Analyzing the Field Performance of a GM-GCL Landfill Bottom Lining System

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ABSTRACT: *With the increase in the use of geomembrane-geosynthetic clay liners (GM-GCL) in landfill barrier systems, extensive research has been conducted on the leakage rate across GM-GCL systems using analytical solutions, empirical equations, and numerical methods. On the other hand, research on comparing the field performance of GM-GCL composite lining system to prediction methods is limited. The objectives of this study were to assess the field-collected leakage rate across a GM-GCL landfill bottom lining system, to analyze its performance against the leakage estimation equations, and to provide an explanation regarding the volume of liquids pumped from the leakage detection system (LDS) using theoretical equations and numerical modelling. The liquids pumped from the leakage detection system of a landfill lined with a GM-GCL double composite system analyzed in this study were relatively high when compared to the results of theoretical equations used in estimating leakage rate. Results of the analysis performed using theoretical equations and numerical modelling indicate that eighty-eight to ninety-eight percent of the liquids pumped from the LDS was as a result of groundwater intrusion from outside of the landfill. Specifically, there is an upward movement of groundwater into the leakage detection system due to the inward hydraulic gradient nature of the landfill.*

KEYWORDS: landfill bottom liners, geomembranes, geosynthetic clay liners, field leakage, numerical model

SITE LOCATION: Undisclosed Location, Florida, USA

INTRODUCTION

In our earlier research, Okine et al. (2023), conducted on the field performance of a landfill lined with a geomembrane-geosynthetic clay liner (GM-GCL) double composite system, we discussed that the probable causes of the relatively high liquid volumes pumped from the leakage detection system were: (1) a higher number of defects in the geomembrane than what earlier researchers have proposed, i.e., 1 cm^2 per acre (4047 m^2) by Giroud and Bonaparte (1989a; b); (2) a high leachate head; (3) an ineffective GCL; and (4) an upward groundwater seepage into the leak detection system (LDS). It was concluded in that paper that the most likely cause of the relatively high liquid volumes pumped from the leakage detection system was an upward groundwater seepage.

A summary of the reasons why the other factors are less likely to cause the high liquid volumes pumped from the LDS are as follows: nine defects, each with an area of 1 cm^2 for every acre (4047 m^2), will need to be assumed in the primary geomembrane to account for the high leakage rate. This is less probable due to the quality control and assurance the Florida Department of Environmental Protection (FDEP) has put in place in the construction of waste containment barriers. Furthermore, a leachate head of 1 m on the primary GM is needed to result in the average of the liquid volumes pumped from the LDS. This is also not likely, as landfill operators are required to maintain a 0.3 m maximum leachate head on the primary geomembrane in Florida. As part of the regular inspections of landfills conducted by the FDEP, operators of landfills are also required to perform periodic jet cleaning exercises to wash out all blockades in the leachate collection

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system (LCS). Having a 1 m leachate head on the primary geomembrane over the 5-year period that the field leakage data was obtained from the landfill is less likely to occur. For the scenario of an ineffective GCL, a hydraulic conductivity of 1.09×10^{-6} m/s must be assumed to have the average field liquid volumes pumped from the LDS (when a good contact condition is assumed for the gap between the GM and the GCL). Research conducted on the effect of aggressive leachates (from landfills that accept municipal solid waste and coal ash) on GCLs showed that the hydraulic conductivity of the GCLs, when permeated with the aggressive leachates, are in the order of $\times 10^{-10}$ m/s (Abichou and Tang, 2019; Li et al., 2019). It is therefore highly unlikely that the relatively high liquid volumes are caused by an increase in the hydraulic conductivity of the GCL.

To further analyze the contribution of groundwater intrusion to the liquids pumped from the LDS, this paper is written as an extension of the findings made in Okine et al. (2023). In this paper, two approaches are used to determine the rate of seepage of groundwater to the LDS. In the first approach, theoretical equations in literature are used to estimate the rate of groundwater seepage across the GCL and defects in the GM. In the second approach, an innovative methodology was developed to numerically model the groundwater intrusion to the LDS using the COMSOL Multiphysics finite element software package.

METHODOLOGY

The liquids pumped from the LDS of an active landfill (landfill accepting waste material) in Florida lined with a GM-GCL double composite system were analyzed in this study. In order to have a better understanding of the volume of liquids pumped from the LDS of the landfill, the elevations of the subgrade and groundwater were obtained and analyzed. The landfill was determined to have an inward hydraulic gradient (i.e., the groundwater level was at a higher elevation as compared to the subgrade level).

