Hinkley Center
for Solid and Hazardous
Waste Management

The Equivalency of Florida Double Liner System and EPA Composite Liners for Coal Ash Disposal based on Leakage Rate and Mass Transport

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2023 SWANA FL Summer Conference and Hinkley Center Research Forum
July 25th, 2023

Project History

- Project period: Sep 2021 to Feb 2023.
- This project is the Year II of PI Abichou's one-year funded project entitled "Equivalency of Double Liner System for Florida Coal Ash Landfills".
- During the project period, three Technical Awareness Groups (TAG) meetings were held for UCF and FSU teams to showcase the results and gather ideas.
- The UCF had the 1st TAG in Nov. 2021, FSU had the 2nd TAG meeting in May 2022, and UCF and FSU had the 3rd TAG meeting in Feb 2023.

The Research Team at UCF and FSU

Meet the PIs

Dr. Tarek Abichou, Ph.D., PE
Florida State University

Dr. Jiannan Chen, Ph.D.
University of Central Florida

Dr. Debra R. Reinhart, Ph.D., PE, BCEE
University of Central Florida

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Meet the Graduate Students

Leslie Okine (FSU),
Ph.D. Student

Poyu Zhang (UCF),
Ph.D. Student

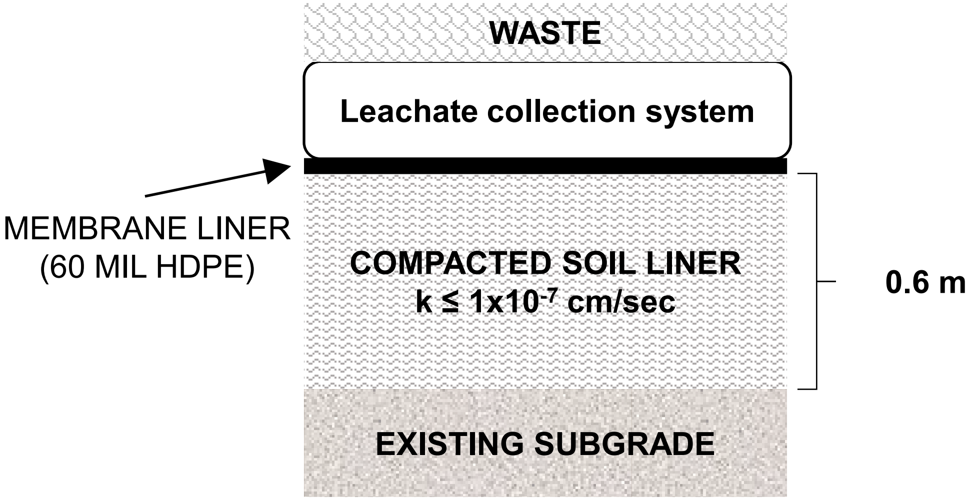
Tim Copeland (UCF),
Ph.D. Student

Overview of Today's Presentation

- Project Rationale and Background
- Research Objectives and Tasks
- Results
    - Field Observation and Modeling for the Equivalency of Florida's Double Liner to EPA Liner
    - Leakage Rate and Mass Transport

Project Rationale and Background

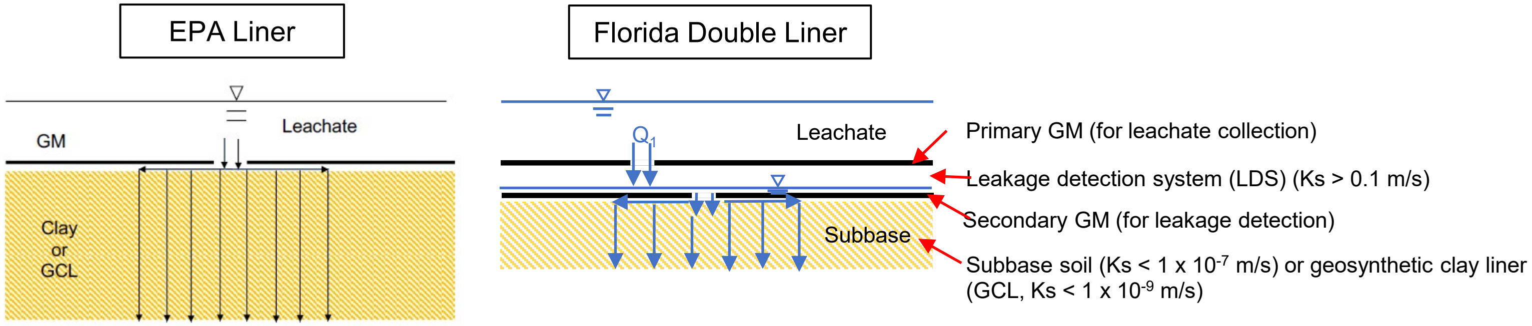
- Federal and state regulations are requiring new CCR landfills, new CCR surface impoundments, and all lateral expansions be constructed with a composite liner.
- The composite liner must consist of two components;
  - an upper component consisting of a geomembrane (GM) liner … and
  - a lower component consisting of at least a two-foot layer of compacted soil with a hydraulic conductivity of no more than 1 x 10^{-7} cm/sec.
  - GM components should consist of (HDPE) and must be at least 60-mil thick.
  - The GM … must be installed in direct and uniform contact with the compacted soil.



