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Thinning Effect Due to Bentonite Migration on Performance of GCL

벤토나이트 유실로 인한 협착이 GCL 거동에 미치는 영향

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ABSTRACT

Recently, geosynthetic clay liners (GCLs) have increasingly been used to replace compacted clay liners (CCLs) in composite liner systems. Since the introduction of GCLs to waste containment facilities, one of the major concerns about their use has been the hydraulic equivalency to CCLs 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 presents field case histories that confirm the laboratory observations of bentonite migration and the effect of bentonite migration on hydraulic equivalency and contaminant transport through a GCL.

요 지

근래에 들어, 복합 라이너 시스템에서 점토차수재를 대신하여 GCL(Geosynthetic clay liner)의 사용이 급증하고 있다. 그러나, 과연 GCL의 수리학적 특성이 점토차수재와 대등하게 매립장 설계규준을 만족 시키는가의 여부는 오래동안 논란이 되어왔다. 실내시험 및 현장조사 결과 여러 가지 원인에 의해 GCL에 응력집중이나 비등방 분포 하중이 생길 때 국부적인 벤토나이트 유실로 팽윤된 GCL의 두께가 감소할 수 있음을 보여준다. 이 논문에서는 현장조사를 통하여 실내시험에서 얻어진 벤토나이트 유실을 확인하고 감소된 GCL 두께에 대한 수리학적 특성을 분석했다.

Keywords : GCL, CCL, Bentonite, Chloride, TCE

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

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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 and Anderson 1996). Koerner and Daniel (1995) conclude that GCLs are hydraulically equivalent to CCLs if puncture and bentonite thinning do not occur. Stark et al. (2004) showed the effect of bentonite migration in case of 2 mm and 7 mm thick GCL.

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 uncontained 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.

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. During hydrotesting, i.e., filling of the ponds with water before placing the ponds 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 1 shows the GCL after removal of the cover soil and it shows that 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 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 that require the subgrade soils to have at least 80 percent of the soil finer than 0.2 mm (#60 sieve) and no sharp rocks larger than 50 mm.

Fig. 1. GCL overlying an incompatible subgrade (from Peggs and Olsta 1998)

Figure 2 shows the base of the sump area of municipal solid waste landfill in the western US 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 3 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. The cause of the bentonite migration may be one or more the following mechanisms: (1) gravity flow or migration of the bentonite down the 24 degree sideslopes, (2) lateral pressure exerted by the ponded water forcing the bentonite down the sideslope, (3) washing of the bentonite down the sideslopes by leakage through liner defects, and/or (4) these mechanisms enhanced by variability of needle-punching in the GCL. Figure 4 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 4 the GCL and overlying geomembrane are visible and bentonite can be seen exiting the GCL.

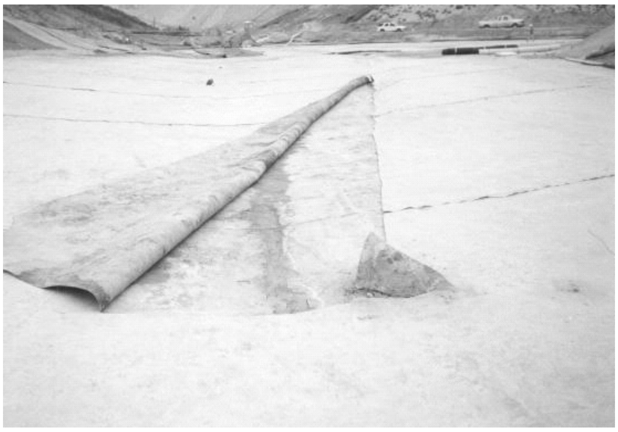

Fig. 2. Layer of hydrated bentonite on top of geomembrane on cell base after removal of overlying sacrificial geomembrane.

Fig. 3. Close-up of hydrated bentonite accumulated on top of geomembrane on cell base after removal of overlying sacrificial geomembrane.

