s in water at 25 °C (Daniel and Shackelford 1998; Reddi and Inyang 2000), and the retardation factor, R_d, is equal to unity (Shackelford 1990). A retardation factor of unity means chloride is non-adsorbing as it travels through a soil. Therefore, chloride represents a worst case scenario because most, if not all, of the compound diffuses through the GCL and CCL. TCE is an organic compound and is used to contrast with the behavior of chloride. TCE is a halogenated hydrocarbon which has the highest reported concentration in the drinking water wells among various hydrophobic organic contaminants. TCE is an industrial solvent used frequently for degreasing metal as well as in dry-cleaning operations, organic synthesis, and refrigerants. The molecular weight of TCE is 131.4 and D^0 is 9.9×10^{-10} m^2/s in water at 20 °C (Thibodeaux 1979) and 7.2×10^{-10} m^2/s in water at 27 °C (Acar and Haider 1990). The retardation factor of TCE is reported as 40 for a high plastic clay by Acar and Haider (1990). Thus, TCE provides a contrast to chloride in the analysis because it has an absorbing potential as it travels through a clayey soil.

The steady diffusion analysis was conducted using the typical material properties for a CCL and GCL as shown in Table 1. The typical values of τ for a CCL and GCL are comparable with the reported value for a natural clay by Johnson et al. (1989) which ranges from 0.20 to 0.33. Furthermore, the effective diffusion coefficients of chloride in a CCL and GCL are in agreement with a proposed range of 2.0 to 6.0×10^{-10} m^2/s for a clay liner (Daniel and Shackelford 1988; Johnson et al. 1989; Quigley et al. 1987; Shackelford 1990, 1992).

A low concentration of TCE (e.g., 500 ppm) rather than pure solution of TCE is used in the steady diffusion analysis because it better simulates field conditions and the low dielectric constant of pure TCE substantially reduces the thickness of diffusive double layers of the clay. This reduction of the double layers reduces the free-swell potential of fine-grained soils, which results in increasing hydraulic conductivity. Acar and Haider (1990) show that a low concentration of TCE (e.g., 500 ppm) leads to free-swell values comparable to those of water, which implies that the clay-pore fluid interactions, e.g., diffusive double layer thickness, is not significantly different for water and 500 ppm of TCE. Thus, the hydraulic conductivity with a low concentration of TCE is expected to be similar to the hydraulic conductivity with water for the same clay. Permeating a clayey soil with a TCE concentration of 500 ppm, Acar and Haider (1990) measured the porosity and hydraulic conductivity of a clayey compacted soil liner to be 0.36 and 1×10^{-9} m/s, respectively. These values are in agreement with the typical values for a CCL permeated with water as shown in Table 1.

Table 1. Typical material properties for CCL and GCL.

Barrier	Effective porosity, n_e	Tortuosity factor, τ	Hydraulic conductivity (m/s)	Effective diffusion coefficient, D^* [from Equation (7)] (m^2/s)	
				Chloride	TCE
CCL	0.37	0.34	1.0×10^{-9}	7.0×10^{-10}	2.9×10^{-10}
GCL	0.60	0.10	1.0×10^{-11}	2.0×10^{-10}	8.5×10^{-11}

The steady diffusive mass flux ratio, F_D, of a GCL to a CCL using Equation (6) is defined as:

$$F_D = \frac{(J_D)_{GCL}}{(J_D)_{CCL}} = \frac{D^*_{GCL}(n_e)_{GCL}\left[\dfrac{\Delta C}{L_{GCL}}\right]}{D^*_{CCL}(n_e)_{CCL}\left[\dfrac{\Delta C}{L_{CCL}}\right]} = \frac{D^*_{GCL}(n_e)_{GCL}\,L_{CCL}}{D^*_{CCL}(n_e)_{CCL}\,L_{GCL}} \qquad (8)$$

If F_D equals unity, the steady diffusive mass fluxes through the GCL and CCL are equal. If F_D is greater than unity, there is more diffusion through the GCL than the CCL. Conversely, if F_D is less than unity, there is more diffusion through the CCL than the GCL.

