Performance of Double Composite Landfill Liner considering Leakage Rate and Mass Flux

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SYNOPSIS: Performance of a landfill liner is evaluated based on leakage rate and mass flux. In this study, the recently utilized double composite liner system, which consists of a geomembrane (GM), a geosynthetic clay liner (GCL), a GM, and a compacted clay layer (61 or 91.5 cm) is compared with other popular composite liners including the single GCL system, the Subtitle D liner system, and the Wisconsin NR500 liner system. The leakage rate through circular and long defects in the GM of the landfill liners is analyzed using numerical models. For the mass flux criterion, the analyses of inorganic contaminant transport through defects in the GM component of liner systems and diffusion of organic compounds through intact landfill liners are conducted using three- and one-dimensional numerical models, respectively. Cadmium and toluene are used in the analyses as a typical inorganic and organic substance, respectively, which will be chemical species encountered during landfill operation. The comparison shows that the double composite liner systems are superior to the other liner systems according to the performance-based evaluation.

Keywords : composite landfill liner, leakage rate, mass flux, geomembrane, geosynthetic clay liner.

1. Introduction

Leakage rate has been commonly used to evaluate the performance of municipal solid waste (MSW) landfill liner systems. However, several studies suggest that the criterion of leakage rate might not be sufficient for assessing the performance of composite liner systems (Foose et al. 2002). Instead, solute transport should also be considered so the importance of volatile organic compounds is addressed to fully evaluate liner system performance (Foose et al. 2002). In this study, contaminant mass flux from the base of the liner system is calculated and compared with other liner system to evaluate performance of each liner system.

The following three types of composite liner systems are commonly used in MSW landfills, the Subtitle D liner, a GCL composite liner, and the Wisconsin NR500 liner. The GCL composite liner consists of a geomembrane (GM) and underlain by a GCL. The Subtitle D and the Wisconsin NR500 liners consist of a GM and underlain by low permeability compacted soil with thicknesses of ≥61 and ≥122 cm, respectively. This study highlighted the need for a more effective composite liner, which not only possessed a low leakage rate but also a low mass flux for organic and inorganic substances. A double composite liner comprised of a GM/GCL liner and a GM/ low permeability compacted soil layer (61 or 91.5 cm thick), has been recently proposed for several new landfills or landfill expansions to protect important groundwater resources and facilitate permitting. This liner system is believed to exceed all performance requirements for a landfill liner and provide superior performance to the Subtitle D liner, GCL composite liner, and the Wisconsin NR500 liner systems because it combines the benefits of these liner systems, e.g., two GMs, a GCL to reduce advective flow, and a low permeability compacted soil liner to reduce diffusive flow. However, there is no published evidence to demonstrate the performance of this double composite liner system and its performance compared to the Subtitle D liner, GCL composite liner, and the Wisconsin NR500 liner systems. As a result, this paper compares the performance of the proposed double composite liner system to the Subtitle D liner, GCL composite liner, and the Wisconsin NR500 liner systems considering the following two performance criteria: (1) leakage rate and (2) mass flux from the base of the liner system. Analysis of leakage rate is estimated assuming defects in the GM. A solute transport analysis is performed to estimate the mass flux through the double composite liner system using a geomembrane with and without defects.

2. Leakage Rate Estimation

2.1 Leakage rate model

Foose (1997) employed a finite difference numerical program, MODFLOW (McDonald and Harbaugh 1988), to estimate leakage rates through a composite liner with a defective GM. The numerical simulation is useful because it is usually difficult to conduct laboratory and field experiments on the performance of composite liner systems (Foose et al. 2001).

In this study, an upgraded version of MODFLOW, MODFLOW 2000 (Harbaugh et al. 2000), was used to solve the three-dimensional governing equation for flow through the proposed double composite liner system assuming a steady-state condition. The conceptual flow model through two vertically coaxial circular defects in the GMs of a double composite liner system is presented in Fig. 1(a). In addition, the finite difference mesh used for the numerical analysis is shown in Fig. 1(b). The modeling of the composite liners and the boundary conditions were instructed by Foose (1997); Foose et al. (2001, 2002).

