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Theoretical effect of bentonite migration on contaminant transport through GCLs

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ABSTRACT: Since the introduction of geosynthetic clay liners (GCLs) to waste containment facilities, one of the major concerns about their use has been the hydraulic equivalency to a compacted clay liner. Field observations and laboratory test results show that the thickness, or mass per unit area, of hydrated bentonite can decrease under normal stress, especially around zones of stress concentration, such as a rock or roughness in the subgrade, a leachate sump, or wrinkles in an overlying geomembrane. This paper presents the results of steady water flux, steady solute flux, steady diffusion, and dispersion analyses that illustrate the importance of bentonite migration on contaminant transport using the chemical compound chloride. Suggestions for protecting hydrated bentonite from stress concentrations and for reducing contaminant transport are presented.

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 are: (1) 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 engineering properties, (6) more resistance to the effects of wetting/drying and freeze/thaw cycles, (7) increased airspace resulting from smaller thickness, and (8) easier repair during and after installation. Some of the disadvantages of GCLs versus CCLs include: (1) a potential for lower internal and interface shear strength, (2) a possible large post-peak strength loss in reinforced GCLs, (3) lower puncture resistance, (4) smaller leachate attenuation capacity, (5) shorter containment time, (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) and, 7) chemical transport and alterations. Koerner and Daniel (1995) conclude that GCLs could be considered 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 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).

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, a fine gravel, and a medium gravel. They recommend an H/D ratio between 1 and 2 to protect the GCL for this range of cover soils. The U.S. Army Corps of Engineers (United States 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.

The thickness of hydrated bentonite also may decrease under nonuniform 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, 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.

The presence of wrinkles in an overlying geomembrane creates zones of nonuniform 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 nonuniform 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 can lead to stress concentrations.

Anderson and Allen (1995) and Anderson (1996) showed that the thickness of a hydrated GCL could 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. The hydrated bentonite migrated toward the void under the geomembrane wrinkle where the normal stress was at or near zero. The thickness of the GCLs under the wrinkle was 20 to 25 mm while the thickness farthest away from the wrinkle was approximately 2.0 mm. The nominal manufactured thickness of the GCL was 7.0 mm. One limitation of this compression test is that the normal stress of 958 kPa was applied at an average rate of 4.5

kPa/min and thus the normal stress of 958 kPa was achieved in approximately 3.5 hours. This loading rate is faster than typical landfilling and thus some consolidation of the bentonite could have occurred if the loading simulated field loading conditions. However, consolidation still would not have occurred under the wrinkle at a slower loading rate because the applied normal stress could not influence the bentonite under the wrinkle. Therefore, any consolidation that might occur would occur outside of the wrinkle. The presence of unconsolidated bentonite adjacent to consolidating bentonite will probably result in bentonite migration towards the wrinkle, but possibly a smaller amount, even at a slower loading rate. As a result, the transport analyses described subsequently will investigate the affect of reducing the bentonite thickness from 7.0 to 2.0 mm to represent a worst case scenario.

3 CONTAMINANT TRANSPORT THROUGH A GCL

This section describes the four analyses, steady water flux, steady solute flux, steady diffusion and mechanical dispersion, used to investigate the effect of bentonite migration on contaminant transport through GCLs and the hydraulic equivalence between CCLs and GCLs. Because of space constraints, unsteady diffusion is not covered in this paper.

3.1 *Steady Water Flux and Steady Solute Flux*

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 given as:

$$V = K\left[\frac{H+T}{T}\right] \tag{1}$$

where K is the saturated hydraulic conductivity, H is the depth of liquid ponded above the layer, and T is the thickness of the layer. Koerner and Daniel (1995) suggest that hydraulic equivalency between a CCL and GCL for steady water flux can be expressed as $V_{GCL} = V_{CCL}$ which can be used to solve for the required hydraulic conductivity of the GCL using:

$$K_{GCL} = K_{CCL}\left[\frac{T_{GCL}}{T_{CCL}}\right]\left[\frac{H+T_{CCL}}{H+T_{GCL}}\right] \tag{2}$$

This expression was used to estimate the value of K_{GCL} required for steady water flux equivalency for various values of CCL thickness, i.e., T_{CCL}. The analysis assumed a regulatory CCL thickness of 0.3 m, saturated hydraulic conductivity, K_{CCL}, of 1 x 10^{-9} m/s, and a maximum depth of liquid ponded above the GCL of 0.3 m. The thickness of the GCL, T_{GCL}, was varied from 7 mm to 2 mm to estimate the required saturated GCL hydraulic conductivity, K_{GCL}, for various CCL thicknesses. From Figure 1 it can be seen that for a 0.6 m and 0.9 m thick CCL, the GCL hydraulic conductivity must be approximately 4.5 and 3.5 times, respectively, less than if the GCL thickness decreases to 2 mm versus an initial thickness of 7 mm. However, a hydraulic conductivity of less than 1 x 10^{-11} m/s is probably still achievable with existing GCLs (Gleason et al. 1997). Therefore, bentonite migration does not seem to preclude equivalency in terms of steady water flux.