Equation (8) can be simplified for the analysis of chloride and TCE because n_e and τ are constant for chloride and TCE for a CCL and a GCL (see Table 1). Therefore, F_D is expressed as:

$$F_D = \frac{D^*_{GCL}(0.6)L_{CCL}}{D^*_{CCL}(0.37)L_{GCL}} = 1.62\frac{D^*_{GCL}L_{CCL}}{D^*_{CCL}L_{GCL}} \tag{9}$$

Thus, the steady diffusive mass flux ratio is only a function of D^* and liner thickness. The ratio of D^*_{GCL} to D^*_{CCL} for both chloride and TCE is 0.29 using the values in Table 1. Therefore, Equation (9) reduces to:

$$F_D = 1.62\frac{(2.0\times10^{-10}\ \text{m}^2/\text{s})L_{CCL}}{(7.0\times10^{-10}\ \text{m}^2/\text{s})L_{GCL}} = 1.62(0.29)\frac{L_{CCL}}{L_{GCL}} = 0.47\frac{L_{CCL}}{L_{GCL}} \tag{10}$$

and F_D is only a function of liner thickness because the ratio of D^*_{GCL} to D^*_{CCL} is the same for chloride and TCE for a CCL and a GCL. As a result, chloride and TCE at 500 ppm have the same relationship between F_D and the thickness of the CCL and GCL as shown in Figure 2. For a 0.6 m and 0.9 m thick CCL, the value of F_D is about 40 and 60, respectively, for a 7 mm thick GCL. This analysis suggests that a GCL with no thinning or bentonite migration is not equivalent to a CCL in terms of steady diffusive mass flux because the steady diffusive mass flux ratio is much greater than unity. If the hydrated bentonite thickness is reduced to 2 mm by bentonite migration, the steady diffusive mass flux ratio increases to 139 and 208 for a CCL thickness of 0.6 m and 0.9 m, respectively. Therefore, bentonite migration causing a thickness reduction from 7 mm to 2 mm will significantly increase the amount of diffusive mass flux through the GCL by a factor of 3 to 4, respectively, for both chloride and TCE. A GCL thickness of 0.28 m and 0.42 m is required to achieve hydraulic equivalence with a 0.6 m and 0.9 m thick CCL, respectively, for steady diffusion. However, a GCL thickness of 0.28 m (280 mm) and 0.42 m (420 mm) is not achievable and thus possible alternatives are subsequently introduced in this paper.

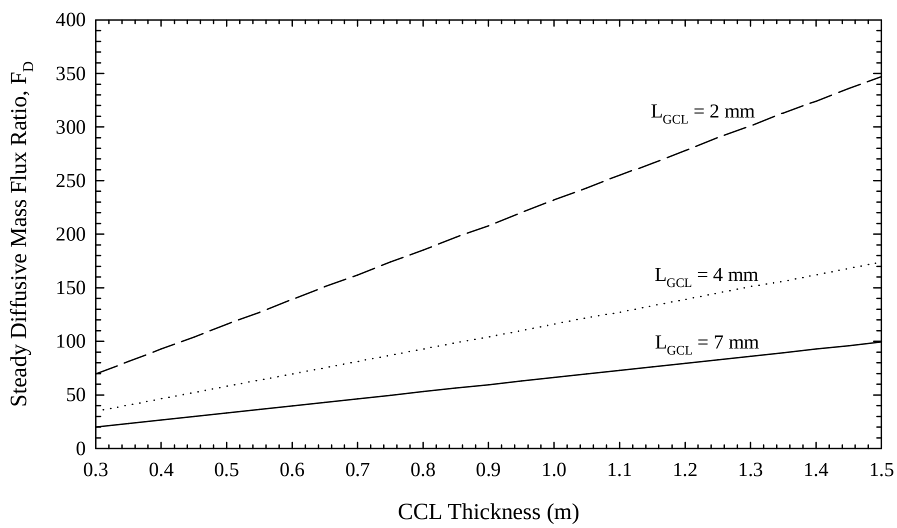

Figure 2. Effect of hydrated bentonite thickness on steady diffusive mass flux ratio for both chloride and TCE.

2.4 Advective-Dispersion

Shackelford (1990) presents the following expression to describe contaminant transport due to advective-dispersion:

$$\frac{C}{C_0} = \frac{1}{2}\left[erfc\left(\frac{1-T}{2\sqrt{\frac{T}{P}}}\right) + \left(e^{P}\right)erfc\left(\frac{1+T}{2\sqrt{\frac{T}{P}}}\right)\right] \tag{11}$$

where T is the time factor [dimensionless] and P is the Peclet number [dimensionless].