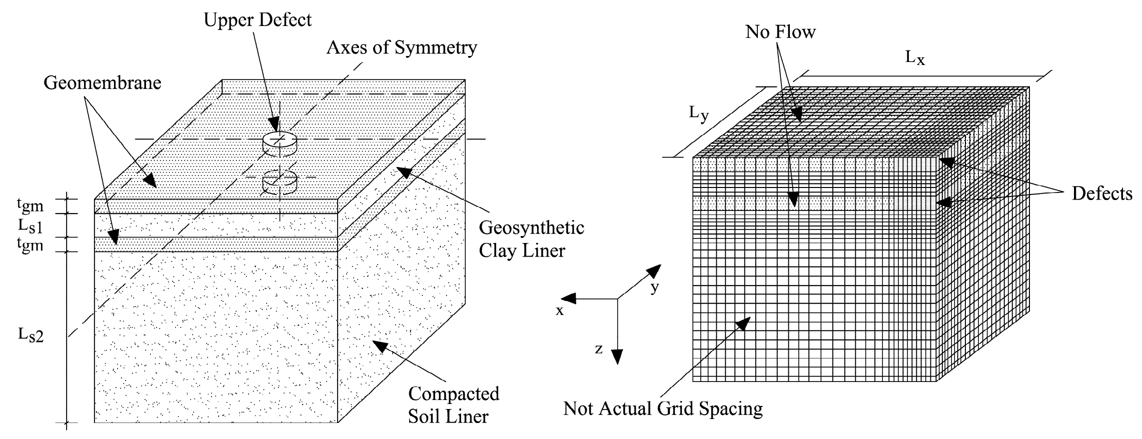

FIG. 1. Numerical modeling of flow through a circular defect in a double composite liner system

Only one quadrant of a circular defect was modeled due to the axisymmetric geometry. Two layers of no-flow cells are modeled to simulate the two layers of GM. To model the worst situation, the two GM defects are assumed to be vertically coaxial. The upper defect was simulated using constant head cells. The constant head assigned to these cells is $h_t = 2t_{gm} + L_{s1} + L_{s2} + h_p$, where t_{gm} = thickness of the geomembrane, L_{s1} and L_{s2} = thicknesses of the GCL and the compacted soil liner, respectively (see Fig. 1 (a)), and h_p = 30 cm = depth of leachate in the landfill. It was assumed that the depth of leachate was constant due to the lack of data about the variation of leachate depth with time and to be conservative. The side boundaries were modeled as no-flux boundaries. The bottom boundary was modeled as a fully draining boundary with a constant head of zero. The geosynthetic and compacted soil liners were assumed to be saturated, homogeneous, and isotropic. The width of the model is 100 cm (L_x = L_y = 100 cm), which is large enough for simulation of flow through defects (Foose et al. 1998).

Two numerical models were developed to consider cases of infinitely and finitely long defects. A two-dimensional numerical model with a unit length in the y direction is used to evaluate the leakage rate through the infinitely long defects in the geomembranes. Only half of the defect width is modeled due to the symmetric geometry. The mesh size in the x- and z-directions is identical to that of the three-dimensional model for circular defects (see Fig. 2(a)). A three-dimensional numerical model is developed to estimate the leakage rates through the finitely long defects in the double composite liners (see Fig. 2(b)). Only one quadrant of a long defect is modeled due to the symmetric geometry. The dimension is large enough for simulation of flow through the defect. Other conditions and parameters are the same as the three-dimensional model of the circular defect.