The secondary lining system of the landfill understudy is comprised of a GM and a GCL (Figure 1). However, due to the groundwater pressure underneath the secondary GCL, groundwater seeps across the secondary GCL and then through defects in the secondary GM. Therefore, to model the groundwater seepage into the LDS, the water pressure is applied at the base of the GCL. Two approaches were used to compute the rate of groundwater intrusion into the LDS. In the first approach, theoretical equations (Darcys Law, Giroud's equation for computing leachate head on a membrane liner, and Bernoulli's equation) were used to estimate the groundwater seepage into the LDS. A steady state analysis was conducted using the finite element software, COMSOL Multiphysics, to model the groundwater intrusion for the second approach.

For the modelling and the use of theoretical equations, the area of the circular defect on the GMs was 1 cm^2. Concerning the interface contact condition of the gap between the GM and the GCL, the good and poor contact conditions were modelled as per the research conducted by Giroud (1997) and Rowe (1998). The good contact condition is when the soil liner or GCL has a smooth finish and the installed GM has just few waves, whereas the poor contact condition is where there are lots of waves in the GM liner (Bonaparte et al., 1989). A comparison of the field-measured, theoretically calculated, and numerically modelled seepage rates was then conducted.

Theoretical Equations for Predicting Leakage Rates

With the objective of assessing the equivalency of the performance of bottom lining systems, researchers have developed equations for predicting the leakage across single and composite systems used as barriers in the geo-environmental engineering industry (Foose et al., 2001; Touze-Foltz et al., 1999; Rowe ,1998; and Giroud et al. ,1992).

Composite lining systems work effectively because the soil liner complements the upper flexible membrane; leakage that occurs through defects in the flexible membrane liner is impeded by the soil liner with low hydraulic conductivity. One of the major concerns of composite lining systems is the interface condition between the flexible membrane liner and the soil liner which underlies it. Wrinkles develop in GMs as a result of the climatic factors present during installation and the uneven surface of the compacted soil on which the GM is placed (Rowe, 2005). The good and poor interface conditions are used in literature to describe the contact that the flexible membrane liner makes with the soil (Giroud et al., 1989). Equations 1 and 2, proposed by Giroud (1997), are widely used by industry experts when designing landfill bottom systems with a flexible membrane liner overlying a soil liner or GCL.

$$Q_{good} = 0.21\left[1 + 0.1\left(\frac{h}{t_s}\right)^{0.95}\right] a^{0.1} h^{0.9} {k_s}^{0.74} \qquad \text{good contact} \qquad (1)$$

$$Q_{poor} = 1.15\left[1 + 0.1(\frac{h}{t_s})^{0.95}\right] a^{0.1} h^{0.9} k_s{}^{0.74} \qquad \text{poor contact} \qquad (2)$$

Where a is the area of defect, h is the leachate head, k_s is the hydraulic conductivity of soil/GCL, t_s is the thickness of the soil layer/GCL, Q_{good} is the leakage rate for good contact condition, and Q_{poor} is the leakage rate for poor contact condition.

Giroud (1984), as cited in Giroud et al. (1997b), proposed the use of Bernoulli's Equation (Equation 3) to estimate the leakage through defects in a GM sandwiched between soil or geosynthetic material of high hydraulic conductivity. In a subsequent research, Giroud et al. (1997c) observed that Bernoulli's Equation cannot be used in certain scenarios, since the leakage rate through the defects in the GM was more than the leachate impingement rate. Equation 4 was therefore proposed for cases where the head of leachate on the GM is small and/or the hydraulic conductivity of the LCS is lower than assumed in the free flow case (i.e., when using Bernoulli's Equation).

$$Q = 0.6a(2gh)^{0.5} \qquad (3)$$

$$h = \{\frac{aq_i}{2k_{om}\pi} + \frac{Q}{2k_{om}\pi}\left[\ln\left(\frac{Q}{aq_i}\right) - 1\right] + \frac{1}{4g^2}(\frac{Q}{0.6a})^4\}^{0.5} \qquad (4)$$

Where g is acceleration due to gravity, k_{om} is hydraulic conductivity of the layer overlying the GM, Q is leakage rate, q_i is leachate supply rate (impingement rate), a is area of defect, and h is leachate head.

For landfills lined with double lining systems, the leakage that occurs across the secondary soil and/or geosynthetic layer (into subsurface soil or water) is dependent on the rate of leakage across the primary soil and/or geosynthetic layer and the location of the defect in the secondary geomembrane in relation to the area of leachate flow in the LDS, e.g., the wetted area (Giroud et al., 1997a). To compute the leakage across the secondary lining system, Giroud and Houlihan (1995)—as cited in Giroud et al., 1997d—proposed the use of Equations 5 and 6 to compute the average leachate head on the secondary geomembrane.

$$h_2 = \frac{q_i L}{2k_2 tan\beta} \qquad (5)$$

$$q_i = FQ \qquad (6)$$

Where h_2 is the leachate head on the secondary geomembrane, L is the horizontal projection of the landfill length in the slope direction, k_2 is the hydraulic conductivity of the LDS, β is the angle of slope of the lining system, F is the frequency of defects in the membrane liner, and Q is the leakage across the primary lining system.