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

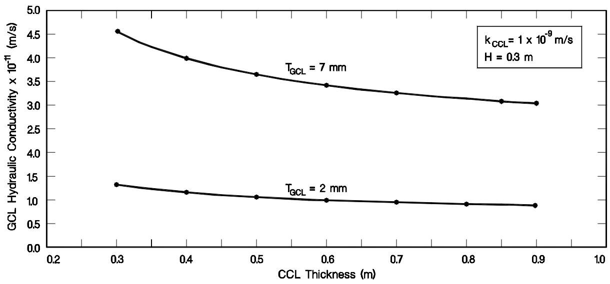

Figure 1. Effect of bentonite thickness on required K_{GCL} based on steady water flux equivalence

$$V_{m,A} = C_{leachte}(K)\left[\frac{H+T}{T}\right] = C_{leactate}(V) \tag{3}$$

where $V_{m,A}$ = the advective mass flux [m^3/s]; and $C_{leachate}$ = the concentration of solute in leachate [mg/l].

The advective mass flux ratio, $F_{m,A}$, is the mass flux of solute through a GCL divided by the mass flux of solute through a CCL as shown below:

$$F_{m,A} = \frac{V_{m,A}(GCL)}{V_{m,A}(CCL)} \tag{4}$$

Therefore, the advective mass flux ratio is identical to the steady water flux ratio, i.e., $V_{GCL} = V_{CCL}$ or V_{GCL}/V_{CCL}. Therefore, if equivalency is demonstrated in terms of steady water flux, equivalency is also demonstrated in terms of steady mass flux of the solute. Figure 1 shows that a hydraulic conductivity of 1 x 10^{-11} m/s is required for a GCL that has thinned to 2 mm. This hydraulic conductivity is probably achievable with current bentonite (Gleason et al. 1997) and thus a thinned GCL should not preclude equivalency in terms of steady solute flux. If the regulatory requirement is a saturated hydraulic conductivity for the CCL less than 10^{-9} m/s, e.g., in Germany, equivalency will not be satisfied with a GCL having a hydrated bentonite thickness of 2 mm.

3.2 *Steady Diffusion*

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

$$J_D = D^*(\eta)\left[\frac{\Delta C}{L}\right] \tag{5}$$

where D* = diffusion coefficient [m^2/s]; η = porosity; ΔC = concentration change or the concentration at point A minus the concentration at point B; and L = thickness [m].

The steady diffusive flux ratio, F_D, is then defined as:

$$F_D = \frac{(J_D)CCL}{(J_D)GCL} \tag{6}$$

Therefore, if F_D equals unity, the steady diffusive fluxes for the CCL and GCL are equal. If F_D is greater than unity, there is more diffusion through the CCL than GCL. Conversely, if F_D is less than unity, there is more diffusion through the GCL than CCL. The steady diffusion analysis was conducted using the following diffusion parameters:

Table 1: Typical Parameters for a GCL and CCL (Daniel, 1998; Shackelford 1990)

BARRIER	EFFECTIVE POROSITY	DIFFUSION COEFFICIENT (m^2/s)
GCL	0.60	1×10^{-9}
CCL	0.37	7×10^{-9}

The chemical compound used in the steady diffusion analysis is chloride (Cl^-) because it has a large diffusion coefficient (4.7×10^{-10} m^2/s) and the retardation factor, R_d, is equal to unity (Shackelford 1990). A retardation factor of unity means chloride is non-absorbing as it travels through a soil. For comparison purposes cadmium (Cd^{+2}) absorbs as it travels through a soil, which results in a retardation factor of 371. Therefore, (Cl^-) represents a worst case scenario because most, if not all, of the compound diffuses through the GCL and CCL. Figure 2 presents the relationship between steady diffusive flux ratio as a function of thickness of the CCL. It can be seen that for a 0.6 m and 0.9 m thick CCL, the value of F_D is 5.6×10^{-3} and 3.4×10^{-3}, 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 flux. If the hydrated bentonite thickness is reduced to 2 mm by bentonite migration, the steady diffusive flux ratio is 1.8×10^{-3} and 8.0×10^{-4} 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 increase the amount of diffusive flux through the GCL by a factor of 3 to 4.

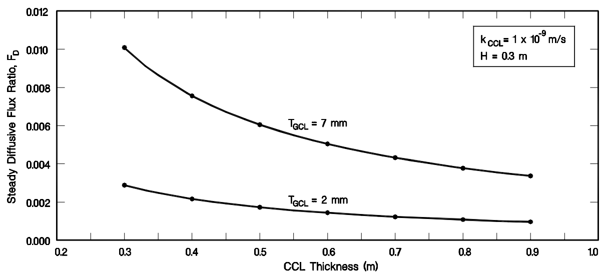

Figure 2. Effect of hydrated bentonite thickness on steady diffusive flux ratio of chloride.

