

Occurrence and effect of bentonite migration in geosynthetic clay liners

T. D. Stark¹, H. Choi² and R. Akhtarshad³

¹Professor, Department of Civil and Environmental Engineering, The University of Illinois, 2217 NCEL, 205 N. Mathews Ave., Urbana, IL 61801, USA, Telephone: +1 217 333 7394, Telefax: +1 217 333 9464, E-mail: tstark@uiuc.edu

²Post-doctoral Research Associate, Department of Civil and Environmental Engineering, The University of Illinois, B156 NCEL, 205 N. Mathews Ave., Urbana, IL 61801, USA, Telephone: +1 217 333 1773, Telefax: +1 217 333 9464, E-mail: hchoi2@uiuc.edu

³Civil/Environmental Engineer, California Regional Water Quality Control Board, Riverside, CA 92501, USA, Telephone: +1 909 320 2024, Telefax: +1 909 781 6288, E-mail: rakhtars@rb8.swrcb.ca.gov

Received 8 September 2002, revised 18 November 2003, accepted 26 November 2003

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 equivalence 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 non-uniform stresses, such as a rock or roughness in the subgrade, a leachate sump, or wrinkles in an overlying geomembrane. This paper presents field case histories that confirm the laboratory observations of bentonite migration and the effect of bentonite migration on hydraulic equivalence and contaminant transport through a GCL. Finally, the paper presents suggestions for protecting hydrated bentonite from stress concentrations and reducing contaminant transport through a GCL.

KEYWORDS: Geosynthetics, Geosynthetic clay liners, Flow rates, Fluid barrier, Permeability, Shear strength

REFERENCE: Stark, T. D., Choi, H. & Akhtarshad, R. (2004). Occurrence and effect of bentonite migration in geosynthetic clay liners. *Geosynthetics International*, 11, No. 4, 296–310

1. INTRODUCTION

In recent years, geosynthetic clay liners (GCLs) have increasingly been 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:

- usually lower and more predictable cost;
- prefabricated/manufactured quality;
- easier and faster construction;
- reduced need for field hydraulic conductivity testing;
- availability of a range of engineering properties;
- more resistance to the effects of wetting–drying and freeze–thaw cycles;
- increased airspace resulting from smaller thickness; and
- easier repair during and after installation.

Some of the disadvantages of GCLs compared with CCLs include:

- a potential for lower internal and interface shear strength (Gilbert *et al.* 1996; Eid and Stark 1997);
- a possible large post-peak shear strength loss in reinforced GCLs (Stark and Eid 1997);
- lower puncture resistance (Daniel 1991);
- smaller leachate attenuation capacity (Daniel 1991);
- shorter breakthrough time depending on the contaminant (Daniel 1991) as discussed herein; and
- 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.

2. BENTONITE MIGRATION IN GCLS

Field experiences, including the GCL slope stability research project in Cincinnati, Ohio (Koerner *et al.*

1996), show that bentonite will absorb moisture in the field because of its high matric suction potential. An increase in water content is accompanied by an increase in compressibility regardless of the normal stress at which hydration occurs (Terzaghi *et al.* 1996). Field experience with bentonite clearly shows that unconfined hydrated bentonite will migrate in the presence of stress concentrations. Thus the main issue addressed in this paper is whether hydrated, and thus compressible, bentonite will migrate when it is confined within a GCL.

2.1. Laboratory evidence of bentonite migration

Koerner and Narejo (1995) show that if a circular piston is applied to a hydrated GCL, the bentonite will flow away from the load, and the thickness of the hydrated GCL beneath the applied load will decrease. They conclude that the soil covering a GCL must have a thickness (H) greater than or equal to the diameter (D) of the loaded area to adequately protect the GCL. Fox *et al.* (1996) present results of similar GCL bearing capacity tests using three cover soils: a clean sand, fine gravel, and medium gravel. They recommend an H/D ratio between 1 and 2 to protect the GCL for this range of cover soils. The US Army Corps of Engineers (USACE 1995) simply requires a minimum cover soil thickness of 0.45 m, instead of an H/D ratio, before construction equipment can operate on top of a GCL.

Fox (1998) and Fox *et al.* (1998) extend their GCL bearing capacity tests discussed above using controlled field tests of GCL installation to study installation damage and the potential for bentonite migration. The results show that bentonite migration is significant for a cover soil thickness of 152 mm and an adhesive-bonded GCL. At this cover soil thickness, bentonite migration occurred vertically through the upper geotextile into the overlying gravel layer, with the upper geotextile remaining intact and bentonite simply extruding through it. Fox *et al.* (1998) report that the percentage reduction in mass per unit area of bentonite in the adhesive-bonded GCL is 81%, 42%, 12% and -10% for cover soil thicknesses of 152, 305, 457 and 610 mm respectively during the field study.

The thickness of hydrated bentonite also may decrease under non-uniform normal stresses that may be imposed by waste placement activities. Stress concentrations in a liner system can cause hydrated bentonite to migrate to zones of lower stress. Stress concentrations are ubiquitous in a liner system, especially around a sump, under leachate collection pipes and geomembrane wrinkles, above an uneven subgrade or rock (Peggs and Olsta 1998), at the edge of an anchor trench, at slope transitions, and around slope benches. Bentonite migration may be particularly important in sump areas because high hydraulic heads in a sump can increase leakage rates. As a result, Tedder (1997) recommends additional protection for sump areas. Stress concentrations can also be induced in a cover or liner system by a subgrade that contains stones or is uneven and/or contains ruts prior to GCL placement. Another possible mechanism for stress concentration is local differential

settlement caused by natural variations in foundation compressibility and shear strength, i.e. bearing capacity. Shear displacement may be another mechanism for bentonite migration, as noted by Gilbert *et al.* (1996), who describe bentonite migration to the shear plane during laboratory interface shear tests.

The presence of wrinkles in an overlying geomembrane creates zones of non-uniform normal stress, which can cause hydrated bentonite to migrate into the airspace under the wrinkle. Soong and Koerner (1997) indicate that the shape of a wrinkle or wave can change with time and normal stress, but the height does not appear to reduce substantially under a range of normal stresses. Recent observations (Eith and Koerner 1996; Koerner *et al.* 1997) show that wrinkles are not removed after landfilling, and can be long-term zones of non-uniform normal stress acting on an underlying GCL. The lack of intimate contact between the geomembrane and GCL due to wrinkles can result in hydrated bentonite migrating into the airspace under the wrinkle. In addition, there are a number of places around the sump and subsequent piping that lead to stress concentrations.

