Two-Dimensional Analysis of Dichloromethane Migration in Landfills with Various Clayey Barrier Systems

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Two-Dimensional Analysis of Dichloromethane Migration in Landfills with Various Clayey Barrier Systems

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Abstract

Engineered sanitary landfills for solid waste are designed and constructed to prevent environmental damage and groundwater contamination. To prevent landfill leachate from penetrating the underlying soil layers, effective contaminant barrier systems must be properly designed and implemented. These barrier systems can be single-liner, double-liner or multi-liner systems. Landfill leachate can migrate into the underlying soil layers through various mechanisms, including advection, molecular diffusion and dispersion leading to environmental pollution and groundwater contamination. The primary function of the contaminant barrier system is to prevent the transport of pollutants and their infiltration into the underlying soil layers of the landfill, making it one of the key components of an engineered sanitary landfill. In this study, the migration of dichloromethane ions from landfill leachate in the lateral and central sections of the landfill, within different clay barrier systems, has been investigated using the MIGRATEv9 software. Comparison of the MIGRATEv9 software results showed that design No. 3, which have the thickest primary and secondary liners and include a geomembrane layer and a geosynthetic clay liner in the barrier system along with compacted clay, perform well in reducing contaminant migration from the landfill base to the groundwater table. Additionally, the presence of an unsaturated natural soil layer along with the barrier system plays a significant role in reducing pollutants.

Keywords: Advection, Molecular diffusion, Dispersion, GCLs, Geomembrane, MIGRATEv9

1.1 Studies conducted on the migration of contaminants through liners

Badv and Farsimdan conducted swelling and molecular diffusion tests on GCL samples and determined the molecular diffusion coefficients for these samples. They concluded that the manufacturing method of GCL had no significant impact on the results of the molecular diffusion coefficient[1].

Giroud et al., through examining and comparing leachate flow rates through Compacted Clay Liners (CCL) and Geosynthetic Clay Liners (GCLs) in landfill barrier systems, demonstrated that the leachate flow rate through GCLs is typically lower than through CCLs due to their lower thickness and much lower permeability. Using Darcy's equation and hydraulic analyses, they showed that hydraulic conductivity (K) and effective thickness (D) are key parameters in barrier system performance[2].

Barroso et al. conducted experiments to determine the flow rate through composite liners, GCLs, GM, and clay liners. They found that pre-hydrating GCLs before testing, considering confined stress, influences the flow rate. While increasing confined stress had little effect on non-hydrated GCLs, it significantly impacted hydrated GCLs. Additionally, they concluded that an increase in hydraulic head above the geomembrane leads to a higher flow rate[3].

2. Methods

2.1 Introduction to the MIGRATEv9

The nineth version of MIGRATE is developed by Rowe and Booker based on the studies published in 1985 and 1994. Its purpose is to simulate pollutant transport [4-7]. It provides analytical solutions for pollutant transport in layers with limited thickness, without requiring step-by-step time computations like common numerical methods. MIGRATEv9 is capable of simulating multilayer systems with different physical and chemical properties, handling complex boundary conditions, and providing fast computations using Laplace and Fourier transforms. It is particularly useful for modeling systems like landfills and chemical leaks, and is a powerful tool for predicting and controlling pollution in long-term, complex projects.

2.2 Assumptions for Modeling Clayey Barrier Liners

The aquifer thickness is assumed to be three meters, and the landfill dimensions are 1000 meters in length and one meter in width. The initial concentration of the contaminant source (dichloromethane ion) is 3300 µg/L, treated as a finite mass. The leachate level above the liner in all examined cases is assumed to be 0.3 meters. The relative density of the waste is considered to be 600 kg/m³, and the relative height of the waste is ten meters. The mass percentage of dichloromethane ions is assumed to be 0.15%. The software analysis starts at time zero, corresponding to the completion of landfill construction. It is assumed that the concentration reaches its maximum at the beginning of the landfill's lifetime, with no further increase in concentration over time, and the increase is measured relative to time zero. Additionally, the lateral length of pollutant transport is considered to be 1000 meters. In Figure 1, a tree diagram for the studied designs is presented.