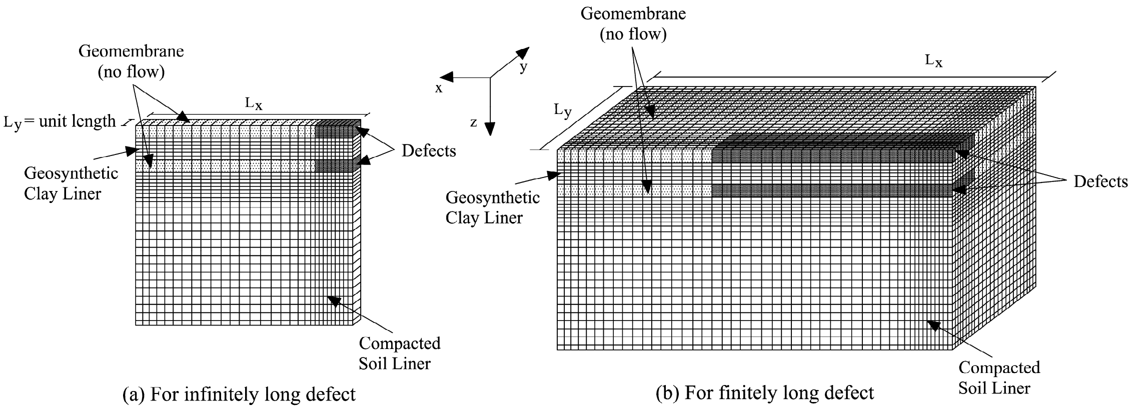

FIG. 2. Numerical models for flow through (a) infinitely and (b) finitely long defects in a double composite liner system

In this analysis, the contact between the GCL/GM system and GM/compacted soil liner system was assumed to be perfect. This assumption is feasible because Walton et al. (1997) found that if the liner is loaded by waste thicker than about 5 m, the flow rate through defects in a composite liner system converges to an analytical solution for leakage through defective composite liners with perfect contact. The modeling is based on the requirement of small mass balance errors and convergence to the analytical solutions for a simple geometry. The hydraulic conductivities of the geosynthetic clay liner and compacted soil liner were selected as 1×10^{-9} and 1×10^{-7} cm/s, respectively. These values represent common regulatory values and data from studies on compacted soil liners (Giroud 1997).

Leakage rates through a defect of the three composite liner systems (see Fig. 3) frequently used in practice are presented in this study and consist of:

1. Subtitle D liner system with 61 cm (2 feet) or 92 cm (3 feet) thick low permeability compacted low permeability soil liner overlain by a GM
2. Wisconsin NR500 Liner which consist of a GM and underlain by low permeability compacted soil with thicknesses of 122 cm (4 feet)
3. GCL composite liner system with a GM underlain by a 6.5 mm thick GCL

4. Proposed double composite liner system consists of four components from top to bottom of GM, 6.5 mm thick GCL, GM, and 61 cm (2 feet) or 92 cm (3 feet) thick compacted soil liner.

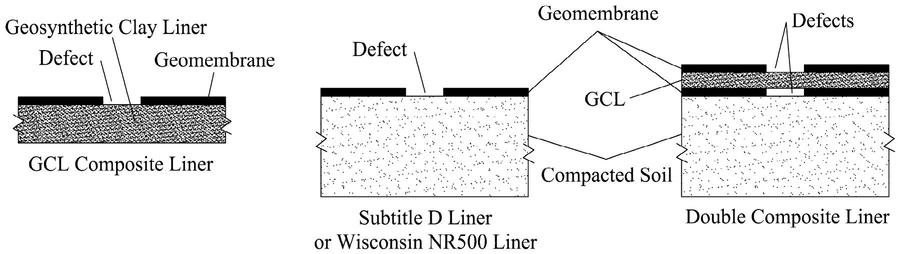

FIG. 3. Profile of GCL composite, Subtitle D required, and proposed double composite liner systems

2.2 Leakage rate evaluation

(1) Circular defects

Fig. 4 compares the leakage rates through circular defects in the composite liner systems and the proposed double composite liner system estimated using MODFLOW 2000. The double composite liner system with a 0.6 or 0.9 m thick soil liner yields significantly lower leakage rates than the Subtitle D liner system. Similar to the case of Subtitle D liners, the thicker the compacted soil liner in the proposed double composite liner system, the slightly higher the leakage rate. The leakage rates for the proposed double composite liner system ranges from 0.86 to 11.94 mL/defect/year for a defect radius of 1 to 6 mm. These leakage rates are comparable with those of the GCL composite liner system.

For comparison purposes only, the leakage rates for a GCL composite liner underlain by an attenuation layer of 0.6 and 0.9 m thick are compared with the proposed double composite liner system having the same compacted soil liner thicknesses. The attenuation layers have a hydraulic conductivity of 1×10^{-5} cm/s (Rowe 1998). Fig. 4 shows the leakage rates of the GCL liners with the attenuation layers are slightly higher than the proposed double composite liner, which shows that the proposed double composite liner system provides a superior performance to the other liner systems considered in terms of leakage rate.