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. A normal stress of 958 kPa was applied to a hydrated GCL in the presence of a geomembrane wrinkle using a one-dimensional compression apparatus (see Figure 1). The hydrated bentonite migrated toward the void under the geomembrane wrinkle where the normal stress is at or near zero. The thickness of the GCLs under the wrinkle after the test shown in Figure 1 was 20 to 25 mm, whereas the thickness farthest away from the wrinkle was approximately 2.0 mm. The nominal manufactured thickness of the GCL prior to the test is 7.0 mm. One limitation of this compression test is that the normal stress of 958 kPa was applied at a rate of 4.5 kN/min, and thus the normal stress of 958 kPa was achieved in approximately 3.5 h. This loading rate is probably representative of heavy vehicular traffic. This loading

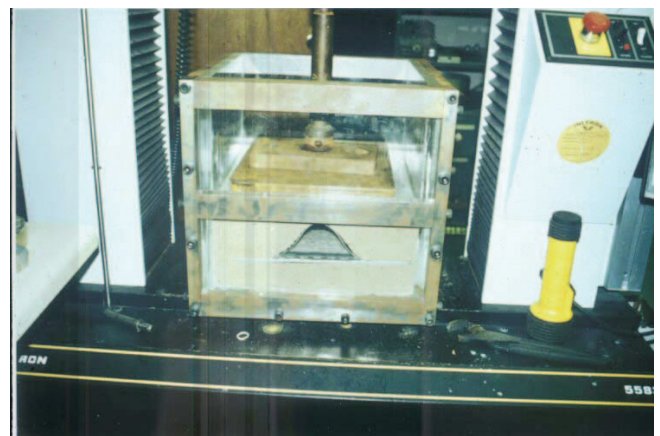


Figure 1. Hydrated GCL in the presence of a geomembrane wrinkle using a one-dimensional compression apparatus (photo courtesy J. Anderson)

rate is faster than typical landfilling, and thus some consolidation of the bentonite may have occurred if the loading rate simulated field landfilling conditions. Bentonite consolidation still would not have occurred under the wrinkle at a slower loading rate because the applied normal stress did not influence the bentonite directly under the wrinkle near the middle of the confined specimen (see Figure 1). This is caused by the height of wrinkle not reducing substantially under the normal stresses, as reported by Soong and Koerner (1997) and illustrated in Figure 1. Therefore any consolidation that might occur in the bentonite due to a slower loading rate would occur outside the wrinkle area. The presence of unconsolidated bentonite adjacent to consolidating bentonite will still probably result in bentonite migration towards the wrinkle even if a slower loading rate was used. 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). However, the contaminant transport analyses described subsequently investigate the effect of reducing the bentonite thickness from 7.0 mm to 2.0 mm to represent a worst-case scenario or a leachate on the effect of bentonite thinning.

2.2. Field evidence of bentonite migration

Field experiences with GCLs that confirm laboratory observations of bentonite migration are starting to appear in the literature. For example, Peggs and Olsta (1998) describe the investigation of the hydraulic failure of three wastewater treatment lagoons in the western United States. The liner system for each of the three ponds consists of a GCL overlain by 450 mm of cover soil. Because of the coarse native soils, a needle-punched GCL (Bentomat ST) instead of a geomembrane was selected for containment because of the potential for puncture of the geomembrane by the native soils. The design depth of liquid in the ponds is about 3.4 m, and State regulations require a leakage rate of less than 44 lphd (litres per hectare per day). During hydrotesting, i.e. filling of the ponds with water before placing them into service, the leakage rate was estimated to be about 50,000 lphd. This leakage rate exceeded the required value even though the liquid level was only 2.1 m. This leakage situation developed in each of the three ponds (Peggs and Olsta 1998), and was caused by leakage through the GCL.

Figure 2 shows the GCL after removal of the cover soil: clearly, the GCL deformed to the shape of the coarse particles/rocks underlying the GCL. As vertical load was applied to the GCL in the form of the cover soil and water during the hydrotesting, local stress concentrations developed in the GCL at the contact points of the rocks with the overlying GCL. These stress concentrations resulted in the hydrated bentonite migrating into the gaps or air voids between the underlying stones. Peggs and Olsta (1998) conclude that, in extreme cases, all of the bentonite was either squeezed sideways or out of the GCL in the vicinity of a rock. After all of the bentonite was squeezed out, the upper and lower geotextiles of the GCL



Figure 2. GCL overlying an incompatible subgrade (from Peggs and Olsta 1998)

made contact and thus leaking commenced. The GCL also was compromised in some locations because of holes in the GCL due to angular coarse particles and stones in contact with the GCL. The use of this coarse subgrade was not in accordance with product specification guidelines, which require the subgrade soils to have at least 80% of the soil finer than 0.2 mm (#60 sieve) and no sharp rocks larger than 50 mm.

In summary, this case history illustrates 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.

Fox *et al.* (2000) describe laboratory flexible-wall permeameter tests used to evaluate the hydraulic conductivity of adhesive-bonded and needle-punched GCLs covered by uniformly graded gravel similar to the gravel shown in Figure 2. After permeameter testing, local measurements of bentonite mass/area show that bentonite migration occurred in the GCL specimens covered with gravel because of stress concentrations imposed by the gravel (Fox 1998). The extent of bentonite migration increases with increasing cover soil particle size and rate of loading. Thus the laboratory testing is in agreement with field observations of bentonite migration.

The following paragraphs detail another instance of field evidence of bentonite migration in GCLs. Figure 3 shows the sump area of a municipal solid waste landfill in the western US with a base liner system that consists, from the bottom to the top, of

- a smooth natural subgrade;
- 0.61 m of low-permeability compacted soil; and
- 1.5 mm (60 mil) HDPE geomembrane textured on both sides.
- The side slope liner system is different, and consists, from the bottom to the top, of:
 - a smooth, natural subgrade;
 - 1.0 mm (40 mil) HDPE geomembrane textured on both sides to serve as a moisture barrier;
 - needle-punched GCL; and
 - 1.5 mm (60 mil) HDPE geomembrane textured on the side facing the GCL and the smooth side facing up.



Figure 3. Sump area after pumping out storm water

After liner system construction was complete, only a portion of the cell base was placed into service. In the service area a granular drainage and operations layer was placed over the 1.5 mm (60 mil) HDPE geomembrane. In the non-service area of the lined area the liner system was protected by a sacrificial 1.0 mm (40 mil) HDPE geomembrane until this area was placed into service at some future time. An HDPE flap, which was extrusion-welded directly to the base liner, and a separation berm were used to separate the active area from the inactive area. The inactive portion of the landfill was not used for two years. Prior to using this portion of the lined area, the owner/operator had to have the liner system in the empty cell inspected and certified. During the certification process the sacrificial geomembrane was cut so it could be removed and the granular drainage media and operations layer could be placed directly on the 1.5 mm (60 mil) HDPE geomembrane. Upon cutting the sacrificial geomembrane, a layer of bentonite clay was discovered over the surface of the 1.5 mm (60 mil) HDPE geomembrane. After considerable discussion it was established that the bentonite layer on top of the 1.5 mm (60 mil) HDPE geomembrane was the result of bentonite migration from the wetted GCL on the side slopes. This GCL was the only source of bentonite in the vicinity. During the non-use period of this area, the sump filled with precipitation and surface water runoff up to the high water mark shown in Figure 3. Probably as a result of the presence of defects in the geomembrane and seam failures and/or vapour transmission through the geomembrane, the GCL on the side slope was hydrated to just above the high water

mark, or 10–15 vertical feet (3–4.5 m) above the base of the sump.