EPA Required Liner System

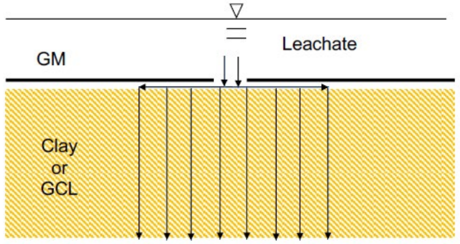
“Liner Designs That Would Not Meet the Requirements of a Composite Liner or Alternative Liner”

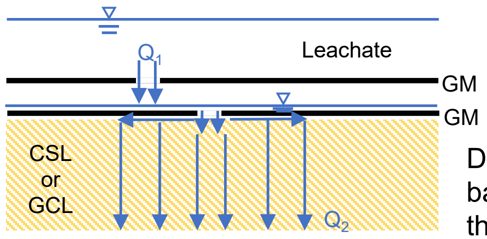
- EPA has also determined that the double liner system set forth in Florida regulations (see Florida Rules 62–701.400(3)(c), F.A.C) also does not meet the level of performance achieved by EPA’s composite liner system or the alternative liner system.
- “the lower composite liner, consisting of a 60-mil HDPE over six inches of soil with a saturated hydraulic conductivity of less than or equal to 1×10^{-5} cm/sec, is not equivalent to a GM over two feet of compacted soil with a hydraulic conductivity of less than or equal to 1×10^{-7} cm/sec.”
- ”….To be hydraulically equivalent, soil with a hydraulic conductivity of 1×10^{-5} cm/sec would need to be on the order of 100 times thicker than soil with a hydraulic conductivity of less than or equal to 1×10^{-7} cm/sec.



Liner Equivalency Demonstration

EPA Liner	Florida's Double Liner	Equivalency: Leakage Rate + Mass Transport





$$Q_1 \approx 1.64(aq_i)^{0.075}h^{1.85}k_{om}^{0.925}$$

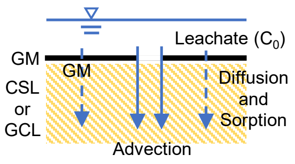
$$Q = \beta_c(1 + 0.1\left(\frac{h_w}{L_s}\right)^{0.95})a^{0.1}{h_w}^{0.9}{k_s}^{0.74}$$

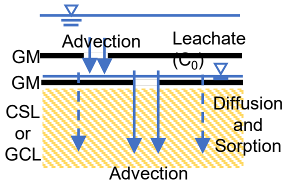
$$Q_2 = \beta_c(1 + 0.1\left(\frac{D_{ave}}{L_s}\right)^{0.95})a^{0.1}{D_{ave}}^{0.9}{k_s}^{0.74}$$

β_c = contact factor (0.21/1.15); D_{ave} = depth of leachate at the leakage detection system; L_s = thickness of liner; a = area of hole; h_w = depth of leachate; K_s = hydraulic conductivity.

Leakage Rage Calculation

Demonstrate *leakage rate* from base of alternative liner no more than conventional liner – *effective in managing leachate*.





$$R\frac{\partial C_r}{\partial t} = \frac{\partial(D_{ij}^*\frac{\partial C_r}{\partial x_i})}{\partial x_i} - \frac{\partial(v_{siC}C_r)}{\partial x_i}$$

$$R\frac{\partial C_r}{\partial t} = \frac{\partial(D_{ij}^*\frac{\partial C_r}{\partial x_i})}{\partial x_i} - \frac{\partial(v_{siD)}C_r)}{\partial x_i}$$

R = retardation factor; C_r = resident concentration of solute in the pore water;
t = time; x_i = distance along the respective Cartesian coordinate; D^*_{ij}= effective diffusion coefficient tensor; and v_{siC} and v_{siD} = seepage velocity in the direction x_i of composite liner and double liner.