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

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 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

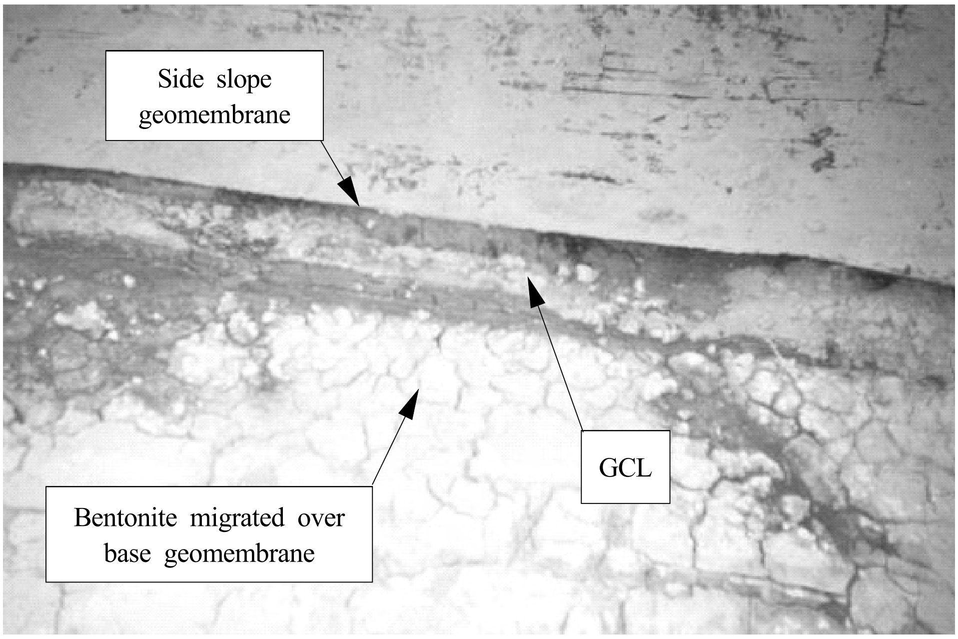

Fig. 4. Cross-section of side slope liner system near cell base showing from top to bottom the 1.5 mm thick HDPE geomembrane, hydrated GCL, and bentonite covering the geomembrane on the cell base.

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:

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

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

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

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 0.7 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 5 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 0.7 mm the required GCL hydraulic conductivity for equivalency ranges from about 0.35 to 0.31 × 10^{-11} m/s for a 0.6 m and 0.9 m thick CCL,

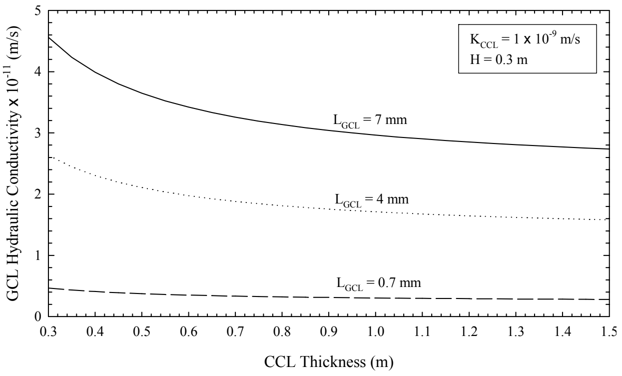

Fig. 5. Effect of hydrated bentonite thickness on required K_{GCL}base on steady water flux equivalence.

respectively. Therefore, the GCL hydraulic conductivity must be approximately 10 times lower if the GCL thickness decreases from the manufactured thickness of 7 mm to 0.7 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.

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:

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

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:

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

Therefore, the advective mass flux ratio is identical to the water flux ratio, i.e., 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 5, a hydraulic conductivity of 0.35 to 0.31 × 10^{-11} m/s is required for a GCL that has thinned to 0.7 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).

3.3 Steady Diffusion

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

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

where J_D is the diffusive mass flux [mg/s/m^2], D^* is the effective diffusion coefficient [m^2/s], ne 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:

$$D^* = \tau D^0 \tag{7}$$

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 1993; 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 ismainly affected by the viscosity of the liquid. Theoretical and/or empirical expressions for $D^0$are found in references such as Grathwohl (1998), Hayduk and Laudie (1974), 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℃ (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℃ (Thibodeaux 1979) and 7.2×10^{-10} m^2/s in water at 27℃ (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.

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

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

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 FD is less than unity, there is more

Table 1. Typical material properties for CCL and GCL.

Barrier	Effective porosity, n_e	Tortuosity factor,	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}

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:

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

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 6. 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 0.7 mm by bentonite migration, the steady diffusive mass flux ratio increases to 397 and 596 for a CCL thickness of 0.6 m and 0.9m, respectively.