The cross-section in Figure 4 illustrates the configuration of the liner system in this area, and is used to describe how the bentonite was able to migrate from the base of the sump. Figure 4 shows that the GCL on the side slope is encapsulated by 1.0 mm- and 1.5 mm-thick geomembranes. More importantly, the upper 1.5 mm-thick HDPE geomembrane on the side slope is extrusion-welded to the 1.5 mm-thick HDPE geomembrane on the base of the cell. Thus the upper 1.5 mm-thick geomembrane is welded closer to the centre of the sump than the underlying 1.0 mm-thick geomembrane. This geomembrane could not be fusion-welded to the end of the 1.5 mm-thick HDPE geomembrane on the cell base because the 1.0 mm-thick HDPE geomembrane that was serving as a moisture barrier was extrusion-welded to the geomembrane on the cell base.

In theory, bentonite could not migrate from the side slope over the base of the sump area because the upper side slope geomembrane is extrusion-welded to the 1.5 mm-thick HDPE geomembrane on the base of the cell. Therefore, if bentonite migration were occurring, the bentonite would have been stopped by the extrusion weld. Unfortunately or fortunately, the extrusion weld did not remain intact, which is frequently the case, and thus bentonite was able to migrate from the side slope out over the smooth surface of the geomembrane on the base of the cell. The bentonite remained below the sacrificial geomembrane until the cell was ready to be placed into service and the sacrificial geomembrane was cut open. Figure 4 shows that the side slopes correspond to an inclination of 24° or about $2.2H:1V$, and the water level shown simulates the filling of the sump area with precipitation and storm water runoff.

Figure 5 shows the base of the sump area after the precipitation and storm water had been pumped out and the sacrificial geomembrane on the base of the cell cut and pulled back. If bentonite migration had not occurred, the 1.5 mm-thick HDPE geomembrane on the base of the cell would be visible. Instead a thin layer of bentonite is covering the geomembrane on the base of the cell, and the top of the geomembrane is not visible.

Figure 6 presents a close-up of the hydrated bentonite discovered below the sacrificial geomembrane. This figure shows that the bentonite contains some moisture, and the underlying geomembrane is not readily visible.

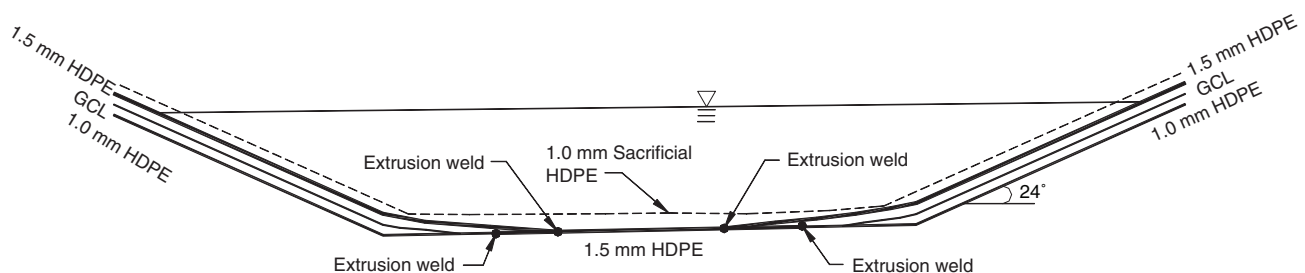


Figure 4. Cross-section of base and side slope liner system in area of bentonite migration



Figure 5. Layer of hydrated bentonite on top of geomembrane on cell base after removal of overlying sacrificial geomembrane



Figure 6. Close-up of hydrated bentonite accumulated on top of geomembrane on cell base after removal of overlying sacrificial geomembrane

The cause of the bentonite migration may be one or more the following mechanisms:

- gravity flow or migration of the bentonite down the 24° side slopes;
- lateral pressure exerted by the ponded water forcing the bentonite down the side slope;
- washing of the bentonite down the side slopes by leakage through liner defects; and/or
- mechanisms enhanced by variability of needle-punching in the GCL.

Figure 7 presents the cross-section of the side slope liner system near the intersection with the base of the cell. The geomembrane underlying the GCL is not visible because bentonite has migrated over the surface of the smooth geomembrane. In Figure 7 the GCL and overlying geomembrane are visible, and bentonite can be seen exiting the GCL.

In summary, this case history also illustrates the potential for bentonite migration in the field, especially for GCLs placed on a side slope. The next section addresses the effect of this bentonite migration on the hydraulic equivalence between a GCL and a CCL.

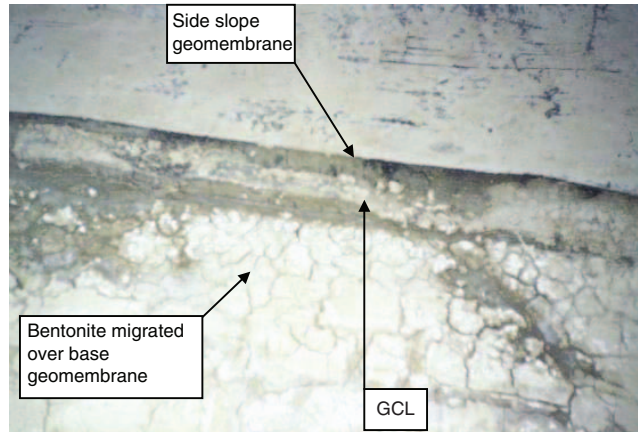


Figure 7. Cross-section of side slope liner system near cell base, showing from top to bottom the 1.5 mm thick HDPE geomembrane, hydrated GCL, and bentonite covering the geomembrane on the cell base

3. CONTAMINANT TRANSPORT THROUGH A GCL

This section describes four analyses—steady water flux, steady solute flux, steady diffusion and advective dispersion—used to investigate the effect of bentonite migration on the hydraulic equivalence between a CCL and GCL and the contaminant transport through a thinned GCL.

3.1. 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

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

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 the 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 applicable only to flow through the bentonite component of the GCL. If the GCL contains a geomembrane, the water flux will be controlled by the water vapour diffusion through the geomembrane component and not the bentonite in the GCL.

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

$$V_{GCL} = V_{CCL} \tag{2}$$

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

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

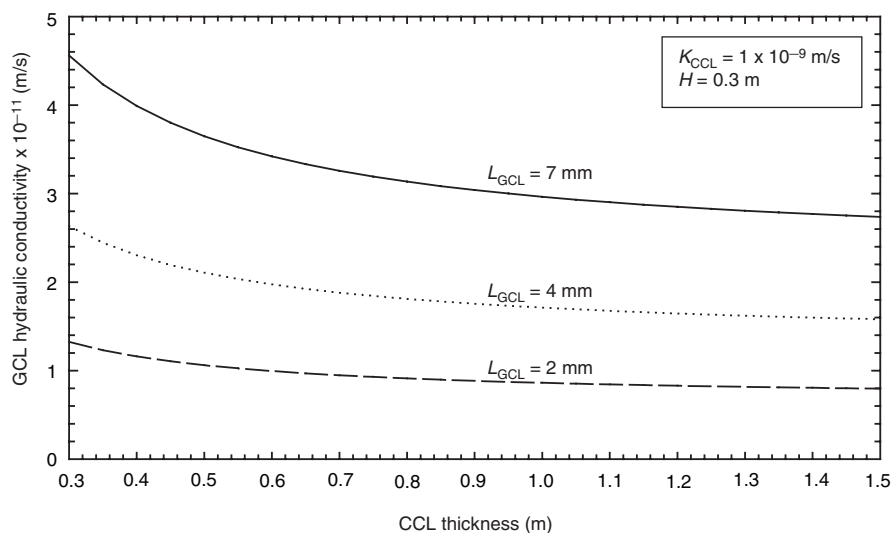


Figure 8. Effect of hydrated bentonite thickness on required K_{GCL} base on steady water flux equivalence

This expression is used to estimate the value of K_{GCL} required for equivalence 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 8 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 equivalence 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 equivalence 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 equivalence 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 equivalence between a GCL and a CCL in terms of steady water flux.