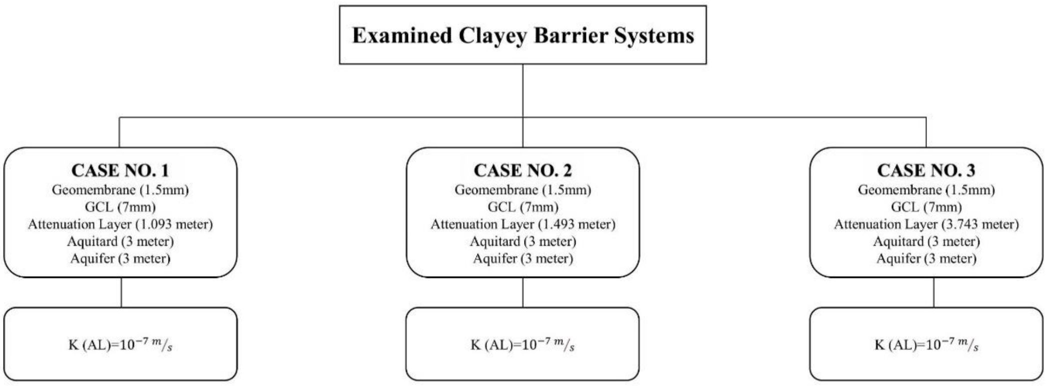


Figure 1. Tree diagram of the studied designs

Table 1 presents the data related to the modeling in MIGRATEv9 software.

Table1. MIGRATEv9 Software Input Data

Parameter	Value
Aquifer Thickness (m)	3
Diffusion Coefficient of Compacted Clay Liner (CCL) (m²/year)	0.02
Diffusion Coefficient of Geosynthetic Clay Liner (GCL) (m²/year)	0.009
Diffusion Coefficient of Attenuation Layer (Natural Soil) (AL) (m²/year)	0.022
Hydraulic Conductivity of Compacted Clay Liner (CCL) (m/s)	1×10^{-9}
Hydraulic Conductivity of Attenuation Layer (Natural Soil) (AL) (m/s)	1×10^{-7}
Hydraulic Conductivity of Geosynthetic Clay Liner (GCL) (m/s)	2×10^{-10}
Porosity of Compacted Clay Liner (CCL)	0.4
Porosity of Attenuation Layer (Natural Soil) (AL)	0.3
Porosity of Geosynthetic Clay Liner (GCL)	0.7
Porosity of Aquifer	0.3
Dry Density of Compacted Clay Liner (CCL) (g/cm³)	1.9
Dry Density of Attenuation Layer (Natural Soil) (AL) (g/cm³)	1.5
Horizontal Inflow Velocity in the Aquifer (m/year)	4
Landfill Length (m)	1000
Landfill Width (m)	1
Initial Dichloromethane Concentration (µg/L)	3300
Thickness of Unsaturated Natural Soil Layer (Aquitard) (m)	3
Diffusion Coefficient of Unsaturated Natural Soil Layer (Aquitard) (m²/year)	0.02
Hydraulic Conductivity of Unsaturated Natural Soil Layer (Aquitard) (m/s)	1×10^{-5}
Dry Density of Unsaturated Natural Soil Layer (Aquitard) (g/cm³)	1.9
Porosity of Unsaturated Natural Soil Layer (Aquitard)	0.3

2.3 Investigation of DCM contamination migration in the lateral direction of the landfill

In the first design, the contamination plume has been analyzed up to a radius of 500 meters from the center of the landfill after 40, 100 years of landfill operation. Figure 2 illustrates the contamination plume in the 40, 100 years after landfill operation for the first design.