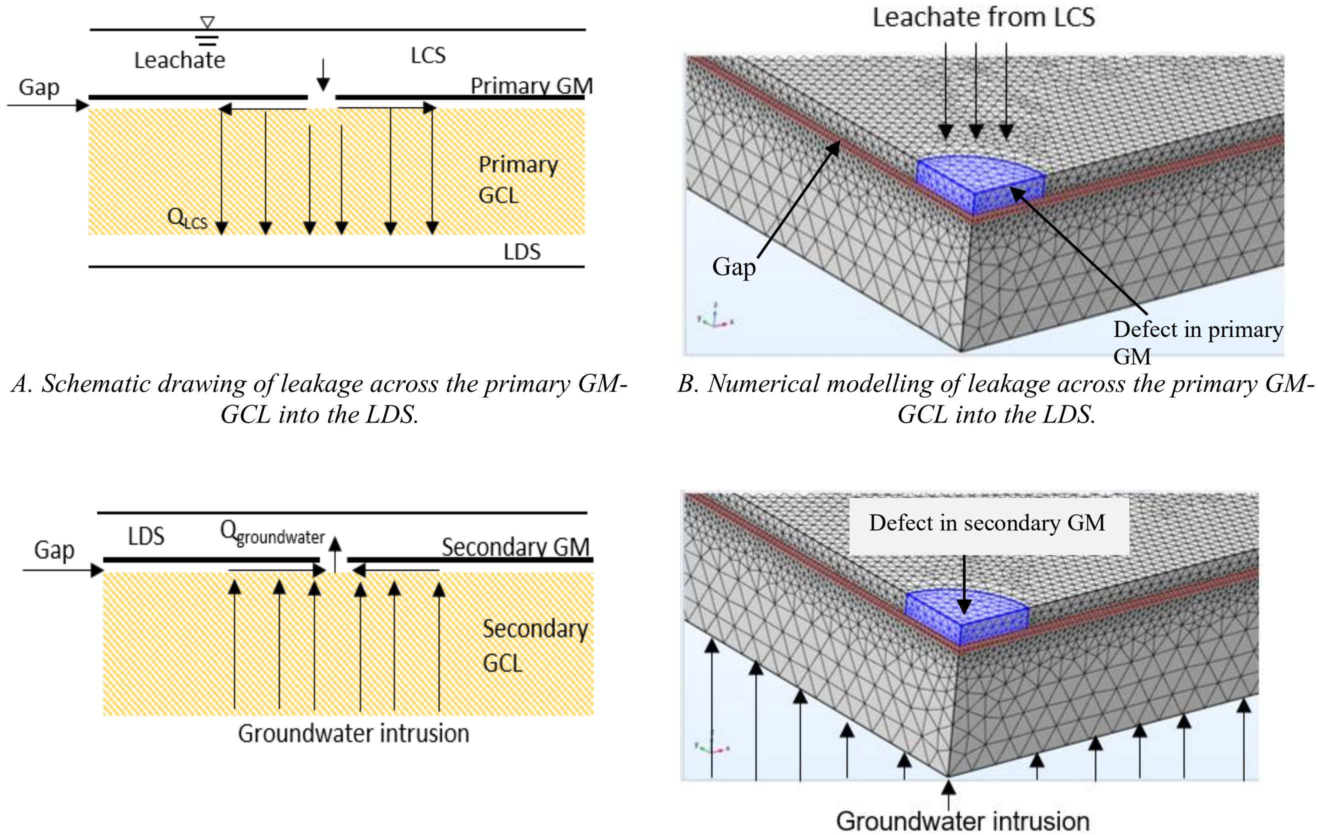
Numerical Simulation of Liquid Seepage Across Primary and Secondary GM-GCLs

COMSOL Multiphysics is a finite element software package which has multiple physical disciplines (multiphysics), and is used for simulating real-world physical phenomena in science and engineering. The laws that govern real-world science- and engineering-related conditions are based on partial and ordinary differential equations, which can be incorporated in the integrated environment provided in COMSOL Multiphysics (COMSOL Multiphysics, 2019). The single and multi-physical categories that can be modelled in the software environment are heat transfer, chemical reactions, structural mechanics, and fluid flow, among others. Modelling in COMSOL Multiphysics can be performed for stationary and transient cases, and for linear and nonlinear studies.

For this study, the steady state fluid flow physical phenomenon was simulated across the various components of the GM-GCL composite lining system. Two separate models were analyzed in this study. In the first model, the primary GM-GCL was simulated to determine the amount of leachate that leaks into the LDS. In the second model, the secondary GM-GCL was simulated with groundwater pressure applied at the bottom of the secondary GCL to compute the groundwater that seeps into the LDS (Figure 1(A-D)).