The Peclet number represents the ratio of advective transport to dispersive/diffusion transport. The initial and boundary conditions used in the advective-dispersion analysis are illustrated as follows:

1) initial (time, t, equals zero), constant concentration in the soil is zero, where x is the distance in the soil layer, i.e., $C (x \geq 0; t = 0) = 0$,
2) boundary condition of initial concentration of the solute is C_0, i.e., $C (x \leq 0; t > 0) = C_0$,
3) C_0 is constant, and
4) concentration at an infinite distance in the soil at a time greater than zero is zero, i.e., $C (x = \infty; t > 0) = 0$

The assumptions used in the advective-dispersion analysis are that the soil barrier is saturated, homogeneous, and of semi-infinite depth, a steady-state (Darcian) fluid flow has been established, and the solute transport only occurs in one direction, i.e., vertical.

The time factor and Peclet number are given as:

$$T = \frac{v_s(t)}{L} \tag{12}$$

$$P = \frac{v(L)}{D^*} \tag{13}$$

where v_s is the velocity of solute $=v/R_d$ [m/s], v is the seepage velocity of the fluid $=q/n_e$, q is the Darcian flow = ki [m/s], and *i* is the hydraulic gradient = (L+H)/L.

Figure 3 presents the concentration ratio of non-reactive chloride (R_d = 1), C/C_0, at the bottom of a 0.9 m thick CCL and bottom of 7 and 2 mm thick GCLs as a function of time and illustrates the effect of thickness on the concentration ratio with time. The breakthrough time with respect to a concentration ratio of 0.5 is shown for a 0.9 m thick CCL, 7 mm thick GCL, and 2 mm thick GCL to be 6.5, 0.0084, and 0.00065 years, respectively. This analysis suggests that a 7 mm thick GCL is not equivalent to a 0.9 m thick CCL in terms of advective-dispersion. In addition, thinning of the hydrated bentonite to 2 mm thick causes a decrease in the time required to achieve a concentration ratio of 0.5 by a factor of 13 from 0.0084 to 0.00065 years.

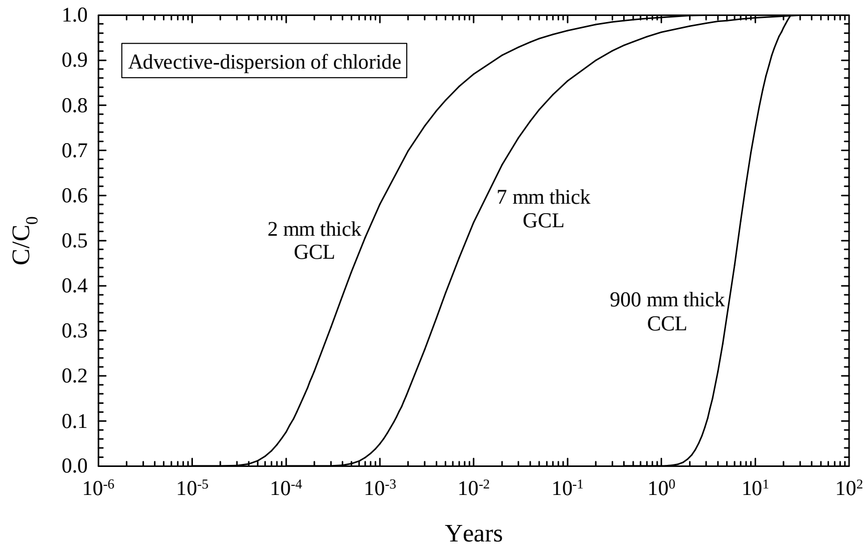

Figure 3. Effect of hydrated bentonite thickness on reduction of chloride (Cl^-) concentration ratio as a function of time at the bottom of the CCL and GCL.

Figure 4 presents the concentration ratio of TCE (R_d = 40), C/C_0, at the bottom of a 0.9 m thick CCL and bottom of 7 and 2 mm thick GCLs as a function of time for the CCL and GCL. The breakthrough time with respect to a TCE concentration ratio of 0.5 is shown for a 0.9 m thick CCL, 7 mm thick GCL, and 2 mm thick GCL to be 291, 0.75, and 0.061 years, respectively. The smaller effective diffusion coefficient and the sorption of TCE onto the fine-gained soil (i.e., R_d = 40) results in a slower solute transport compared to chloride. However, a retardation factor of unity is recommended for most organic leachates to ensure a conservative clay liner design (Acar and Haider 1990; Rowe 1987). This analysis also suggests that a 7 mm thick GCL is not equivalent to a 0.9 m thick CCL in terms of the advective-dispersion of TCE which is highly adsorptive compared to chloride. In addition, thinning of the hydrated bentonite to 2 mm thick causes a decrease in the time required to achieve a concentration ratio of 0.5 by a factor of 12 from 0.75 to 0.061 years.