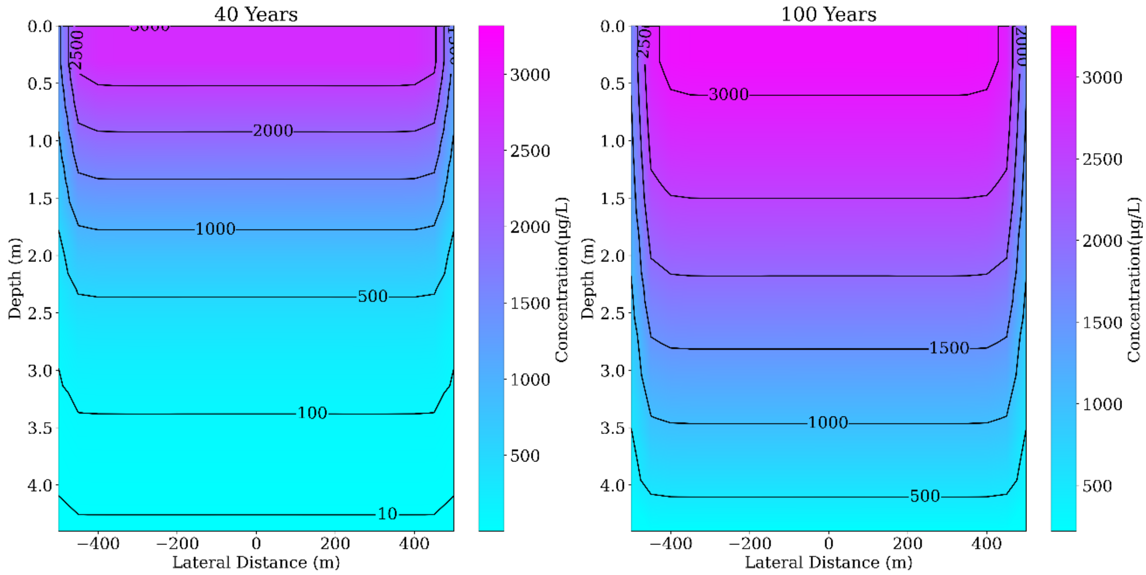


Figure 2. Contour plots and contamination plume of the first design after 40, 100 years of landfill operation

According to Figure 2, after 40 years of landfill operation, the concentration of dichloromethane ions at a depth of approximately four meters in the center of the landfill is ten µg/L, increasing to 500 µg/L after 100 years. Throughout this period, the concentration of the target ion in the aquifer region remains at its minimum level. Additionally, as depth increases, the contamination plume of dichloromethane ions becomes wider, while the concentration gradually decreases and spreads laterally towards the surrounding areas. Furthermore, the maximum concentration occurs in the central area of the landfill, gradually decreasing along the landfill walls as the lateral distance increases. Subsequently, for the second design, the contamination plume has been analyzed up to a radius of 500 meters after 40 and 100 years of landfill operation. Figure 3 illustrates the contamination plume in the 40, 100 years after landfill operation for the second design.