3.2. 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

$$J_A = C_{leachate}(K) \left(\frac{H + L}{L} \right) = C_{leachate}(V) \quad (4)$$

where J_A is the advective mass flux ($\text{mg}/(\text{s}/\text{m}^2)$) and $C_{leachate}$ is the concentration of solute in the leachate (mg/m^3). This equation is applicable to a CCL (Shackelford 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:

$$\begin{aligned} F_A &= \frac{(J_A)_{GCL}}{(J_A)_{CCL}} \\ &= \frac{C_{leachate}(K_{GCL})[(H + L_{GCL})/(L_{GCL})]}{C_{leachate}(K_{CCL})[(H + L_{CCL})/(L_{CCL})]} \\ &= \frac{V_{GCL}}{V_{CCL}} \end{aligned} \quad (5)$$

Therefore the advective mass flux ratio is identical to the water flux ratio, i.e. V_{GCL}/V_{CCL} . If equivalence is demonstrated in terms of steady water flux, equivalence is also demonstrated in terms of steady mass flux of solute via Equation 5. As described above and shown in Figure 8, 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, equivalence 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).

3.3. Steady diffusion

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

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}

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

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 , owing to the tortuosity of the porous medium, which is expressed as follows:

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

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 (Freeze and Cheery 1979; Quigley *et al.* 1987; Rowe 1987; Daniel and Shackelford 1988; Johnson *et al.* 1989; Shackelford 1989; Shackelford and Daniel 1991; Daniel 1993). 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 affected mainly by the viscosity of the liquid. Theoretical and/or empirical expressions for D^0 are found in references such as Wilke and Chang (1955), Hayduk and Laudie (1974), Shackelford and Daniel (1991), and Grathwohl (1998).

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 $2.03 \times 10^{-9} m^2/s$ in water at $25^\circ C$ (Daniel and Shackelford 1988; Reddi and Inyang 2000), and the retardation factor, R_d , is equal to unity (Shackelford 1990). A retardation factor of unity means that 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 that 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 $9.9 \times 10^{-10} m^2/s$ in water at $20^\circ C$ (Thibodeaux 1979)

and $7.2 \times 10^{-10} m^2/s$ in water at $27^\circ C$ (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 to 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 $6.0 \times 10^{-10} m^2/s$ for a clay liner (Quigley *et al.* 1987; Daniel and Shackelford 1988; Johnson *et al.* 1989; 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 simulates field conditions better, 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, are 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 $1 \times 10^{-9} m/s$ respectively. These values are in agreement with the typical values for a CCL permeated with water, as shown in Table 1.

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

$$F_D = \frac{(J_D)_{GCL}}{(J_D)_{CCL}} = \frac{D_{GCL}^*(n_e)_{GCL}(\Delta C/L_{GCL})}{D_{CCL}^*(n_e)_{CCL}(\Delta C/L_{CCL})} = \frac{D_{GCL}^*(n_e)_{GCL}L_{CCL}}{D_{CCL}^*(n_e)_{CCL}L_{GCL}} \quad (8)$$

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 through the CCL. Conversely, if F_D is less than

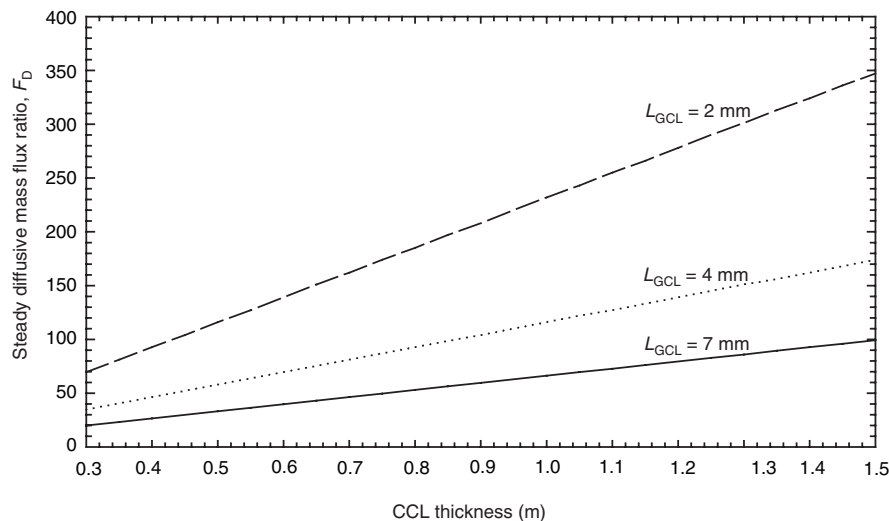


Figure 9. Effect of hydrated bentonite thickness on steady diffusive mass flux ratio for both chloride and TCE

unity, there is more diffusion through the CCL than through 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

$$F_D = \frac{D_{GCL}^*(0.6)L_{CCL}}{D_{CCL}^*(0.37)L_{GCL}} = 1.62 \frac{D_{GCL}^*L_{CCL}}{D_{CCL}^*L_{GCL}} \quad (9)$$

Thus the steady diffusive mass flux ratio is a function only 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

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

and F_D is a function of liner thickness only, 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 9. 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.

3.4. Advective dispersion

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

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

where T is the time factor (dimensionless), P is the Peclet number (dimensionless) and e^P is the exponential of the Peclet number.