In summary, a GCL with a manufactured thickness of 7 mm is not equivalent to a 0.9 m thick CCL in terms of advective-dispersion. If the bentonite in the GCL thins to 2 mm from 7 mm, there is even more transport through the thinned GCL than the manufactured GCL and thus even less hydraulic equivalence with a CCL. A bentonite thickness of about 0.21 m and 0.15 m when permeated with chloride and TCE, respectively, is required to achieve hydraulic equivalence, i.e., the same breakthrough time at C/C_0 = 0.5, between a GCL and 0.9 m thick CCL for advective-dispersion. The required bentonite thicknesses of 0.21 m and 0.15 m are less than the bentonite thickness of 0.42 m to achieve hydraulic equivalence with a 0.9 m thick CCL for steady diffusion because the hydraulic conductivity of a GCL (1×10^{-11} m/sec) is two orders less than the hydraulic conductivity of a CCL (1×10^{-9} m/sec). However, the GCL thickness of 0.21 m (210 mm) and 0.15 m (150 mm) is still not achievable in the field.

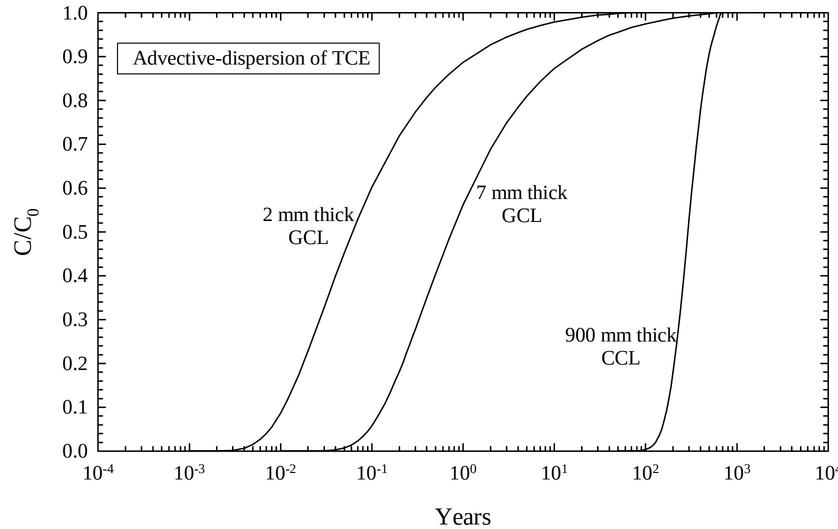

Figure 4. Effect of hydrated bentonite thickness on reduction of TCE concentration ratio as a function of time at the bottom of the CCL and GCL.

3 POSSIBLE SOLUTIONS

The prior analysis of steady diffusion and advective-dispersion show that even without bentonite migration a GCL is not equivalent to a 0.6 or 0.9 m thick CCL for chloride and TCE. As a result, a number of possible solutions are presented to reduce the potential migration of hydrated bentonite in a composite liner system and thus decrease the hydraulic inequivalence between a GCL and CCL and reduce contaminant transport through the GCL.

One possible solution involves reducing stress concentrations in the subgrade by smoothing changes in the geometry, reducing ruts, and removing rocks. The geomembrane also should be installed with a limited number of wrinkles. This can be accomplished by using geomembranes that are light-colored, e.g., white or grey, exhibit a high interface friction coefficient (textured or PVC geomembrane), and/or are flexible (Giroud 1995). Another technique to ensure a minimum long-term thickness of hydrated bentonite is to modify existing GCLs to include an internal structure or stabilizer element (Stark 1997, 1998).

Another possible solution to reduce contaminant transport through a thinned GCL is the use of an attenuation layer below the GCL. This attenuation layer would be designed to attenuate or remediate the contaminant transport that occurs, via diffusion or advective-dispersion. This layer could be any soil type with a hydraulic conductivity greater than 1×10^{-9} m/sec. Thus, CCL borrow material could be used without requiring extensive water content and compaction control as required for the CCL to meet a hydraulic conductivity of 1×10^{-9} m/sec. The main function of the attenuation layer is to increase the length of travel for the contaminant, and thus increase the breakthrough time. In addition, the attenuation layer may provide some adsorptive capacity.