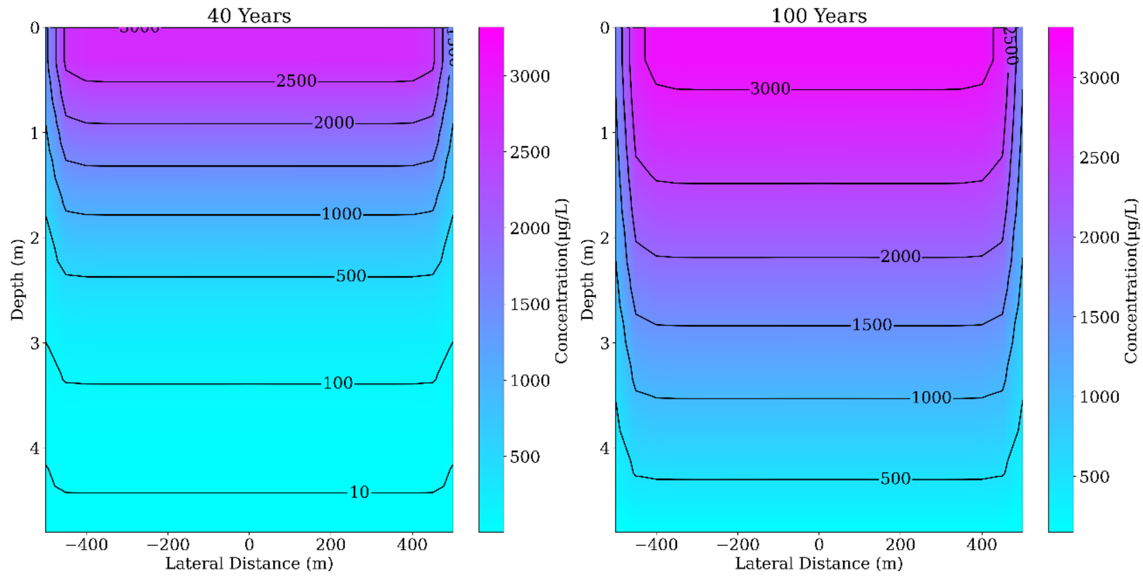


Figure 3. Contour plots and contamination plume of the second design after 40,100 years of landfill operation

According to Figure 3, after 40 years of landfill operation, the concentration of dichloromethane ions at a depth of approximately 4.5 meters in the center of the landfill is ten µg/L, increasing to 500 µg/L after 100 years. Throughout this period, the concentration of the target ion in the aquifer region remains at its minimum level. Additionally, as depth increases, the contamination plume of dichloromethane ions becomes wider, while the concentration gradually decreases and spreads laterally towards the surrounding areas. Furthermore, the maximum concentration occurs in the central area of the landfill, gradually decreasing along the landfill walls as the lateral distance increases. Subsequently, for the third design, the contamination plume has been analyzed up to a radius of 500 meters after 40 and 100 years of landfill operation.

Figure 4 illustrates the contamination plume in the 40, 100 years after landfill operation for the third design.

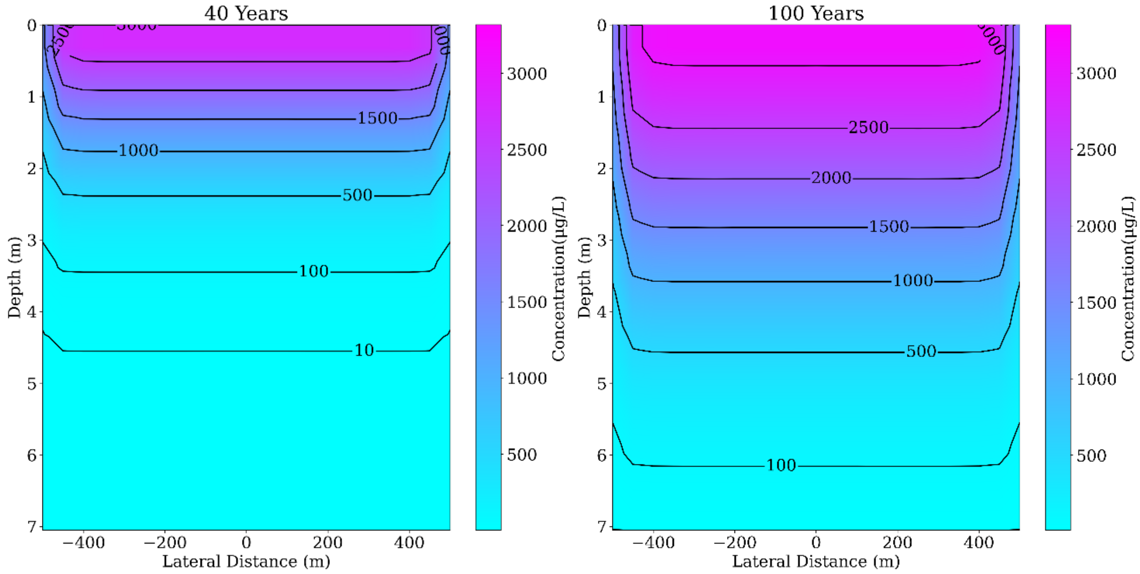
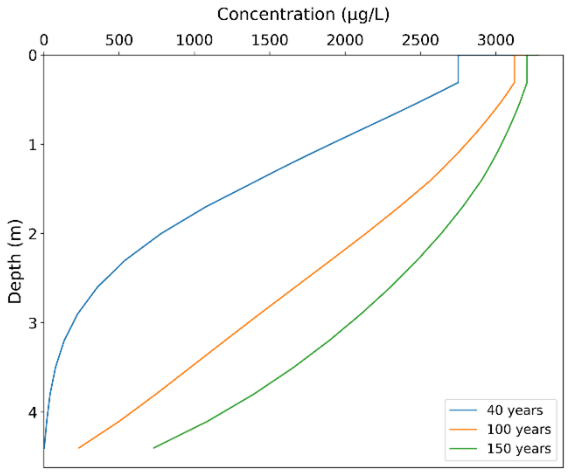