The workflow used in modeling the conditions at the landfill site are: setting up a 3D model environment, creating geometries to represent the various components of the lining system, and defining the properties of the materials such as the hydraulic conductivity of the GCL. Water with a density of 1,000 kg/m^3 was used to simulate leachate and groundwater flow across the GM-GCL composite lining system in the two cases modelled for this study. In specifying boundary conditions, the no-flow boundary condition was used on the four lateral sides of the model. A leachate head of 0.3 m and a groundwater pressure of 20.8 kPa (corresponding to the 2.12 m head difference) were specified on the surface of the primary GM and underneath the secondary GCL (respectively) in the two models simulated.

The transmissivity of the interface or gap between the GM-GCL used in the modelling are 1.05×10^{-10} and 5.0×10^{-10} m^2/s for the good and poor contact conditions respectively. The hydraulic conductivity of the GCL used in the numerical model was 5.0×10^{-11} m/s (as per the field GCL tested prior to installation using non-aggressive liquid).



A. Schematic drawing of leakage across the primary GM-GCL into the LDS.

B. Numerical modelling of leakage across the primary GM-GCL into the LDS.

C. Schematic drawing of seepage across the secondary GM-GCL into the LDS.

D. Numerical modelling of seepage across the secondary GM-GCL into the LDS.

Figure 1. Simulation of the seepage of liquids across the primary and secondary GM-GCL using the COMSOL Multiphysics numerical model.

LANDFILL DESCRIPTION

The landfill facility used for this study is in southern Florida. The landfill accommodates Class I (municipal solid waste (MSW) and coal ash) and Class III (construction and demolition waste) waste materials. The landfill site lies in a humid subtropical climatic zone with long, hot, and wet summers. The investigation conducted for this research was based on the Class I landfill at the site. As at the time data was collected for this study, the Class I landfill was at the active phase of operation (i.e., still accepting waste material). In 2011, the landfill had an area of 28,800 m^2; the active phase was expanded over the years to an area of 145,687 m^2 in 2016. The daily waste accepted by the Class I landfill was between 2,500 and 5,800 metric tons. The Class I landfill cells are lined with a GM-GCL double composite system. Figure 2 is a schematic drawing of the cross-section of the landfill, showing the various components of the barrier system. The leachate collection and leakage detection systems are designed to maintain maximum leachate levels of 0.3 and 0.1 meters respectively. Liquids pumped from the landfill between July 2011 and March 2016 were investigated for this research study.

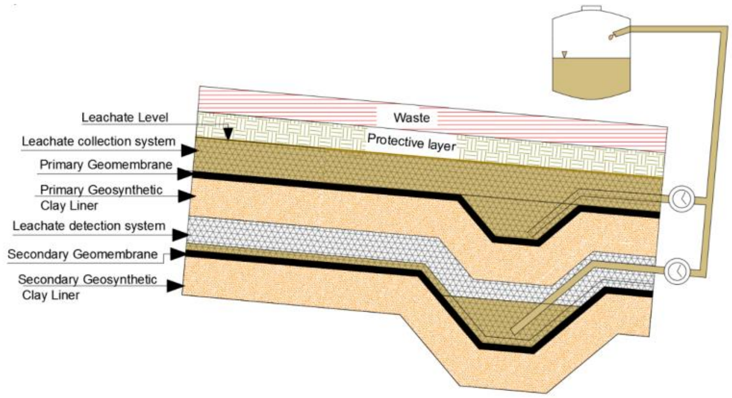
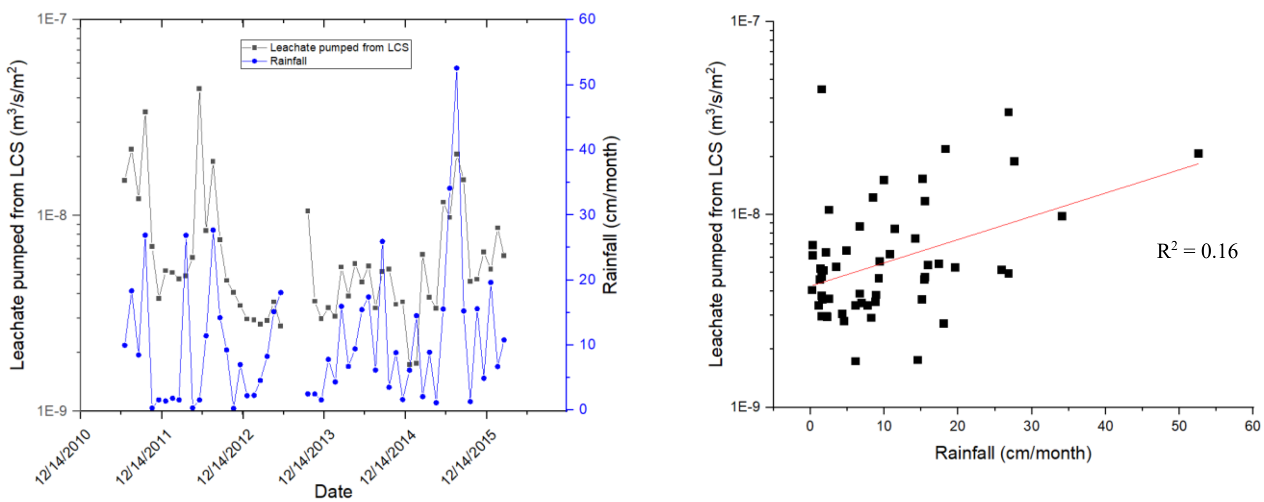