An analysis of the GCL/attenuation layer combination is presented and compared to a CCL to investigate their hydraulic equivalence in terms of advective-dispersion. Chloride (Cl^-) is used in the analysis for comparison with prior analyses because it has a relatively large effective diffusion coefficient (D^*) ranging from 2.0 to 6.0 × 10^{-10} m^2/s for a clay liner (Daniel and Shackelford 1988; Johnson et al. 1989; Quigley et al. 1987; Shackelford 1990, 1992), and the retardation factor (R_d) is equal to unity (Shackelford 1990). A retardation factor of unity means chloride is non-adsorbing as it travels through the liner and attenuation layer. Therefore, chloride again represents a worst case scenario because most, if not all, of the compound will diffuse through the liner and the attenuation layer.

The effect of an attenuation layer is modeled by representing the GCL/attenuation layer combination as a single layer with composite properties. The main parameter influencing the dispersion analysis is the effective diffusion coefficient. As a result, a weighted average value of the equivalent effective diffusion coefficient, D^*_{eq}, is estimated using the following expression:

$$D^*_{eq} = \frac{L_{AL} + L_{GCL}}{\dfrac{L_{AL}}{D^*_{AL}} + \dfrac{L_{GCL}}{D^*_{GCL}}} \qquad (14)$$

where D^*_{AL} is the effective diffusion coefficient for the attenuating layer [m^2/s], D^*_{GCL} is the effective diffusion coefficient for GCL [m^2/s], L_{AL} is the thickness of attenuation layer [m], and L_{GCL} is the thickness of GCL [m].

An equivalent hydraulic conductivity, K_{eq}, for the GCL/attenuation layer is calculated using the following expression from Freeze and Cherry (1979):

$$K_{eq} = \frac{L_{AL} + L_{GCL}}{\dfrac{L_{AL}}{K_{AL}} + \dfrac{L_{GCL}}{K_{GCL}}} \qquad (15)$$

where K_{GCL} is the hydraulic conductivity of the GCL [m/s] and K_{AL} is the hydraulic conductivity of the attenuation layer [m/s].

In the analysis of the GCL/attenuation layer combination compared to CCL performance, an inorganic silt or clayey silt, i.e., ML in the Unified Soil Classification System, is used for the attenuation layer. Hydraulic conductivity of the attenuation layer, K_{AL}, is selected as 5 × 10^{-8} m/s for an ML soil (U.S. Department of the Navy 1982), which is 50 times greater than the required K_{CCL} of 1×10^{-9} m/s used herein. It is assumed that the tortuosity factor of an ML soil is the same as of CCL, i.e., τ=0.34, which is similar to the reported range of 0.13 to 3.0 for a silty clay (Crooks and Quigley 1984). Therefore, the effective diffusion coefficient of chloride in the attenuation layer is calculated to be 7.0 × 10^{-10} m^2/s using Equation (7) and D^0 of chloride = 2.03 × 10^{-9} m^2/s. The thickness of the attenuation layer is selected as 0.9 m.

The value of D^*_{eq} for a 7 mm and 2 mm thick GCL with an attenuation layer are 6.87 × 10^{-10} and 6.96 × 10^{-10} m^2/sec calculated from Equation (14), respectively. The value of K_{eq} for a 7 mm and 2 mm thick GCL with an attenuation layer are 1.26×10^{-9} and 4.14×10^{-9} m/sec calculated from Equation (15), respectively. It is assumed that the effective porosity of the attenuation layer is closer to the effective porosity of the CCL, 0.37, rather than closer to the GCL, 0.60. The effective porosity of the GCL/attenuation combination layer is estimated to be 0.40.

Figure 5 presents the concentration ratio, C/C_0, as a function of time for a CCL and GCL/attenuation layer system. The values of C/C_0 are calculated at the bottom of each layer (i.e., bottom of the CCL, GCL, and attenuation layer). Figure 5 shows that the use of an attenuation layer significantly increases the breakthrough time. This is evident by comparing the relationships for a GCL with a thickness of 7 mm with and without an attenuation layer. However, if thinning of the bentonite occurs, the 2 mm thick GCL and attenuation layer still exhibit a faster breakthrough time than the 0.9 m thick CCL but a slower time than an unthinned GCL with a thickness of 7 mm and no attenuation layer.