Figure 4. Contour plots and contamination plume of the third design after 40, 100 years of landfill operation

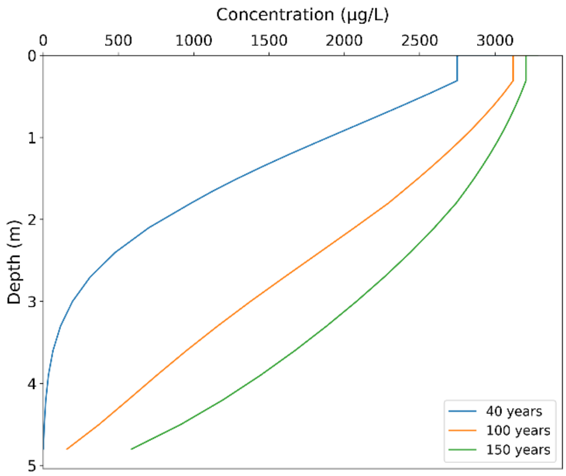
According to Figure 4, after 40 years of landfill operation, the concentration of dichloromethane ions at a depth of approximately seven meters in the center of the landfill remains at ten µg/L, even after 100 years. Throughout this period, the concentration of the target ion in the aquifer region stays at its minimum level, indicating that the landfill liner system effectively prevents significant contaminant infiltration into the groundwater. Additionally, as depth increases, the contamination plume of dichloromethane ions becomes wider, while the concentration gradually decreases and spreads laterally toward the surrounding areas. The highest concentration is observed in the central area of the landfill, where waste decomposition and leachate generation are most intense. As the lateral distance increases, the contaminant levels gradually decrease due to dilution, dispersion, and potential interactions with the liner and surrounding soil, further supporting the effectiveness of the landfill containment system. Figure 4 also demonstrates that in the third design, the concentration of dichloromethane ions is significantly lower at a greater distance from the aquifer region compared to the second design. This improvement suggests that the modifications in the third design have enhanced its ability to limit contaminant migration, thereby providing greater protection for surrounding water resources. The reduced concentration levels at greater depths and lateral distances confirm its superior performance in mitigating groundwater contamination risks. These improvements can be attributed to factors such as the use of more advanced barrier materials, an increased liner thickness, or an optimized permeability structure that reduces contaminant diffusion. Furthermore, the third design may incorporate additional protective layers or engineered enhancements that slow down contaminant transport more effectively than previous designs. By preventing the spread of harmful substances over time, this design ensures that the landfill remains a sustainable and environmentally responsible waste management solution. Overall, the third design offers a more efficient and long-term solution for minimizing the environmental impact of dichloromethane migration, making it a preferable choice for landfill management and groundwater protection.

2.4 The concentration of DCM in different clayey barrier systems at the center of the landfill

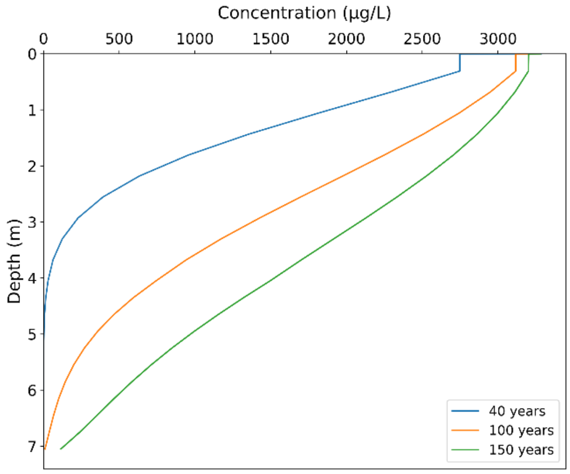
After modeling the first, second, and third clayey barrier systems in the MIGRATEv9 software and performing two-dimensional analysis, the software's output results are presented through concentration-depth graphs of DCM ions at the center of the landfill and the groundwater table at different depths and times (40, 100, and 150 years).