(2) Long defects

Fig. 5 compares the leakage rates through infinitely long defects in the composite liners and the proposed double composite liner system estimated using MODFLOW 2000. The leakage rates through infinitely long defects in the double composite liners are 30 to 40 times lower than those for the Subtitle D liner. The leakage rates for the proposed double composite liner are slightly higher than the GCL composite liner, which is similar for circular defects. A GCL composite liner underlain by an additional attenuation layer of 0.6 or 0.9 m thickness also shows higher leakage rates than the proposed double composite liner. Consequently, the proposed double composite liner system provides the lowest leakage rate for long defects of the liner systems considered.

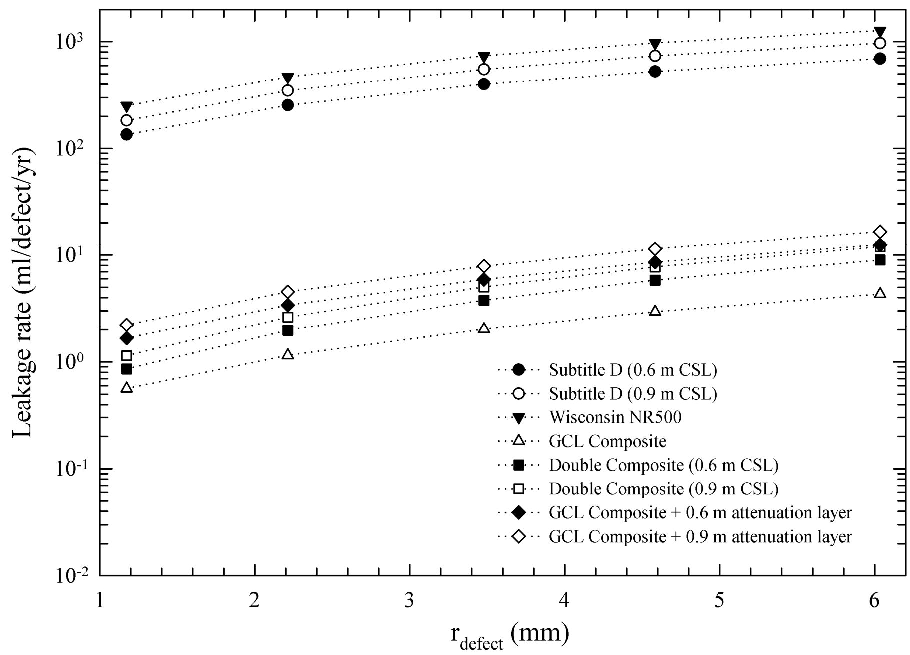

FIG. 4. Leakage rates through circular defects in composite liners with perfect contact