Figure 6 presents the values of C/C_0 at the bottom of each layer that are presented in Figure 5. In addition, the equivalent hydraulic conductivity of the thinned GCL, i.e., L_{GCL} = 2 mm, is varied several orders of magnitude to determine if the comparison with the CCL in Figure 5 could be improved by varying the K_{eq} of the GCL/attenuation layer. Figure 6 shows that lowering of the equivalent hydraulic conductivity by an order of magnitude increases the breakthrough time by about an order of magnitude at all concentration ratios. Therefore, a reduction in the equivalent hydraulic conductivity of the GCL/attenuation layer, via bentonite consolidation or admixtures to the bentonite and/or soil used for the attenuation layer, can increase the breakthrough time in terms of advective-dispersion.

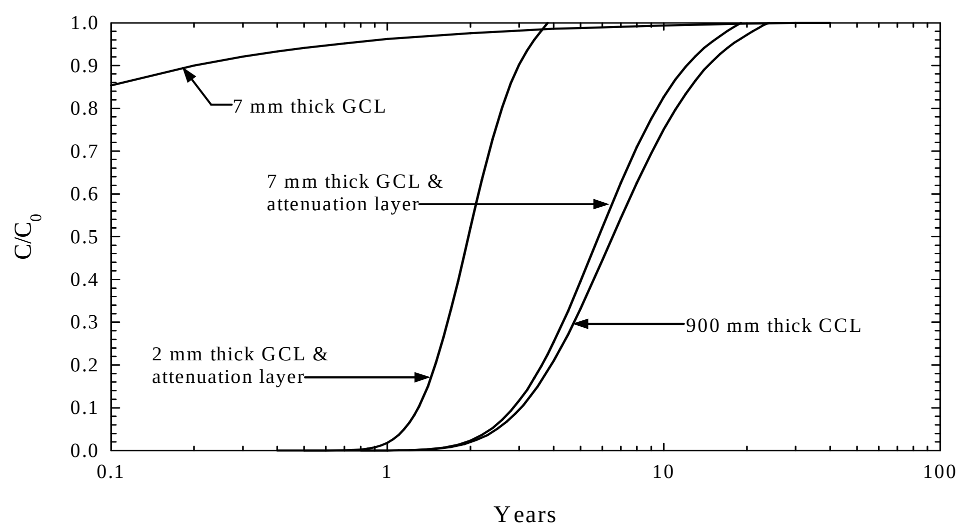

Figure 5. Effect of attenuation layer on breakthrough time for advective-dispersion of chloride for values of C/C_0 calculated at the bottom of each layer.

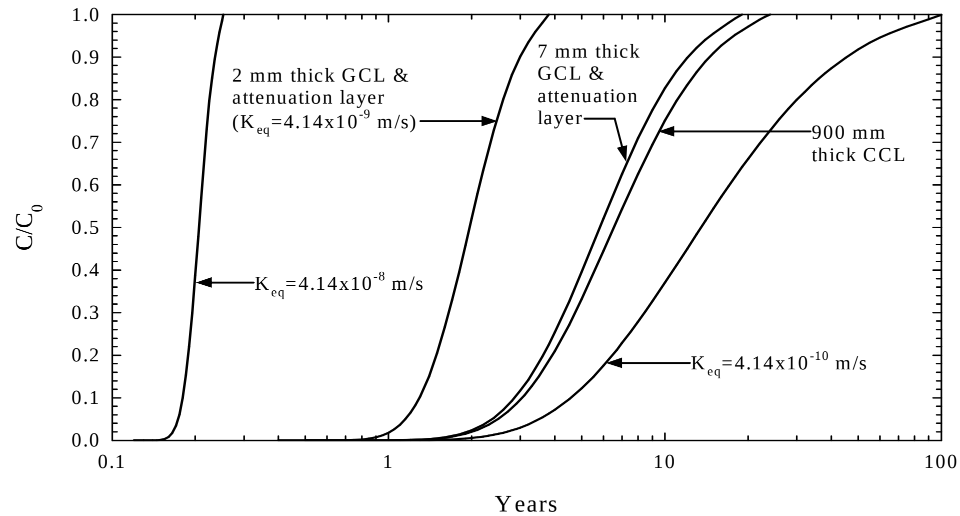

Figure 6. Effect of equivalent hydraulic conductivity on breakthrough time at the bottom of each layer for advective-dispersion of chloride through 2 mm thick GCL and attenuation layer.

4 CONCLUSIONS AND DISCUSSION

Hydrated bentonite can migrate to areas of lower normal stress due to stress concentrations or nonuniform stresses. Field evidence is becoming available and is confirming laboratory and field test results that show bentonite migration does occur in reinforced and unreinforced GCLs in the field.