Mass Transport

Demonstrate *mass discharge* from base of alternative liner no more than conventional liner – *effective in managing contaminants*.

Research Objectives and Tasks

- Objective 1 - Collecting the leakage rate data from the Florida's class I landfills using the double-liner system, revisiting the double-liner equivalency with new data, liner materials, new approaches.

- Objective 2 - Compare the Florida's double-liner to the EPA composite liner based on the leakage rate, mass flux and transport of contaminants considering the CCR leachate chemistry.

- Task 1 - Field data for the equivalency of Florida's double liner to EPA liner

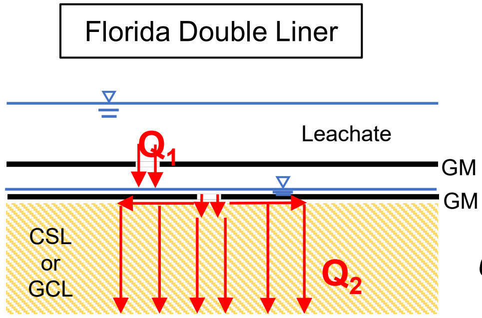
- Task 2 - Numerical simulation for the equivalency of Florida's double liner to EPA liner

Field Data Collection and Analysis

Landfill	Leakage Data Obtained (years)	Landfill	Leakage Data Obtained (years)
Test Site A	2003-2020	Test Site J	2007-2012
Test Site B	1990-2020	Test Site K	1992-1995
Test Site D	2018-2021	Test Site L	1994-1995
Test Site E	2011-2020	Test Site M	1993-1995
Test Site F	2018-2020	Test Site O	1995-2006
Test Site G	2003-2021	Test Site P	1997-2021
Test Site H	2004-2011	Test Site Q	2008-2011
Test Site I	2008-2009		

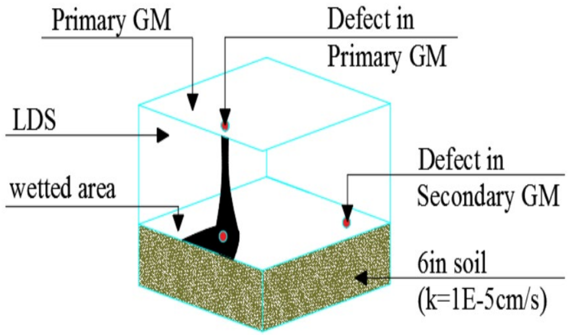
Data Collection and Analysis (Cont'd)

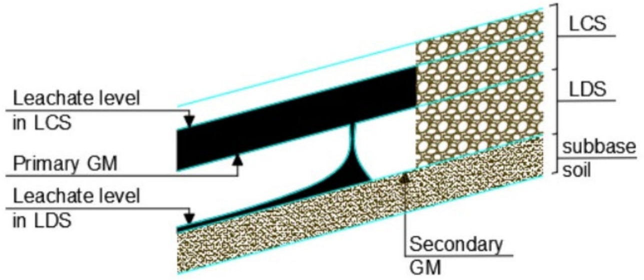
- The field leakage rate (into the LDS) for the landfills were lower than the theoretical equations proposed by **Giroud 1997 (Q_1)**
- Based on the leachate volumes pumped from the LDS, Giroud's equations were used to compute the **leakage through the secondary lining system (Q_2)**.