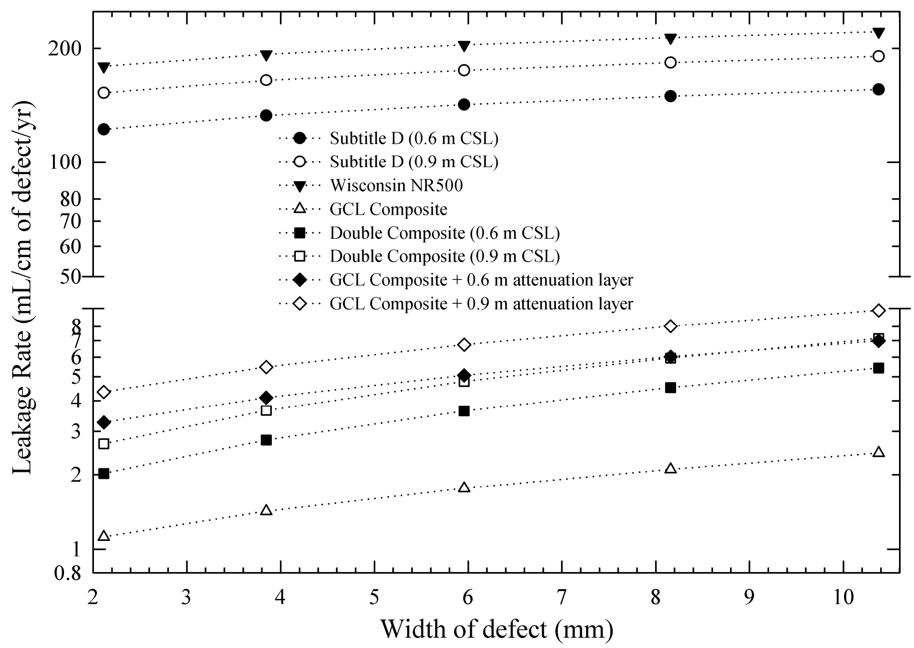

FIG. 5. Leakage rates through infinitely long defects in composite liners with perfect contact

A series of simulations were performed to verify the relationship between leakage rate and defect length for the constant width of 2 mm. The three dimensional model shown in Fig. 2(b) was used for these simulations. The leakage rate of the GCL composite liner is higher than the proposed double composite liner when the defect length is relatively small, and there is a transitional value of defect length at which the GCL leakage rate becomes smaller than the proposed double composite liner (see Fig. 6). The transitional value for a defect width of 2 mm is estimated to be 0.65 m and 0.87 m for the proposed double composite liner with 0.9 and 0.6 m thick compacted soil liners, respectively. Comparing Figures 4 and 6 shows that the leakage rates through long defects are much greater than through circular defects which were also noted by Foose et al. (2001). Therefore, long defects can be a major source of leakage and should be considered in evaluating the performance of landfill liners. In summary, the proposed double composite liner system shows excellent performance compared to the other composite liner systems for both circular and long defects.

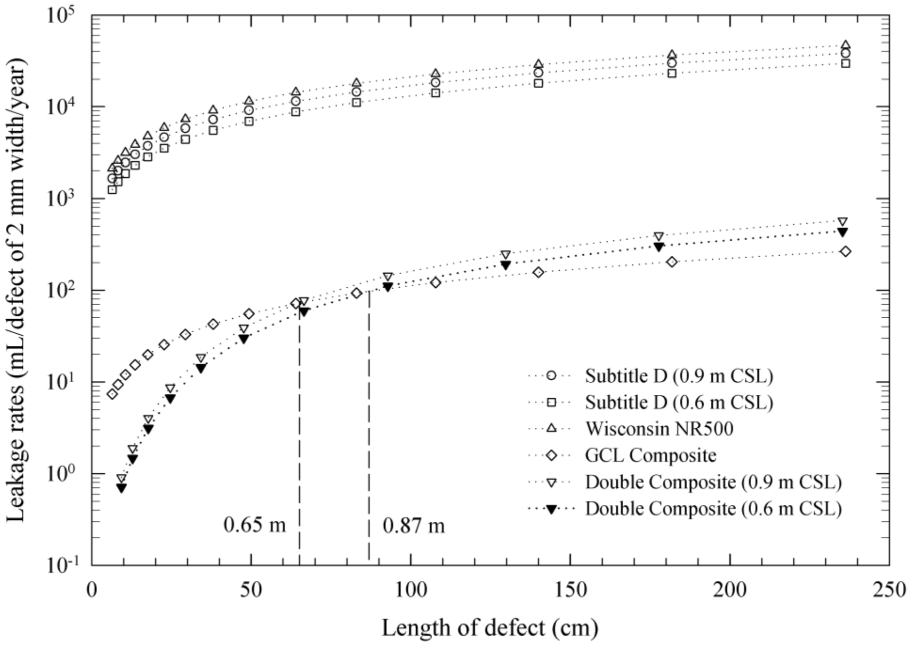

FIG. 6. Effect of defect length on leakage rates with defect widths of 2 mm

3. Solute Transport

3.1 Inorganic solute transport

(1) Inorganic solute transport modeling

Adopting the flow or leakage rate solutions obtained from MODFLOW 2000, the inorganic solute transport through defects in the double composite liner system is simulated using MT3DMS (Zheng 2006), which is a new version of MT3D (Zheng 1992). MT3DMS simulates the solute transport of multiple species in three dimensional groundwater flow systems.