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 in Figure 10 and are:

- initial (time, t , equals zero), constant concentration in the soil is zero, where x is the distance in the soil layer, i.e. $C(x \geq 0; t = 0) = 0$;
- boundary condition of initial concentration of the solute is C_0 , i.e. $C(x \leq 0; t > 0) = C_0$;
- C_0 is constant; and
- 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, homo-

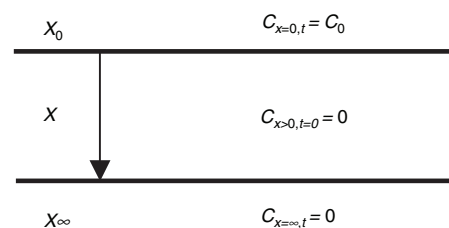


Figure 10. Initial and boundary conditions used in advective dispersion analysis

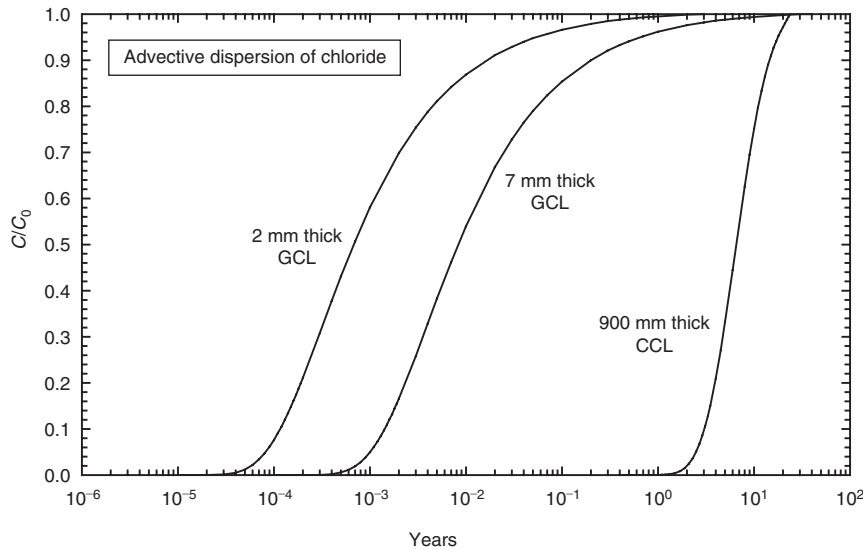


Figure 11. Effect of hydrated bentonite thickness on reduction of chloride (Cl^-) concentration ratio as a function of time at the bottom of the CCL and GCL

geneous, and of semi-infinite depth, that a steady-state (Darcian) fluid flow has been established, and that the solute transport only occurs in one direction, i.e. vertical.

The time factor and Peclet number are given as

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

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

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 11 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 the 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 12 presents the concentration ratio of TCE ($R_d=40$), C/C_0 , at the bottom of a 0.9 m-thick CCL and the 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-grained soil (i.e. $R_d=40$) results in a slower solute transport compared with chloride. However, a retardation factor of unity is recommended for

most organic leachates to ensure a conservative clay liner design (Rowe 1987; Acar and Haider 1990). 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 with chloride. In addition, thinning of the hydrated bentonite to 2 mm 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 to 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/s) is two orders less than the hydraulic conductivity of a CCL (1×10^{-9} m/s). However, the GCL thickness of 0.21 m (210 mm) and 0.15 m (150 mm) is still not achievable in the field.

4. 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

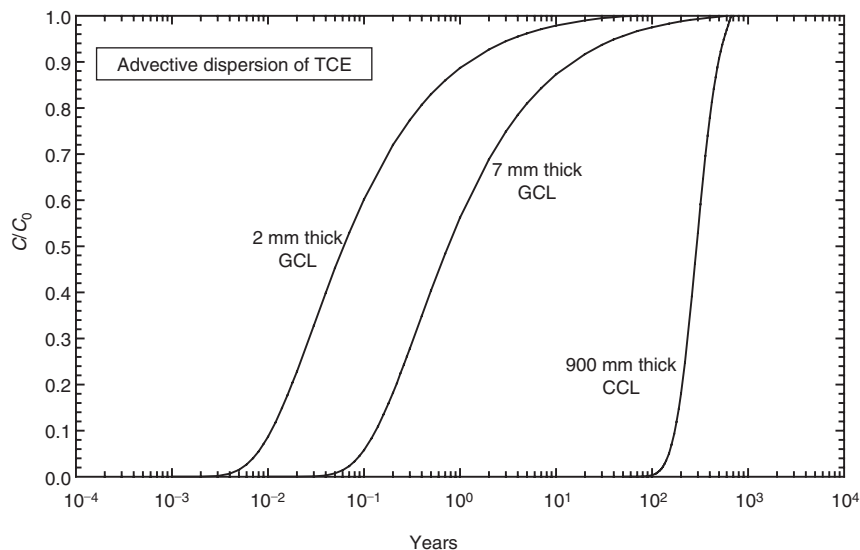


Figure 12. Effect of hydrated bentonite thickness on reduction of TCE concentration ratio as a function of time at the bottom of the CCL and GCL

GCL and CCL and reduce contaminant transport through the GCL.

One possible solution to reduce bentonite migration is to use a CCL instead of a GCL, because a CCL exhibits a much lower compressibility than a GCL and thus is less likely to migrate. An initial bentonite thickness that is greater than 7 mm could also be used. Another solution is to encapsulate the bentonite between two geomembranes to reduce the amount of hydration and thus decrease the compressibility of the bentonite. The encapsulation can be accomplished with smooth or textured geomembranes or a geomembrane with protrusions, i.e. a smooth geomembrane with protrusions or nipples, that prevents squeezing of the bentonite over the entire surface of the geomembrane. Multiple layers of GCL also can be installed at known points of stress concentration, e.g. sumps and changes in slope. The multiple layers of GCL initially provide a thicker layer of bentonite but may exhibit bentonite migration, and the amount of bentonite remaining will still be an issue.

Another possible solution involves reducing stress concentrations in the subgrade by smoothing changes in the geometry, reducing ruts, and removing rocks. The geomembrane should also be installed with a limited number of wrinkles. This can be accomplished by using geomembranes that are light-colored, e.g. white or grey, that exhibit a high interface friction coefficient (textured or PVC geomembrane; Hillman and Stark 2001), and/or that 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 stabiliser element (Stark 1997, 1998). The stabiliser element reduces the compression of the GCL, and thus lateral squeezing of hydrated bentonite, in response to the stress concentrations in a liner or cover system. The internal structure also protects the bentonite from concentrated stresses applied during handling, stockpiling and con-

struction, and provides additional resistance to accidental puncture. Confining the bentonite in an internal structure provides a better assurance of the thickness and integrity of the hydrated bentonite.

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/s. 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/s. 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 with 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 (Quigley *et al.* 1987; Daniel and Shackelford 1988; Johnson *et al.* 1989; Shackelford 1990, 1992), and the retardation factor (R_d) is equal to unity (Shackelford 1990). A retardation factor of unity means that 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 modelled by representing the GCL/attenuation layer combination as a single layer with composite properties. The main

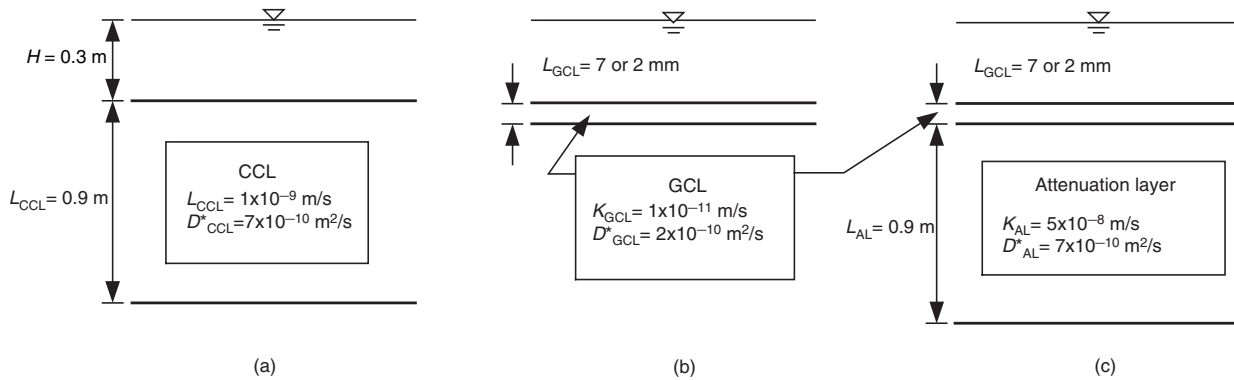


Figure 13. Schematic diagram of three analyses used to evaluate the effectiveness of an attenuation layer to increase the breakthrough time for a GCL: (a) 0.9 m-thick CCL; (b) 7 mm or 2 mm-thick GCL; (c) 7 mm or 2 mm-thick GCL and underlying attenuation layer