Figure 2. Schematic drawing of the cross-section of the GM-GCL double composite lining system for the landfill (Cell 1).

OBSERVATIONS ON LIQUIDS PUMPED FROM LANDFILL

Figure 3(A) is a comparison of leachate pumped from the leachate collection system (LCS) and rainfall recorded at the landfill. The average leachate pumped from the LCS during the period when data was obtained came out to 8.50×10^{-9} $m^3/s/m^2$ with an average rainfall of 8.5 cm/month. The correlation of the rainfall with leachate pumped from the LCS is shown in Figure 3(B) with a root mean squared value of 0.16. The low root mean square value may be attributed to the different measurement periods for rainfall and leachate pumping, and the time of travel of rainwater through the waste material to the LCS. The rainfall data is recorded daily, whereas leachate is pumped at intervals to maintain the 0.3 m maximum leachate level specification.



A. Rainfall and leachate pumped from LCS. *B. Correlation between rainfall and leachate pumped from LCS.*

Figure 3. A graph of rainfall recorded at the landfill site and leachate pumped from the leachate collection system (LCS), and a graph of the correlation between rainfall and leachate pumped from the LCS.

The field leakage data obtained for Cell 1 of the landfill having a GM-GCL composite system is shown in Figure 4. Between July 2011 and March 2016, an average leakage rate of 2.89×10^{-11} $m^3/s/m^2$ was obtained. The maximum and minimum leakage rates obtained during the period were 3.44×10^{-10} $m^3/s/m^2$ and 2.16×10^{-12} $m^3/s/m^2$ respectively.

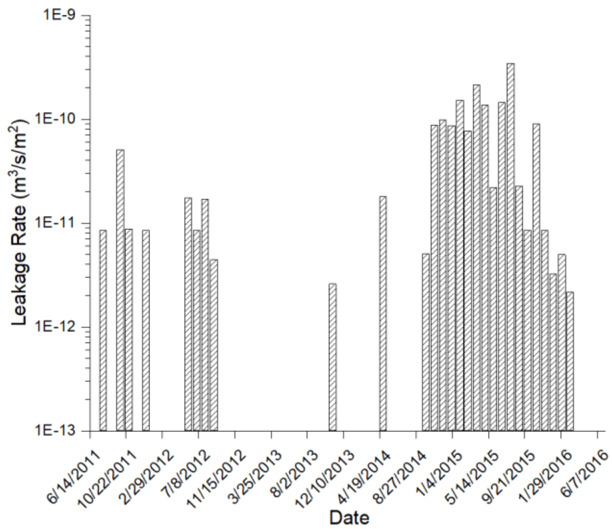


Figure 4. Liquids pumped from the LDS of Cell 1 of the landfill (Okine et al., 2023).

Using Equations 1 and 2, the leakage across a GM-GCL for good and poor contact conditions gives 6.33×10^{-13} and 3.46×10^{-12} $m^3/s/m^2$ respectively (Figure 5). It can be seen that the average field leakage rate is 46 times higher than the estimated leakage rate computed using the good contact scenario of the equation provided by Giroud (1997). For the poor contact condition, the average field leakage rate is 8 times higher. The possible causes of the high liquid volumes pumped from the LDS of the landfill (with a GM-GCL double composite system), as outlined in Okine et al. (2023), are: a higher number of defects in the geomembrane than proposed by researchers Giroud and Bonaparte (1989a, b), a higher leachate head on the primary GM, and ineffective GCL and groundwater intrusion across the secondary GCL and GM. To further investigate the conclusions made in Okine et al. (2023) on the high liquid volumes being attributed to groundwater intrusion into the LDS, the elevation of the subgrade on which the landfill was constructed and the groundwater elevations recorded were obtained and analyzed (Figure 6). Based on the field data recorded at the landfill, the groundwater elevation is on average 2.12 m higher than the subgrade elevation.