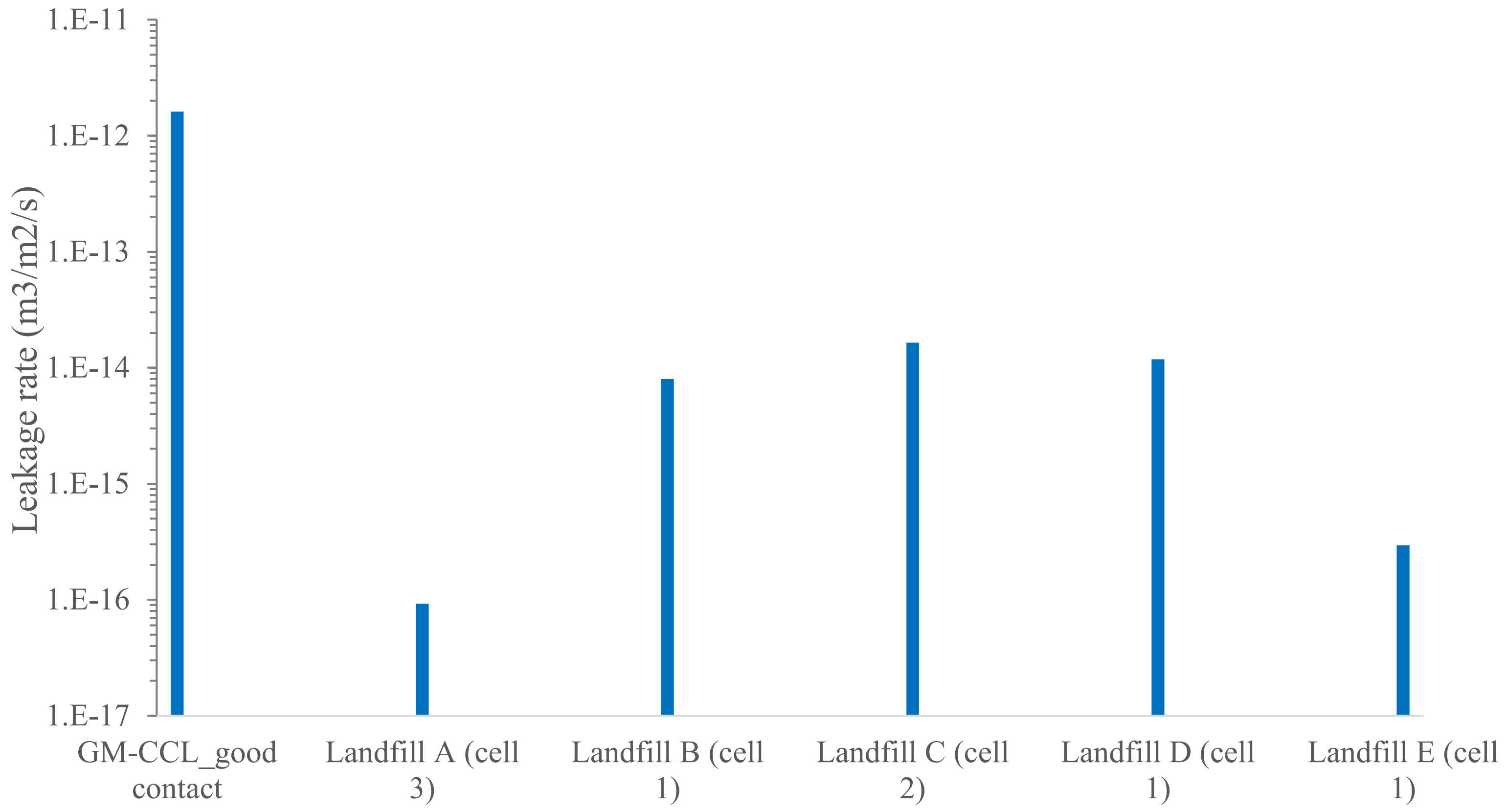
$$Q_1 \approx 1.64(aq_i)^{0.075}h^{1.85}k_{om}^{0.925}$$

$$Q_2 = \beta_c(1 + 0.1\left(\frac{D_{ave}}{L_s}\right)^{0.95})a^{0.1}{D_{ave}}^{0.9}{k_s}^{0.74}$$





Data Collection and Analysis (Cont'd)

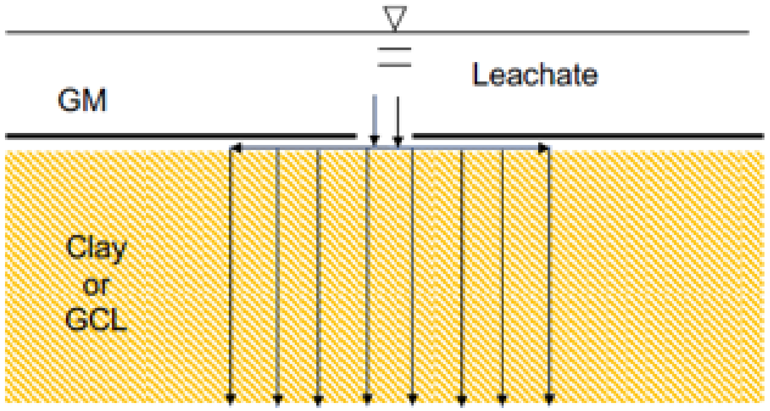


Conclusion: The Florida double lining system is equivalent to the EPA composite lining system based on leakage rate through defects.