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:

$$D_{eq}^* = \frac{L_{AL} + L_{GCL}}{(L_{AL}/D_{AL}^*) + (L_{GCL}/D_{GCL}^*)} \quad (14)$$

where D_{AL}^* is the effective diffusion coefficient for the attenuation layer (m^2/s), D_{GCL}^* is the effective diffusion coefficient for GCL (m^2/s), L_{AL} is the thickness of the 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):

$$K_{eq} = \frac{L_{AL} + L_{GCL}}{(L_{AL}/K_{AL}) + (L_{GCL}/K_{GCL})} \quad (15)$$

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 with CCL performance, an inorganic silt or clayey silt, i.e. ML in the Unified Soil Classification System, is used for the attenuation layer. The hydraulic conductivity of the attenuation layer, K_{AL} , is selected as 5×10^{-8} m/s for an ML soil (US 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. $\tau = 0.34$, 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. Figure 13 shows a schematic comparison of the three analyses used to investigate the effectiveness of an attenuation layer, which are a 0.9 m-thick CCL only, a 7 or 2 mm-thick GCL only, and a combination of a 7 or 2 mm-thick GCL and a 0.9 m-thick attenuation layer. The material properties of the CCL and GCL

used in the analyses are from the typical values shown in Table 1.

The values 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/s calculated from Equation 14, respectively. The values 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/s 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 to that of the GCL, 0.60. The effective porosity of the GCL/attenuation combination layer is estimated to be 0.40.

Figure 14 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 14 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 15 presents the values of C/C_0 at the bottom of each layer that are presented in Figure 14. In addition, the equivalent hydraulic conductivity of the thinned GCL, i.e. $L_{GCL} = 2$ mm, is varied by several orders of magnitude to determine whether the comparison with the CCL in Figure 14 could be improved by varying the K_{eq} of the GCL/attenuation layer. Figure 15 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.

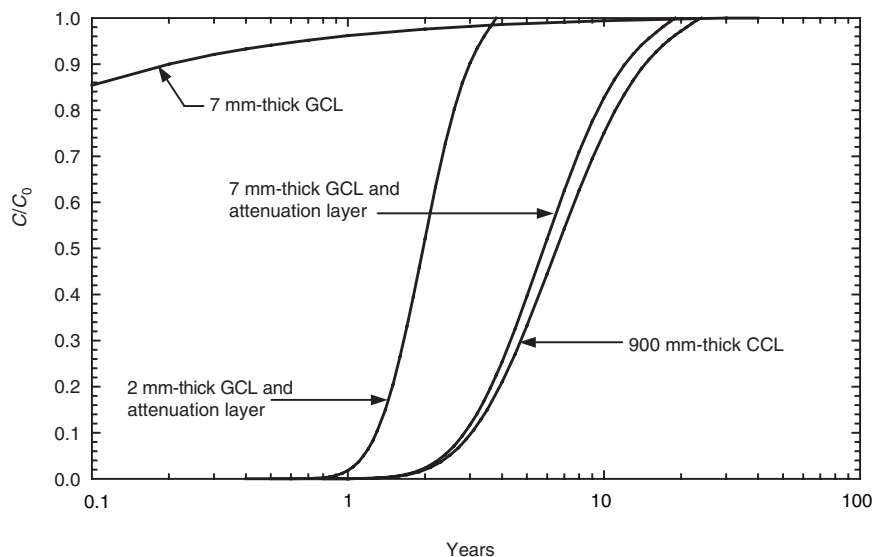


Figure 14. Effect of attenuation layer on breakthrough time for advective dispersion of chloride for values of C/C_0 calculated at the bottom of each layer

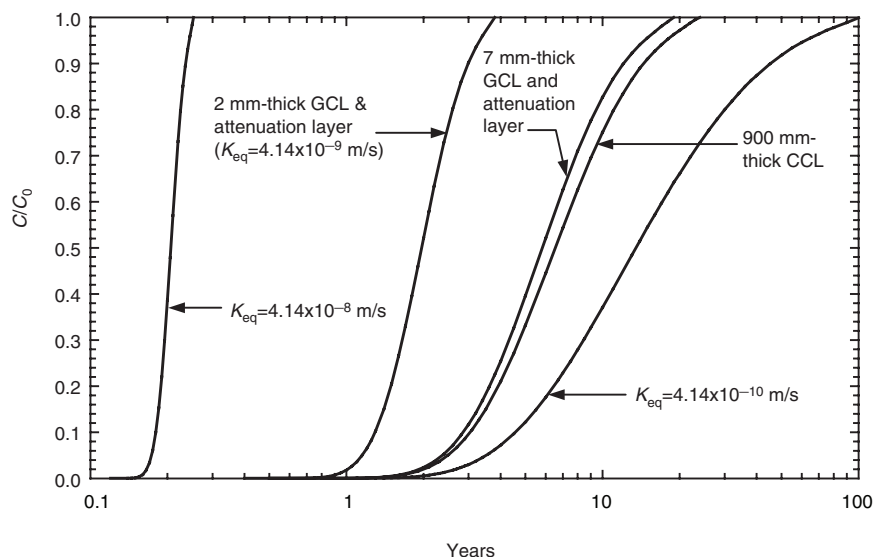


Figure 15. Effect of equivalent hydraulic conductivity on breakthrough time at the bottom of each layer for advective dispersion of chloride through 2 mm-thick GCL and attenuation layer

The analyses related to GCL performance with and without an attenuation layer assume that the GCL properties remain constant and are not a function of the GCL thickness. Additional research is required to determine the change, if any, in the hydraulic properties of a GCL during construction, waste placement, and closure as bentonite thickness changes. If the properties do change significantly, different values of hydraulic conductivity, effective diffusion coefficient and effective porosity should be used in the calculations presented herein. Some of the mechanisms that may lead to a change in the hydraulic properties of a GCL are consolidation, wet/dry and/or freeze/thaw of the bentonite. It is anticipated that wet/dry and freeze/thaw will

increase the rate of contaminant transport through the GCL (Boardman and Daniel 1996; Hewitt and Daniel 1997; Kraus *et al.* 1997; Lin and Benson 2000).