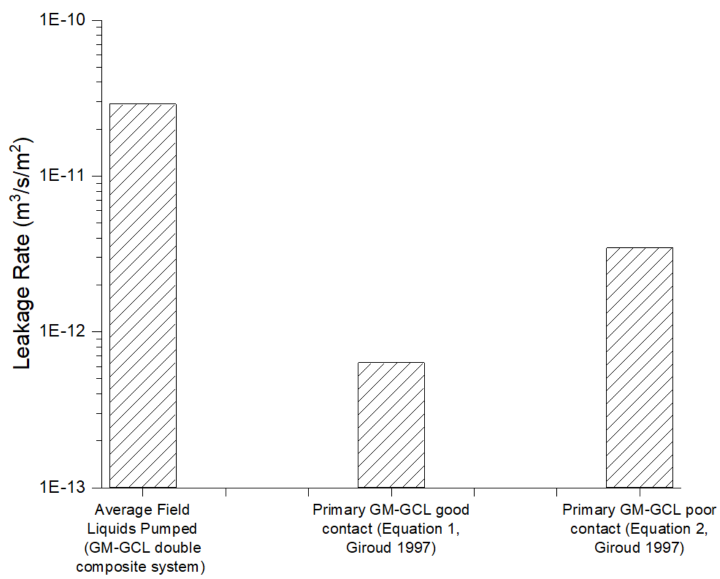


Figure 5. Comparison of the average field leakage rate and the theoretical leakage rates (good and poor contact) using Equations 1 and 2 (Okine et al., 2023).

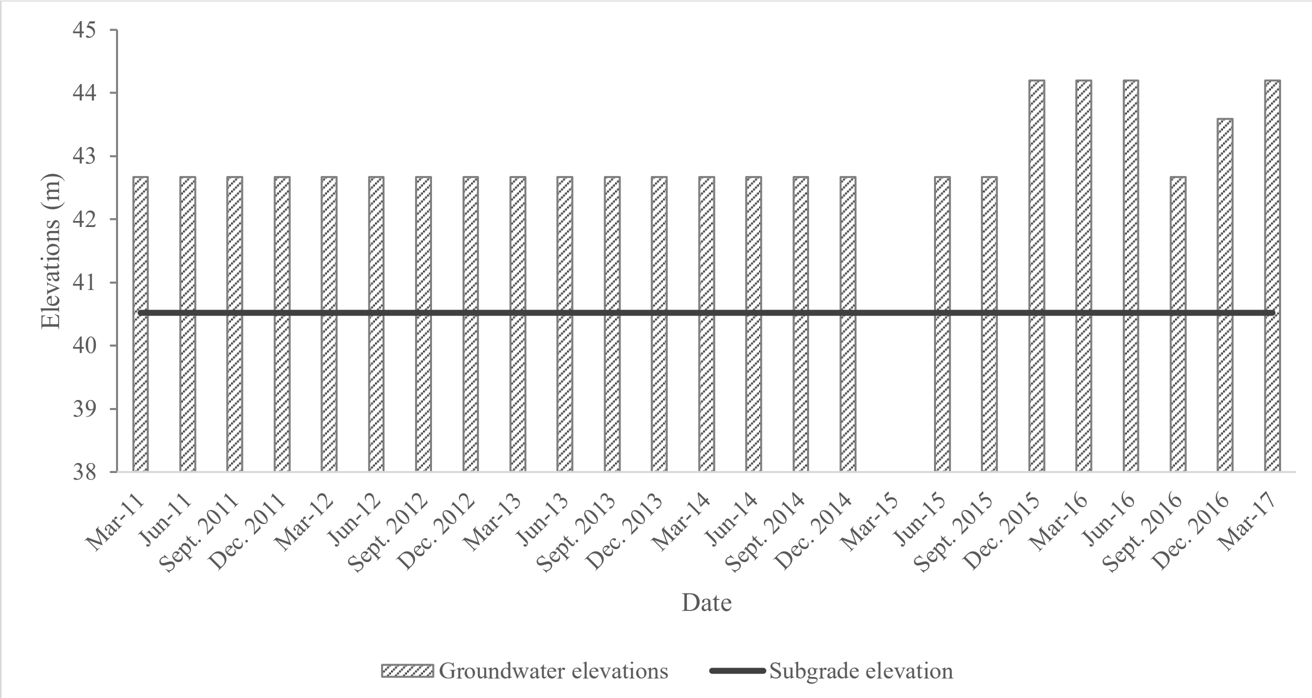


Figure 6. Comparison of the groundwater elevations and the elevation of the subgrade on which landfill is constructed (Reference of elevations – National Geodetic Vertical Datum 29).

ANALYZING GROUNDWATER INTRUSION USING THEORETICAL EQUATIONS

Based on the findings presented in the previous section, theoretical equations in literature were used to estimate the groundwater that seeps across the secondary GCL and GM into the LDS (Figure 7). The secondary GM-GCL composite system was analyzed with a 2.12 m water head on the GCL. The seepage across the secondary GM- GCL composite system was analyzed in three steps. Seepage across the GCL was first computed using Darcy's Law. Equations 5 and 6 were then used to compute the head on the GM based on the seepage across the GCL. Bernoulli's Equation was finally used to compute leakage through a circular defect of area 1 cm^2 in the GM.