3.3 *Mechanical Dispersion*

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

$$\frac{c}{c_0} = \frac{1}{2}\left[erfc\left(\frac{1-T}{2\sqrt{\frac{T}{P}}} \right) + \left(e^P\right) erfc\left(\frac{1+T}{2\sqrt{\frac{T}{P}}} \right) \right] \tag{7}$$

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

The Peclet number represents the ratio of advective transport to dispersive/diffusion transport. The initial boundary conditions used in the mechanical dispersion analysis are:

1) initial (time, t, equals zero), constant concentration in the soil is zero, where x is the distance in the soil layer, i.e., C ($x \geq 0$; t = 0) = 0,
2) initial, constant concentration of the solute is C_o, i.e., C ($x \leq 0$; $t > 0$) = C_o,
3) 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 mechanical 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:

$$T = \frac{V_s(t)}{L} \tag{8}$$

$$P = \frac{V(L)}{D^*} \tag{9}$$

where V_s = velocity of solute = [m/s]; V = seepage velocity = q/η_e; q = Darcian flow = ki [m^3/s]; η_e = effective porosity = volume of voids conducting flow per unit total volume of soil; and i = hydraulic gradient = (L+H)/L.

Figure 3 presents the concentration ratio, c/c_0, as a function of time for the CCL and GCLs. It can be seen that a concentration ratio of 0.5 is obtained for a CCL, 7 mm thick GCL, and a 2 mm thick GCL after 6.0, 0.009, and 0.0006 years, respectively. This analysis suggests that a 7 mm thick GCL is not equivalent to a CCL in terms of mechanical dispersion. In addition, thinning of the hydrated bentonite to 2 mm thick causes an order of magnitude decrease in the time required to achieve a concentration ratio of 0.5.

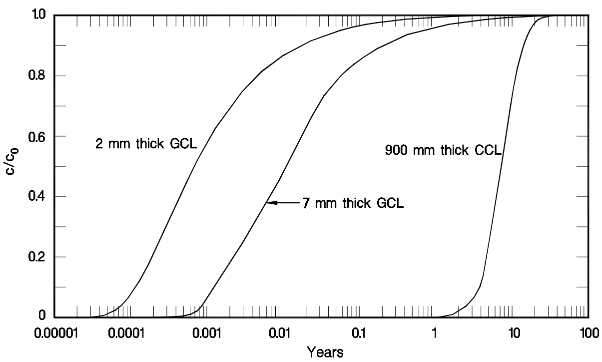

Figure 3. Effect of bentonite thickness on reduction of concentration ratio as a function of time.

4 POSSIBLE SOLUTIONS

A number of possible solutions were considered to reduce the potential migration of hydrated bentonite in a composite liner system to reduce contaminant transport and increase the likelihood of hydraulic equivalence between a GCL and CCL. One possible solution 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 in the GCL. Another solution is to encapsulate the bentonite between two geomembranes to reduce the amount of hydration and thus increase the bearing capacity of the bentonite. This can be accomplished with planar geomembranes or geomembranes with protrusions. 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. Another possible solution involves reducing stress concentrations in the subgrade by smoothing changes in the geometry, reducing ruts, and removing rocks. The geomembrane also should be installed with a limited number of wrinkles. This can be accomplished by using geomembranes that are light-colored (white), exhibit a high interface friction coefficient (textured or PVC), and/or are flexible. Another possible solution is to include an attenuation layer under the GCL to attenuate or remediate any contaminant transport that occurs via diffusion or mechanical dispersion.

Another technique to ensure a minimum long-term thickness of hydrated bentonite is to modify existing GCLs to include an internal structure or stabilizer element (Stark 1997, 1998). The stabilizer element would reduce the compression, and thus lateral squeezing, of hydrated bentonite in response to the stress concentrations in a liner or cover system. The internal structure would also protect the bentonite from concentrated stresses applied during handling, stockpiling, and construction, and may provide additional resistance to accidental puncture. Confining the bentonite in an internal structure provides a better assurance of the thickness or integrity of the hydrated bentonite.

5 CONCLUSIONS

Hydrated bentonite can migrate to areas of lower normal stress due to stress concentrations. 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. The results of steady water flux, steady solute flux, steady diffusion, and mechanical dispersion analyses based on chloride presented herein illustrate the importance of hydrated bentonite thickness on contaminant transport. Because of space constraints, unsteady diffusion was not covered in this paper. In addition, the effect of bentonite migration on organic solvents, hydrocarbons, low dielectric constant fluids are not included but the subject of a subsequent paper.

These analyses suggest that a GCL is hydraulically equivalent to a CCL (hydraulic conductivity of 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 is not equivalent to a CCL in terms of steady diffusion or mechanical dispersion even if the hydrated bentonite does not thin from the manufactured thickness of 7 mm. To reduce the amount of diffusive or dispersive flux through a GCL the initial thickness of the GCL could be increased from 7 mm. If the thickness is not increased, bentonite migration should be minimized to protect the initial 7 mm bentonite thickness and reduce the amount of flux through the GCL.

Possible solutions to eliminate or reduce the 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-colored (white), exhibits a high interface coefficient of friction (textured or PVC), and/or is flexible. Another alternative is to modify existing GCLs to include an internal structure or stabilizer element (Stark 1998). The stabilizer element appears to protect the bentonite from stress concentrations thereby reducing bentonite migration and provide additional puncture resistance.

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