The results of steady water flux, steady solute mass flux, steady diffusion, unsteady diffusion, and advective-dispersion analyses presented herein illustrate the importance of hydrated bentonite thickness on contaminant transport through GCLs and CCLs. These analyses suggest that a GCL is hydraulically equivalent to a CCL (hydraulic conductivity of 1×10^{-9} m/s) in terms of steady water and solute flux even if the bentonite thickness decreases from 7 mm to 2 mm. However, a GCL without bentonite migration is not equivalent to a CCL in terms of steady diffusion or advective-dispersion of chloride, which is a worst-case scenario because chloride has a retardation factor of unity, or TCE. If the bentonite migrates and the manufactured thickness decreases from 7 mm to 2 mm, the degree of non-equivalence and contaminant transport increases. To reduce the amount of diffusive and dispersive flux through a GCL, the initial thickness of a GCL could be increased significantly from 7 mm. If the initial thickness is not increased, bentonite migration should be minimized so that the degree of non-equivalence is not increased by protecting the initial 7 mm thickness of bentonite.

Possible solutions to eliminate or reduce the effect of migration of hydrated bentonite include encapsulating the bentonite between two geomembranes to reduce the amount of hydration and decrease bentonite compressibility, installing multiple layers of GCL at known stress concentrations, eliminating stress concentrations in the subgrade by smoothing changes in geometry, reducing ruts and removing rocks, and/or installing geomembranes with a limited number of wrinkles. The number of wrinkles could be reduced using a geomembrane that is light-colored (white or gray), exhibits a high interface coefficient of friction (textured or PVC geomembrane), and/or is flexible (Giroud 1995). Another alternative is to modify existing GCLs to include an internal structure or stabilizer element (Stark 1998). The stabilizer element protects the bentonite from stress concentrations thereby reducing bentonite migration and provides additional puncture resistance to the GCL. Another possible solution is the use of an attenuation layer below the GCL. The attenuation layer would attenuate the contaminant transport that exits the GCL by increasing the length of travel and possibly the amount of adsorption.

REFERENCES

Acar, Y.B. and Haider, L., 1989, "Transport of Low-Concentration Contaminants in Saturated Earthen Barriers", *Journal of Geotechnical Engineering*, ASCE, Vol. 116, No. 7, pp. 1031-1052.

Anderson, J.D., 1996, "Are Geosynthetic Clay Liners (GCLs) Really Equivalent to Compacted Clay Liners", *Geotechnical News*, BiTech Publishing, Ltd., British Columbia, Canada, Vol. 14, No. 2, June, pp. 20-23.

Anderson, J.D. and Allen, S.R., 1995, "What Are the Real Design Considerations When Using a Geosynthetic Clay Liner (GCL)", *Proceedings of the 9th Annual Municipal Solid Waste Management Conference*, Austin, TX.

Crooks, V.E. and Quigley, R.M., 1984, "Saline Leachate Migration through Clay: A Comparative Laboratory and Field Investigation", *Canadian Geotechnical Journal*, Vol. 21, No. 2, pp. 349-362.

Daniel, D.E., 1991, "Geosynthetic Clay Liners," *Geotechnical Fabrics Report*, IFAI, Vol. 9, No. 9, December, pp. 28-33.

Daniel, D.E. and Shackelford, C.D., 1988, "Disposal Barriers that Release Contaminants Only by Molecular Diffusion", *Nuclear Chemical Waste Management*, Vol. 8, pp. 299-305.

Eid, H.T. and T.D. Stark, 1997, "Shear Behavior of an Unreinforced Geosynthetic Clay Liner," *Geosynthetics International Journal*, IFAI, Vol. 4, No. 6, pp. 645-659.

Freeze, R.A. and Cherry, J.A., 1979, *Groundwater*, Prentice-Hall, Inc.

Fox, P.J., DeBattista, D.J. and Chen, S.H., 1996, "Bearing Capacity of Geosynthetic Clay Liners for Cover Soils of Varying Particle Size", *Geosynthetics International*, IFAI, St. Paul, MN, Vol. 3, No. 4, pp. 447-461.

Fox, P.J., DeBattista, D.J. and Mast, D.G., 2000, "Hydraulic Performance of Geosynthetic Clay Liners under Gravel Cover Soils", *Geotextiles and Geomembranes*, Elsevier Science, Ltd., Vol. 18, pp. 179-201.

Freeze, R.A. and Cherry, J.A., 1979, *Groundwater*, Prentice-Hall, Inc., 604 pp.