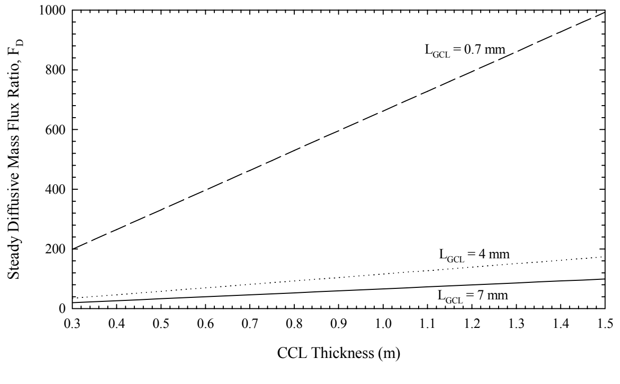

Fig. 6. Effect of hydrated bentonite thickness on steady diffusive mass flux ratio for both chloride and TCE

Therefore, bentonite migration causing a thickness reduction from 7 mm to 0.7 mm will significantly increase the amount of diffusive mass flux through the GCL by a factor of 9 to 10, 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.

3.4 Advective-Dispersion

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

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

where T is the time factor [dimensionless] and P is the Peclet number [dimensionless] 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-dispersionanalysis are illustrated in Figure 7 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

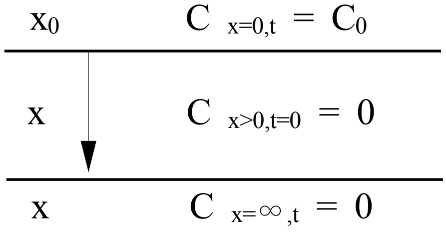

Fig. 7. Initial and boundary conditions used in advective-dispersion analysis.

greater than zero is zero, i.e., C (x =∞; 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 (Daracian) 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:

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

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

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 8 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 0.7 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 0.7 mm thick GCL to be 6.5, 0.0084, and 0.000085 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 0.7 mm thick causes a decrease in the time required to achieve a concentration ratio of 0.5 by a factor of about 100.

Figure 9 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 0.7 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 0.7 mm thick GCL to be 291, 0.75, and 0.008 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 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 0.7 mm from 7 mm, there is even more transport through the thinned GCL thanthe 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

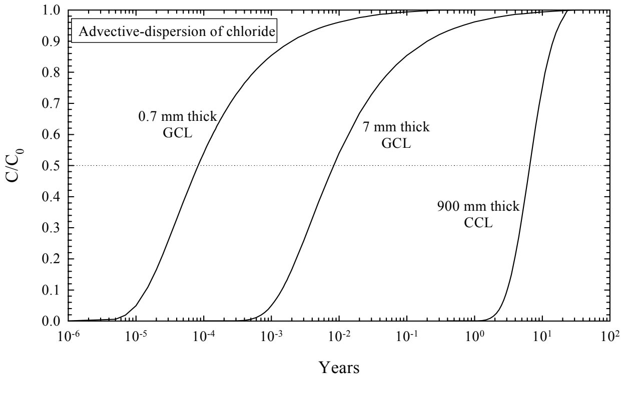

Fig. 8. Effect of hydrated bentonite thickness on reduction of chloride (Cl$^-$) concentration ratio as a function of time at the bottom of the CCL and GCL

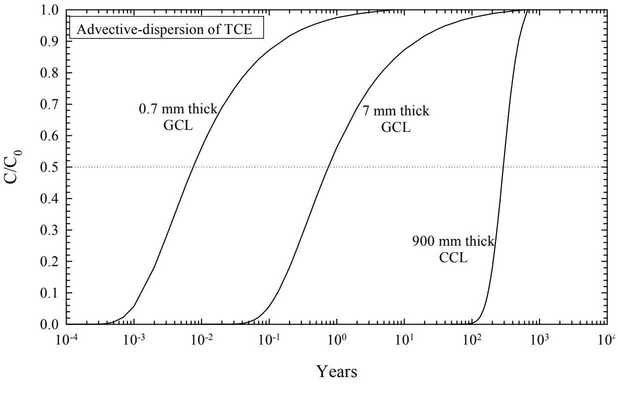

Fig. 9. Effect of hydrated bentonite thickness on reduction of TCE concentration ratio as a function of time at the bottom of the CCL and GCL

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.

4. CONCLUSIONS

Hydrated bentonite can migrate to areas of lower normal stress due to stress concentrations or nonuniform 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 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 0.7 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 becausechloride has a retardation factor of unity, or TCE. If the bentonite migrates and the manufactured thickness decreases from 7 mm to 0.7 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.

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