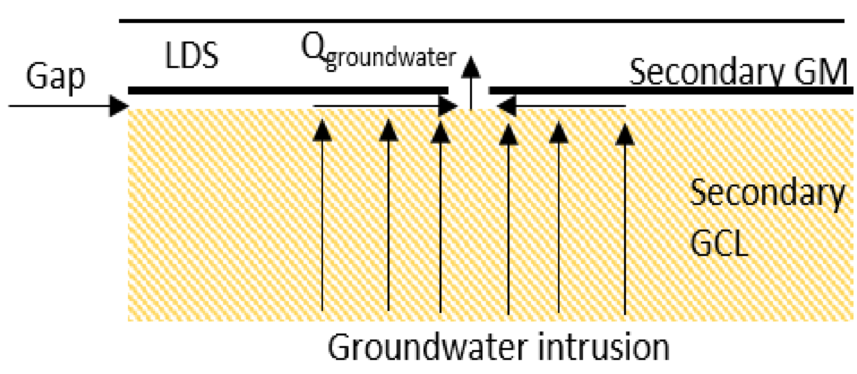


Figure 7. Schematic drawing of the GM -GCL composite system for analyzing groundwater seepage into the LDS using theoretical equations.

In the analysis conducted, the frequency of defects in the GM was taken as 1 defect per 4047 m^2 (1 acre), and the horizontal projection of the landfill length was taken as 45.72 m (150 feet). The hydraulic conductivity of the gap between the GCL and the GM and the slope of the lining system were assumed as 1 m/s and 2% respectively.
The leakage across the secondary GCL computed using Darcy's Law is 4.77×10^{-5} m^3/s. The liquid head on the secondary GM computed using Equations 5 and 6 is 1.35×10^{-5} m. With the liquid head obtained, the seepage through a circular defect in the GM computed using Bernoulli's Equation is 2.41×10^{-10} $m^3/s/m^2$ (Figure 8).

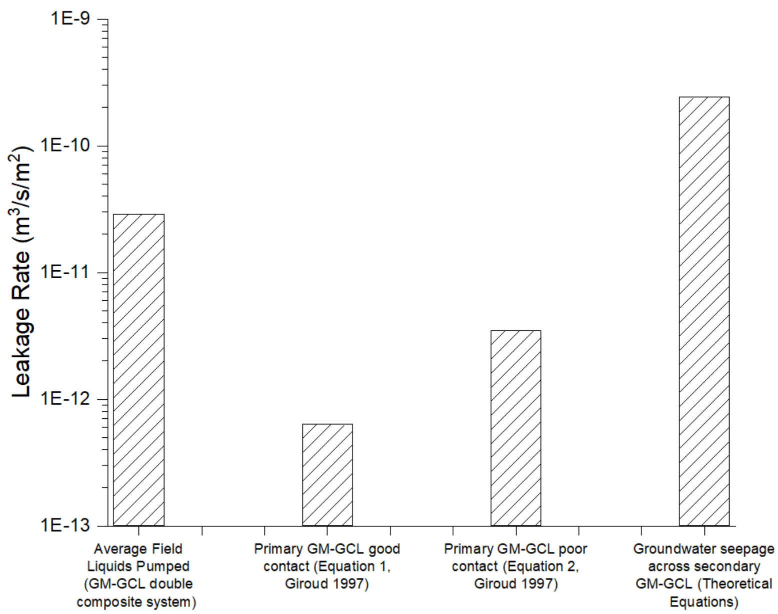


Figure 8. Comparison of the average field liquids pumped from the LDS and theoretical equations used in computing seepage across the primary and secondary GM-GCL lining systems.

ANALYZING LIQUID VOLUMES PUMPED USING A NUMERICAL MODEL

As mentioned earlier, the COMSOL Multiphysics finite element software was used in simulating the seepage of leachate across the primary GM-GCL and the groundwater intrusion across the secondary GM-GCL into the leakage detection system.

Based on the numerical model performed for the leakage across the primary GM-GCL, leakage rates of 6.40×10^{-13} and 3.51×10^{-12} $m^3/s/m^2$ were obtained for good contact and poor contact conditions respectively. In the case of the upward intrusion of groundwater into the LDS, a seepage rate of 8.4×10^{-10} $m^3/s/m^2$ was obtained (Figure 9).