MT3DMS employs the implicit method in solving the governing equation, which is more time efficient than the older version (MT3D). In this study, the cadmium transport through defects in the double composite liner is calculated and compared with the mass flux through the Wisconsin NR500, Subtitle D, and GCL composite liners. The finite-difference used for the flow solution in MODFLOW 2000 (see Fig. 1(b)) was also used in MT3DMS. In the numerical model, the lateral sides and geomembranes are modeled as zero solute flux conditions. The defect in the upper geomembrane and the bottom boundary are modeled as constant solute concentration cells. The constant solute concentration cells in the defect represent a constant solute source which is conservative because leachate solute concentration decreases with time during solute transport. The constant solute concentration of cadmium is fixed to be 100 μg/L. The input parameters can be found in Foose et al. (2002).

(2) Inorganic solute transport results

To calculate the mass flux and cumulative mass of cadmium for one hectare of liner, the values obtained from MT3DMS for one defect are multiplied by 2.5 because Giroud and Bonaparte (1989) recommended the frequency of geomembrane defects is 2.5 defects/ha. The area of circular defects in the GMs of the double composite liner system is selected as 0.66 cm2. The total simulation period is 100 years. Fig. 7 presents the results of the simulation of cadmium transport through defects in the geomembranes of the Wisconsin NR500, Subtitle D, GCL composite, and proposed double composite liner systems. The mass balance errors of the simulations are less than 1%. The three former liners are reanalyzed using MT3DMS with the same input parameters used by Foose et al. (2002) to verify the model develop herein because Foose et al. (2002) used MT3D. The MT3DMS results show good agreement with those in Foose et al. (2002). For the proposed double composite liner, the mass flux from the base of the liners is the smallest during the 100 year period for the four liner systems considered. For the proposed double composite liner with 0.6 m and 0.9 m of compacted soil liner (CSL), the mass flux after 100 years are 3.75 μg/ha/year and 2.12 μg/ha/year, respectively. The comparison shows excellent solute transport performance of the proposed double composite liner systems with extremely small mass flux of cadmium being transported through the liner system.

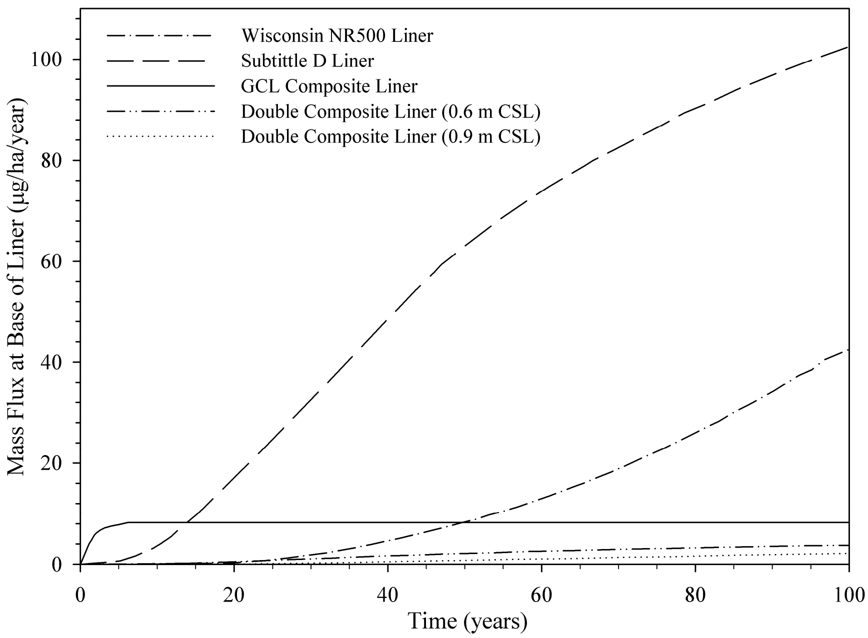

FIG. 7. Comparison of mass flux of cadmium transported through the four landfill liner systems considered

3.2 Organic solute transport

(1) Diffusive transport modeling for organic solute

Fig. 8 shows the transport process of toluene having concentration C_o through the intact double composite liner. The toluene compound in the leachate initially partitions into the upper GM ($C_1 = K_{d,gm}C_o$), then diffuses downward through the upper GM and partitions back into the pore water at the base of the upper GM (C_2). Subsequently, toluene compound diffuses through the GCL layer until partitioning again into the lower GM ($C_4 = K_{d,gm}C_3$). Next, the transport process identical to that through the upper GM and the GCL layer occurs through the lower GM and the compacted clay liner layer.