5. CONCLUSIONS

Hydrated bentonite can migrate to areas of lower normal stress due to stress concentrations or non-uniform stresses. Stress concentrations are ubiquitous in a liner system, especially around sump and pipe locations, at the edge of an anchor trench, around slope transitions and slope benches, under geomembrane wrinkles, and above an uneven subgrade or rock. Field evidence is becoming available and is confirming laboratory and

field test results that show that 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 minimised 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 using a compacted clay liner, 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-coloured (white or grey), 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 stabiliser element (Stark 1998). The stabiliser 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.

ACKNOWLEDGEMENTS

The first author acknowledges the support provided by a University Scholar award. This support is gratefully acknowledged. The contents and views in this paper are the authors' and do not necessarily reflect those of any of the contributors or represented organisations. The authors appreciate the helpful and thorough review comments. The first author invented the modified GCL

that contains an internal structure. Patent rights have been assigned to Geosynthetics, Inc.

NOTATIONS

Basic SI units are given in parentheses.

C	concentration of solute (mg/m^3)
C_{leachate}	concentration of solute in leachate (mg/m^3)
C_0	initial concentration of solute (mg/m^3)
ΔC	change in concentration (mg/m^3)
D^0	free-solution diffusion coefficient (m^2/s)
D^*	effective diffusion coefficient (m^2/s)
D_{AL}^*	effective diffusion coefficient of attenuation layer (m^2/s)
D_{CCL}^*	effective diffusion coefficient of CCL (m^2/s)
D_{GCL}^*	effective diffusion coefficient of GCL (m^2/s)
D_{eq}^*	equivalent effective diffusion coefficient (m^2/s)
F_A	advective mass flux ratio (dimensionless)
F_D	diffusive mass flux ratio (dimensionless)
H	depth of liquid ponded above layer or liner (m)
i	hydraulic gradient (dimensionless)
J_A	advective mass flux ($\text{mg}/(\text{s}/\text{m}^2)$)
$(J_A)_{\text{CCL}}$	advective mass flux through CCL ($\text{mg}/(\text{s}/\text{m}^2)$)
$(J_A)_{\text{GCL}}$	advective mass flux through GCL ($\text{mg}/(\text{s}/\text{m}^2)$)
J_D	diffusive mass flux ($\text{mg}/(\text{s}/\text{m}^2)$)
$(J_D)_{\text{CCL}}$	diffusive mass flux through CCL ($\text{mg}/(\text{s}/\text{m}^2)$)
$(J_D)_{\text{GCL}}$	diffusive mass flux through GCL ($\text{mg}/(\text{s}/\text{m}^2)$)
K	saturated hydraulic conductivity (m/s)
K_{AL}	saturated hydraulic conductivity of attenuation layer (m/s)
K_{CCL}	saturated hydraulic conductivity of CCL (m/s)
K_{GCL}	saturated hydraulic conductivity of GCL (m/s)
K_{eq}	equivalent hydraulic conductivity (m/s)
L	thickness of layer or liner (m)
L_{AL}	thickness of attenuation liner (m)
L_{CCL}	thickness of CCL (m)
L_{GCL}	thickness of GCL (m)
n_e	effective porosity (dimensionless)
$(n_e)_{\text{CCL}}$	effective porosity of CCL (dimensionless)
$(n_e)_{\text{GCL}}$	effective porosity of GCL (dimensionless)
P	Peclet number (dimensionless)
q	Darcian flow (m/s)
R_d	retardation factor (dimensionless)
T	time factor (dimensionless)
t	time (s)
V	steady water flux ($\text{m}^3/(\text{s}/\text{m}^2)$)
V_{CCL}	steady water flux through CCL ($\text{m}^3/(\text{s}/\text{m}^2)$)
V_{GCL}	steady water flux through GCL ($\text{m}^3/(\text{s}/\text{m}^2)$)
v	seepage velocity of fluid (m/s)
v_s	velocity of solute (m/s)
x	distance in soil layer (m)
τ	tortuosity factor (dimensionless)

ABBREVIATIONS

CCL	compacted clay liner
GCL	geosynthetic clay liner
HDPE	high-density polyethylene geomembrane
RCRA	Resource Conservation and Recovery Act
TCE	trichloroethylene