(a) CASE NO.1



(b) CASE NO.2



(c) CASE NO.3

Figure 5. Concentration-depth graph of the first, second, and third design at the center of the landfill

According to Figures 5-a and 5-b, as the depth approaches the groundwater table at approximately four meters, the concentration of dichloromethane (DCM) ions decreases. After 40 years of landfill operation, the ion concentration in the groundwater table reaches its minimum value at depths of 4.4 meters (Figure 5-a) and 4.8 meters (Figure 5-b).

After 100 years, the concentration of DCM ions in the groundwater table remains below 500 µg/L, which is considered an acceptable level. However, after 150 years, a slight increase in DCM concentration is observed, indicating a gradual decline in the effectiveness of the barrier systems over time. Comparing the three systems, the clayey barrier system (Figure 5-b) demonstrates better performance than the first system (Figure 5-a), though their overall behavior remains similar. This suggests that while both systems effectively limit contaminant migration in the short term, long-term efficiency gradually diminishes, highlighting the importance of long-term monitoring and potential reinforcement of the barrier layers. The performance of the third clayey barrier system, compared to the first and second systems, is excellent (Figure 5-c). It can be concluded that in the third design, over different years, the greatest reduction of DCM in the groundwater table is observed.

3. Results and Discussion

3.1. Contaminant Migration Trends in Different Barrier Systems

The movement of dichloromethane (DCM) ions was tracked over 40, 100, and 150 years across three different landfill barrier designs. Figures 2–5 illustrate how the contamination spreads over time, providing insights into the performance of each system.

3.2. Effectiveness of Clayey Barriers in Reducing DCM Contamination

The concentration-depth graphs (Figure 5) provide a clearer picture of how each barrier system influenced DCM migration. The third design consistently exhibited the lowest contaminant concentrations at the groundwater table, confirming that a thicker compacted clay liner combined with a geomembrane and GCL offers the most effective long-term containment.

3.3. Implications for Landfill Design and Regulatory Considerations

These findings reinforce the importance of multi-layer barrier systems in landfill engineering. Many environmental regulations require low hydraulic conductivity ($K < 10^{-9}$ m/s) and optimized diffusion coefficients, both of which were successfully achieved by the third design. Moving forward, landfill designs should prioritize the use of geomembrane and GCL composite liners in combination with compacted clay to improve long-term containment.

Another important factor to consider is the role of the unsaturated natural soil layer, which helped further reduce contaminant migration. This layer should be factored into landfill site selection and design optimization to enhance overall efficiency.

3.4. Limitations and Future Research

While this study provides valuable insights, there are some limitations that should be acknowledged:

- The model assumes constant landfill conditions, whereas real-world scenarios involve fluctuations in leachate composition and flow rates.
- Long-term degradation of barrier materials (e.g., cracking of clay liners, punctures in geomembranes) was not considered, even though such issues can affect containment over time.
- This study used 2D modeling, which simplifies the system. 3D simulations may offer a more precise representation of contaminant migration patterns.

CONCLUSIONS

Two-dimensional analyses showed that as the lateral distance from the landfill center increases, the concentration of the contaminant decreases in the aquifer region, and the presence of a natural unsaturated soil layer after the secondary liner significantly reduces the contaminant concentration at the landfill bottom. Calculations indicate that designing transfer barrier systems based on two-dimensional results improves system performance. Analyses of three different designs revealed that design number three is the most optimal clayey barrier system design, and using clay-geosynthetic liners positively impacts contaminant concentration reduction.

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