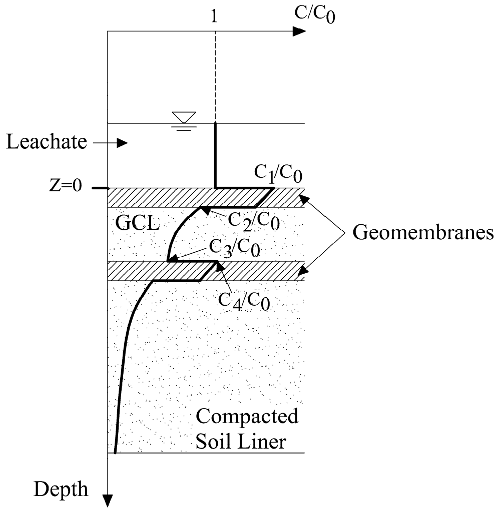

FIG. 8. Concentration profile of transport of toluene in intact double composite liners

The one-dimensional block-centered model of diffusive transport of toluene through intact double composite liners was developed to solve the governing diffusive equations for GM and soil liner layers. In the GM, the concentration of toluene and the coordinate in z-direction are normalized by $K_{d,gm}$ ($K_{d,gm}$ = partition coefficient for the GM and toluene) to account for the large difference between the concentrations of toluene in the GM and soil liner. The explicit method was employed in this model. This approach has an advantage that the interfaces can be handled without difficulty since there is no node on the interface. The bottom boundary conditions for the block-centered models were chosen as previously defined by Foose (1997) and Foose et al. (2002). The constant concentration at the bottom boundary was zero and the locations of it were at the base of the liner or 9 m from the base of liner. In addition, the time of simulations was also selected to be 100 years as in Foose (1997) and Foose et al. (2002).

(2) Organic solute transport results

Fig. 9 shows that the double composite liners are the most effective liners in terms of the mass flow rate of toluene at 100 years for the case of a constant concentration of zero at the base of the liners. The intact double composite liners permit minimum diffusion of toluene among the composite liners. The mass fluxes of toluene through intact double composite liners at the end of the simulation are 1432 and 489 mg/ha/year for the cases of the compacted clay liner layers having thicknesses of 2 and 3 feet, respectively.

For the case of the semi-infinite bottom boundary condition, which can be represented by the bottom boundary at the depth of 9 m from the base of the liner (Foose et al. 2002), the results also show that the double composite liners are most efficient for the landfill constructions (see Fig. 10). With the double composite liner of 2 feet of compacted clay liner, the mass flux after 100 years is almost equal to that for the Wisconsin NR500 liner. In this case, the mass fluxes at the end of the simulation are 445 and 153 mg/ha/year for the cases of the compacted clay liner layers having thicknesses of 2 and 3 feet, respectively.