Table 1 is a summary of the results of the analysis conducted using theoretical equations and numerical modelling. It can be inferred that the leakage across the primary GM-GCL is 2% of the average liquids pumped from the LDS for the good contact condition, whereas it's at 12% for the poor contact condition. It can be concluded that the groundwater intrusion into the LDS across the secondary GM-GCL contributes about 88-98% of the liquids pumped from the LDS (for the two methodologies used in analyzing the movement of liquids across the primary and secondary GM-GCL).

The lower groundwater intrusion rates observed at the landfill (when compared to the results of the numerical model and the theoretical equations) may be attributed to defects having an area less than the modelled 1 cm^2 and/or the frequency of the defects being lower than one defect per acre (4047 m^2).

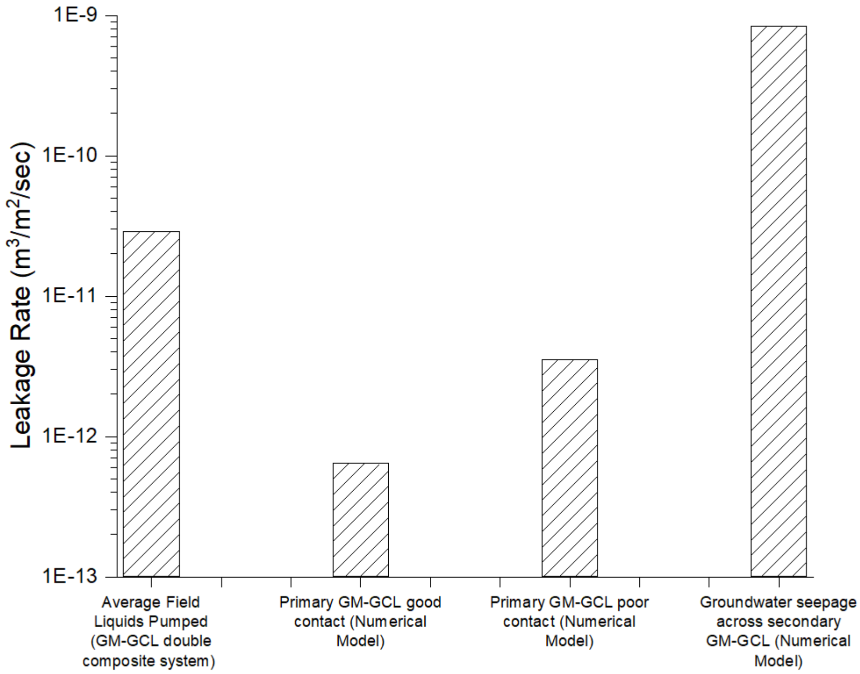


Figure 9. Comparison of the average field liquids pumped from the LDS and the results of the numerical model.

Table 1. Analyzing liquids pumped from the LDS using theoretical equations and numerical modelling.

	Theoretical equations ($m^3/s/m^2$)	Numerical modelling ($m^3/s/m^2$)	Average field leachate pumped from the LDS of the GM-GCL Double Composite System ($m^3/s/m^2$)
Leakage across primary GM-GCL into LDS – good contact condition	6.33×10^{-13}	6.4×10^{-13}	
Leakage across primary GM-GCL into LDS – poor contact condition	3.46×10^{-12}	3.50×10^{-12}	
Seepage across secondary GM-GCL into LDS	2.41×10^{-10}	8.4×10^{-10}	
			2.89×10^{-11}

CONCLUSION

GM-GCL composite systems have been used in lining the base of waste containment systems particularly because of the ease of installation, the low permeability of the material, and the relatively thin GCL material which translates into more waste storage capacity for the landfill. The field performance of the GM-GCL composite lining system was assessed in this study. The field leakage rate for a landfill cell was relatively high when compared to the equations used in predicting the leakage across GM-GCL composite systems.

Research conducted on the hydrogeological setting of the landfill and the subgrade elevations revealed that the landfill had an inward hydraulic gradient. The groundwater levels were 2.12 m higher than the subgrade level during the five-year period leakage data was obtained. Theoretical equations proposed by earlier researchers and the COMSOL Multiphysics finite element modelling software were used to analyze the leakage of leachage across the primary GM-GCL and the upward seepage of groundwater across the secondary GM-GCL into the leakage detection system.

Based on the assumptions made of one circular defect of area 1 cm^2 per 4047 m^2 (1 acre), the results of the use of theoretical equations and the numerical modelling indicate that 2-12% of the liquids pumped from the leakage detection system of the landfill with a GM-GCL double composite lining system can be attributed to leakage across the primary GM-GCL system, whereas 88-98% was a result of groundwater seeping into the leakage detection system.

The groundwater table in Florida is generally known to be a few feet below ground surface in most parts of the state, evidenced by the absence of underground systems and basement floors in most areas. The situation is further compounded by the relatively high rainfall, which translates into seasonal high groundwater levels. Landfills constructed in low lying areas usually have to pump higher volumes of liquids due to the upward seepage of groundwater into the leakage detection system.

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