REFERENCES

- Acar, Y. B. & Haider, L. (1990). Transport of low-concentration contaminants in saturated earthen barriers. *Journal of Geotechnical Engineering*, **116**, No. 7, 1031–1052.
- Akins, P. W. (1985). *Physical Chemistry*, 3rd edn. 857 S. W.H. Freeman & Company, New York.
- Anderson, J. D. (1996). Are geosynthetic clay liners (GCLs) really equivalent to compacted clay liners? *Geotechnical News*, **14**, No. 2, 20–23.
- Anderson, J. D. & 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.
- Boardman, B. & Daniel, D. E. (1996). Hydraulic conductivity of desiccated geosynthetic clay liners. *Journal of Geotechnical and Geoenvironmental Engineering*, **122**, No. 3, 204–208.
- Crooks, V. E. & Quigley, R. M. (1984). Saline leachate migration through clay: a comparative laboratory and field investigation. *Canadian Geotechnical Journal*, **21**, No. 2, 349–362.
- Daniel, D. E. (1991). Geosynthetic clay liners. *Geotechnical Fabrics Report*, **9**, No. 9, 28–33.
- Daniel, D. E. (1993). *Geotechnical Practice for Waste Disposal*, Chapman & Hall, New York, pp. 137–163.
- Daniel, D. E. & Shackelford, C. D. (1988). Disposal barriers that release contaminants only by molecular diffusion. *Nuclear Chemical Waste Management*, **8**, 299–305.
- Eid, H. T. & Stark, T. D. (1997). Shear behavior of an unreinforced geosynthetic clay liner. *Geosynthetics International*, **4**, No. 6, 645–659.
- Eith, A. W. & Koerner, G. R. (1996). Assessment of HDPE geomembrane performance in a municipal waste landfill double liner system after eight years of service. *Proceedings of 10th GRI Conference on Field Performance of Geosynthetics and Geosynthetic Related Systems*, Drexel University, Philadelphia, PA, pp. 97–109.
- Evans, W. D. (1997). *Advisory on Structural Integrity Considerations for Incorporating Geosynthetic Clay Liners in Solid Waste Landfill Facility Designs*, Division of Solid and Infectious Waste Management, Ohio Environmental Protection Agency, August, 14 pp.
- Fox, P. J. (1998). Research on geosynthetic clay liners at Purdue University. *Geotechnical News*, **16**, No. 1, 35–40.
- Fox, P. J., De Battista, D. J. & Chen, S. H. (1996). Bearing capacity of geosynthetic clay liners for cover soils of varying particle size. *Geosynthetics International*, **3**, No. 4, 447–461.
- Fox, P. J., Triplett, E. J., Kim, R. H. & Olsta, J. T. (1998). Field study of installation damage for geosynthetic clay liners. *Geosynthetics International*, **5**, No. 5, 491–520.
- Fox, P. J., De Battista, D. J. & Mast, D. G. (2000). Hydraulic performance of geosynthetic clay liners under gravel cover soils. *Geotextiles and Geomembranes*, **18**, 179–201.
- Freeze, R. A. & Cherry, J. A. (1979). *Groundwater*, Prentice Hall, Englewood Cliffs, NJ, 604 pp.
- Gilbert, R. B., Fernandez, F. & Horsfield, D. W. (1996). Shear strength of reinforced geosynthetic clay liner. *Journal of Geotechnical and Geoenvironmental Engineering*, **122**, No. 4, 259–266.
- Giroud, J. P. (1995). Wrinkle management for polyethylene geomembranes requires active approach. *Geotechnical Fabric Report*, **13**, No. 3, 14–17.
- Gleason, M. H., Daniel, D. E. & Eykholt, G. R. (1997). Calcium and sodium bentonite for hydraulic containment applications. *Journal of Geotechnical and Geoenvironmental Engineering*, **123**, No. 5, 438–445.
- Grathwohl, P. (1998). *Diffusion in Natural Porous Media: Contaminant Transport, Sorption/Desorption and Dissolution Kinetics*, Kluwer Academic Publishers, New York.
- Hayduk, W. & Laudie, H. (1974). Prediction of diffusion coefficients for nonelectrolytes in dilute aqueous solution. *American Institute of Chemical Engineers Journal*, **20**, No. 3, 611–615.
- Hewitt, R. D. & Daniel, D. E. (1997). Hydraulic conductivity of geosynthetic clay liners after freeze-thaw. *Journal of Geotechnical and Geoenvironmental Engineering*, **123**, No. 4, 305–313.
- Hillman, R. P. & T. D. Stark (2001). Shear behavior of PVC geomembrane/geosynthetic interfaces. *Geosynthetics International*, **8**, No. 2, 135–162.
- Johnson, R. L., Cherry, J. A. & Pankow, J. F. (1989). Diffusive contaminant transport in natural clay: a field example and implications for clay-lined waste disposal sites. *Environmental Science Technology*, **23**, No. 3, 340–349.
- Koerner, R. M. & Daniel, D. E. (1995). A suggested methodology for assessing the technical equivalency of GCLs to CCLs. In *Geosynthetic Clay Liners* (eds R. M. Koerner, E. Gartung and H. Zanzinger), Balkema, Rotterdam/Brookfield, pp. 73–98.
- Koerner, R. M. & Narejo, D. (1995). Bearing capacity of hydrated geosynthetic clay liners. *Journal of Geotechnical Engineering*, **121**, No. 1, 82–85.
- Koerner, R. M., Daniel, D. E. & Bonaparte, R. (1996). Current status of the Cincinnati GCL test plots. *Proceedings of 10th GRI Conference on Field Performance of Geosynthetics and Geosynthetic Related Systems*, Drexel University, Philadelphia, PA, pp. 147–175.
- Koerner, G. R., Eith, A. W. & Tanese, M. (1997). Properties of exhumed HDPE field waves and selected aspects of wave management. *Proceedings of 11th GRI Conference on Field Installation of Geosynthetics*, Drexel University, Philadelphia, PA, pp. 152–162.
- Kraus, J. F., Benson, C. H., Erickson, A. E. & Chamberlain, E. J. (1997). Freeze-thaw cycling and hydraulic conductivity of bentonite barriers. *Journal of Geotechnical and Geoenvironmental Engineering*, **123**, No. 3, 229–238.
- Lin, L. & Benson, C. H. (2000). Effect of wet-dry cycling on swelling and hydraulic conductivity of GCLs. *Journal of Geotechnical and Geoenvironmental Engineering*, **126**, No. 1, 40–49.
- Peggs, I. D. & Olsta, J. T. (1998). A GCL and incompatible soil case history: a design problem. *Proceedings of 12th GRI Conference on Lessons Learned from Case Histories*, Drexel University, Philadelphia, PA, pp. 117–138.
- Quigley, R. M., Yanful, E. K. & Fernandez, F. (1987). Ion transfer by diffusion through clayey barriers. *Geotechnical Practice for Waste Disposal '87*, ASCE Geotechnical Special Publication No. 13, New York, pp. 137–158.
- Reddi, L. N. & Inyang, H. I. (2000). *Geoenvironmental Engineering: Principles and Applications*, Marcel Dekker, New York.
- Rowe, R. K. (1987). Pollutant transport through barriers. *Geotechnical Practice for Waste Disposal '87*, ASCE Geotechnical Special Publication No. 13, New York, pp. 159–181.
- Shackelford, C. D. (1989). Diffusion of contaminants through waste containment barriers. *Transportation Research Record 1219*, Transportation Research Board, National Research Council, Washington, DC, pp. 169–182.
- Shackelford, C. D. (1990). Transit-time design of earthen barriers. *Engineering Geology*, **29**, 79–94.
- Shackelford, C. D. (1992). Performance-based design of earthen barriers. *Proceedings of Mediterranean Conference on Environmental Geotechnology* (eds M. A. Usmen and Y. B. Acar), Cese, Turkey, Balkema, Rotterdam, pp. 145–153.
- Shackelford, C. D. & Daniel, D. E. (1991). Diffusion in saturated soil. I: Background. *Journal of Geotechnical Engineering*, **117**, No. 3, 467–484.
- Soong, T.-Y. & Koerner, R. M. (1997). Behavior of waves in high density polyethylene geomembranes: a laboratory study. *Proceedings of 11th GRI Conference on Field Installation of Geosynthetics*, Drexel University, Philadelphia, PA, pp. 128–151.
- Stark, T. D. (1997). Effect of swell pressure on GCL cover stability. *Proceedings of Symposium Testing and Acceptance Criteria for Geosynthetic Clay Liners*, Special Technical Publication 1308 (ed. L. W. Well), ASTM International, West Conshohocken, PA, pp. 30–44.
- Stark, T. D. (1998). Bentonite migration in geosynthetic clay liners. *Proceedings 6th International Conference on Geosynthetics*, IFAI, St Paul, MN, USA, Vol. 1, pp. 315–320.
- Stark, T. D. & Eid, H. T. (1997). Shear behavior of reinforced geosynthetic clay liners. *Geosynthetics International*, **3**, No. 6, 771–786.
- Tedder, R. B. (1997). Evaluating the performance of Florida double-lined landfills. *Proceedings Geosynthetics '97 Conference*, IFAI, St Paul, MN, USA, Vol. 1, pp. 425–438.
- Terzaghi, K., Peck, R. B. & Mesri, G. (1996). *Soil Mechanics in Engineering Practice*, 3rd edn, John Wiley and Sons, New York, 549 pp.
- Thibodeaux, L. J. (1979). *Chemodynamics*, John Wiley & Sons, New York.
- USACE (1995). *Guide Specification for Military Construction: Geosynthetic Clay Liners—Section 02442*, CEGS-02442, United States Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS, 10 pp.

United States Department of the Navy (1982). *Soil Mechanics*, Design Manual 7.1 and 7.2, NAVFAC DM 7.1 and 7.2, Naval Facilities Engineering Command, Alexandria, VA, USA.

Wilke, C. R. & Chang, P. (1955). Correlation of diffusion coefficients in dilute solutions. *American Institute of Chemical Engineers Journal*, **1**, 264–270.

The Editors welcome discussion in all papers published in *Geosynthetics International*. Please email your contribution to discussion@geosynthetics-international.com by 15 February 2005.