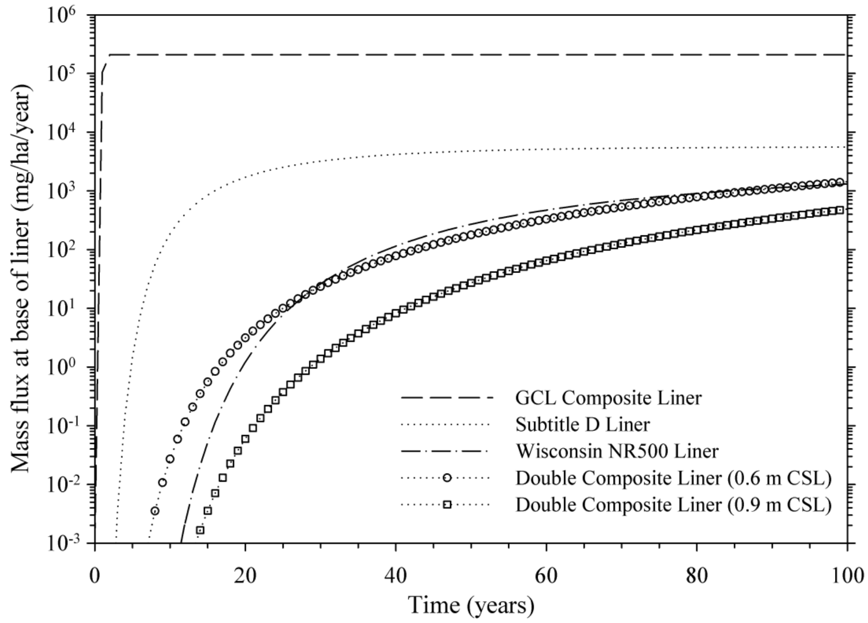

FIG. 9. Mass flux for transport of toluene with concentration at base equal to 0 μg/L

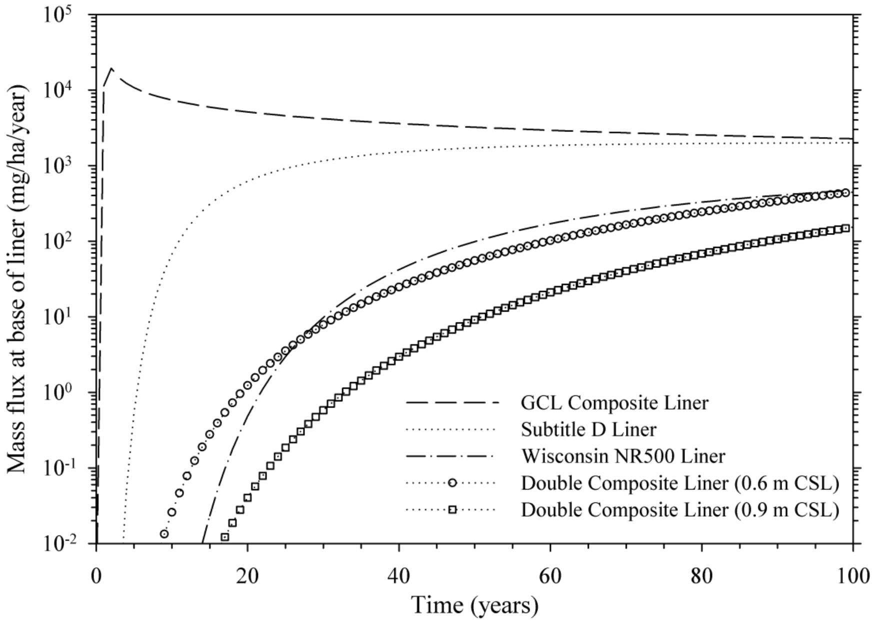

FIG. 10. Mass flux for transport of toluene with semi-infinite bottom boundary condition

4. Conclusions

The performance of the proposed double composite liner system was analyzed and compared to other composite liner systems in terms of leakage rate and mass flux. The numerical models provide a useful approach for evaluating the performance and protectiveness of these and other composite liner systems because there is no field leakage rate and mass flux data published to date for these liner systems. The leakage rates through circular and long defects in the proposed double composite liner are the lower than the Wisconsin NR500 liner and the Subtitle D liner and comparable to the GCL composite liner. To reflect field conditions, the leakage rates of the GCL liner system were also evaluated with an attenuation layer and the rates are slightly higher than the proposed double composite liner, which shows that the proposed double composite liner system probably provide better performance than the other liner systems considered herein in terms of leakage rate.

For the cadmium solute transport analysis, the proposed double composite liner exhibits the lowest the mass flux and cumulative mass of the four liner systems considered. The mass flux and cumulative mass after 100 years of toluene transport through an intact double composite liner is also the smaller than the amounts through the other composite liners. Based on leakage rate, mass flux, and cumulative mass, the proposed double composite liners exhibits the best performance of the four liner systems considered. Transport analyses for other chemical species through the double composite liner system are being performed to evaluate the effectiveness of this system for a wide range of constituents.

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