Gilbert, R. B., Fernandez, F., and Horsfield, D. W., 1996,. "Shear strength of reinforced geosynthetic clay liner," *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 122, No. 4), 259-266.

Giroud, J.P., 1995, "Wrinkle Management for Polyethylene Geomembranes Requires Active Approach", *Geotechnical Fabric Report*, April, Vol. 13, pp. 14-17.

Gleason, M.H., Daniel, D.E., and Eykholt, G.R., 1997, "Calcium and Sodium

Bentonite for Hydraulic Containment Applications", *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 123, No. 5, pp. 438-445.

Grathwohl, P., 1998, *Diffusion in Natural Porous Media: Contaminant Transport, Sorption/Desorption and Dissolution Kinetics*, Kluwer Academic Publishers.

Johnson, R.L., Cherry, J.A., and Pankow, J.F., 1989, "Diffusive Contaminant Transport in Natural Clay: A Field Example and Implications for Clay-lined Waste Disposal Sites", *Environmental Science Technology*, Vol. 23, No. 3, pp. 340-349.

Koerner, R.M. and Daniel, D.E., 1995, "A Suggested Methodology for Assessing the Technical Equivalency of GCLs to CCLs", *Geosynthetic Clay Liners*, Balkema, Rotterdam/Brookfield, pp. 73-98.

Koerner, R.M. and Narejo, D., 1995, "Bearing Capacity of Hydrated Geosynthetic Clay Liners", *Journal of Geotechnical Engineering*, ASCE, Vol. 121, No. 1, pp. 82-85.

Peggs, I.D. and Olsta, J.T., 1998, "A GCL and Incompatible Soil Case History: A Design Problem", *Proceedings of 12th GRI Conf. on Lesson Learned from Case Histories*, Drexel Univ., Philadelphia, PA, pp. 117-138.

Quigley, R.M., Yanful, E.K., and Fernandez, F., 1987, "Ion Transfer by Diffusion through Clayey Barriers", *Geotechnical Practice for Waste Disposal'87*, Geotechnical Special Publication No. 13, ASCE, pp. 137-158.

Reddi, L.N. and Inyang, H.I., 2000, *Geoenvironmental Engineering: Principles and Applications*, Marcel Dekker, Inc.

Rowe, R.K., 1987, "Pollutant Transport through Barriers", *Geotechnical Practice for Waste Disposal'87*, Geotechnical Special Publication No. 13, ASCE, pp. 159-181.

Shackelford, C.D., 1989, "Diffusion of Contaminants through Waste Containment Barriers", *Transportation Research Record 1219*, Washington, DC, pp. 169-182.

Shackelford, C.D., 1990, "Transit-Time Design of Earthen Barriers", *Engineering Geology, Vol. 29*, pp. 79-94.

Shackelford, C.D., 1992, "Performance-Based Design of Earthen Barriers", *Proceedings of Mediterranean Conference on Environmental Geotechnology*, Usmen, M. A. and Acar, Y.B. Eds., A.A. Balkema Publ., Rotteredam, pp. 145-153.

Shackelford, C.D. and Daniel, D.E., 1991, "Diffusion in Saturated Soil. I: Background", *Journal of Geotechnical Engineering*, ASCE, Vol. 117, No. 3, pp. 467-484.

Stark, T.D., 1997, "Effect of Swell Pressure on GCL Cover Stability", ASTM Special Technical Publication 1308, pp. 30-44.

Stark, T.D., 1998, "Bentonite Migration in Geosynthetic Clay Liners", Proc. 6th International Conference on Geosynthetics, sponsored by the Intl. Geosynthetics Society, Atlanta, GA, Vol. 1, pp. 315-320.

Stark, T.D. and H.T. Eid, 1997, "Shear Behavior of Reinforced Geosynthetic Clay Liners," *Geosynthetics International Journal*, Industrial Fabrics Association International (IFAI), Vol. 3, No. 6, pp. 771-786.

Stark, T.D., Williamson, T.A. and Eid, H.T., 1996, "Effect of Textured HDPE Geomembrane/Geotextile Interface Shear Strengths", *J. of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 122, No. 3, pp. 197-203.

Thibodeaux, L.J., 1979, *Chemodynamics*, John Wiley and Sons, New York.

Wilke, C.R. and Chang, P., 1955, "Correlation of Diffusion Coefficients in Dilute Solutions", *American Institute of Chemical Engineers Journal*, Vol. 1, pp. 264-270.