Comparison of leakage rate through EPA's GM-CCL composite system and five landfills with Florida double lining system for good contact condition. Poor contact conditions showed a similar results.

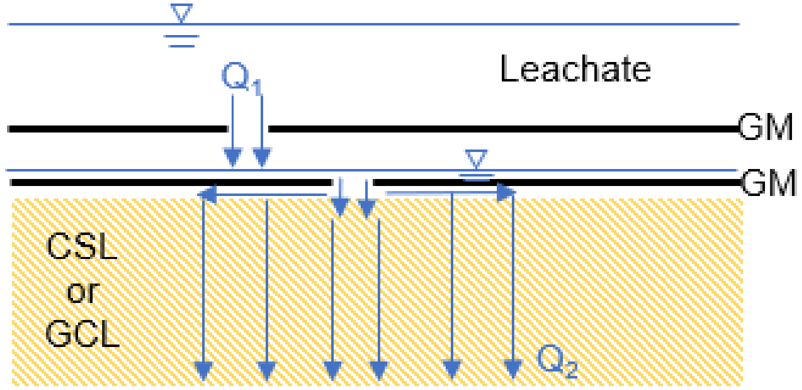
Modeling Leakage Rate in Double Liners and EPA Liners

EPA Liner



$$Q = \beta_c(1 + 2\left(\frac{h_w}{L_s}\right)^{0.95})a^{0.1}{h_w}^{0.9}{k_s}^{0.74}$$ (Giroud 1997)

Florida's Double Liner



$$Q_1 = 3\, a^{0.75}h^{0.75}{k_d}^{0.5}$$

$$Q_2 = \beta_c(1 + 2\left(\frac{D_{ave}}{L_s}\right)^{0.95})a^{0.1}{D_{ave}}^{0.9}{k_s}^{0.74}$$

(Giroud et al. 1997)

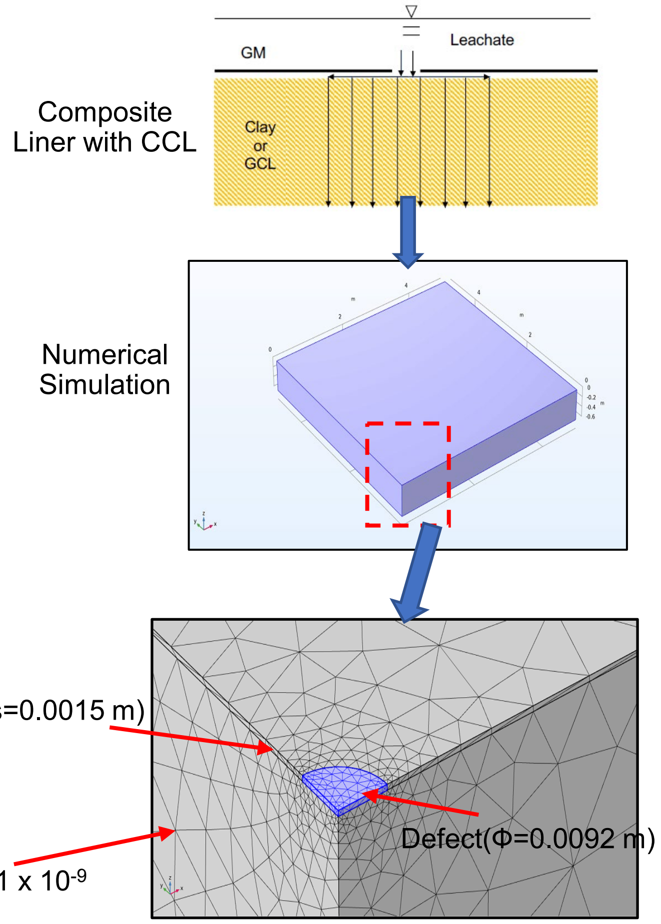
β_c = contact factor C_{qo}(good)-0.21, C_{qo}(poor)-1.15; D_{ave} = depth of leachate at the leakage detection system; L_s = thickness of liner; a = area of hole; h_w = depth of leachate; K_s = hydraulic conductivity.

Leakage Rage Calculation

Demonstrate *leakage rate* from base of alternative liner no more than conventional liner – *effective in managing leachate*.

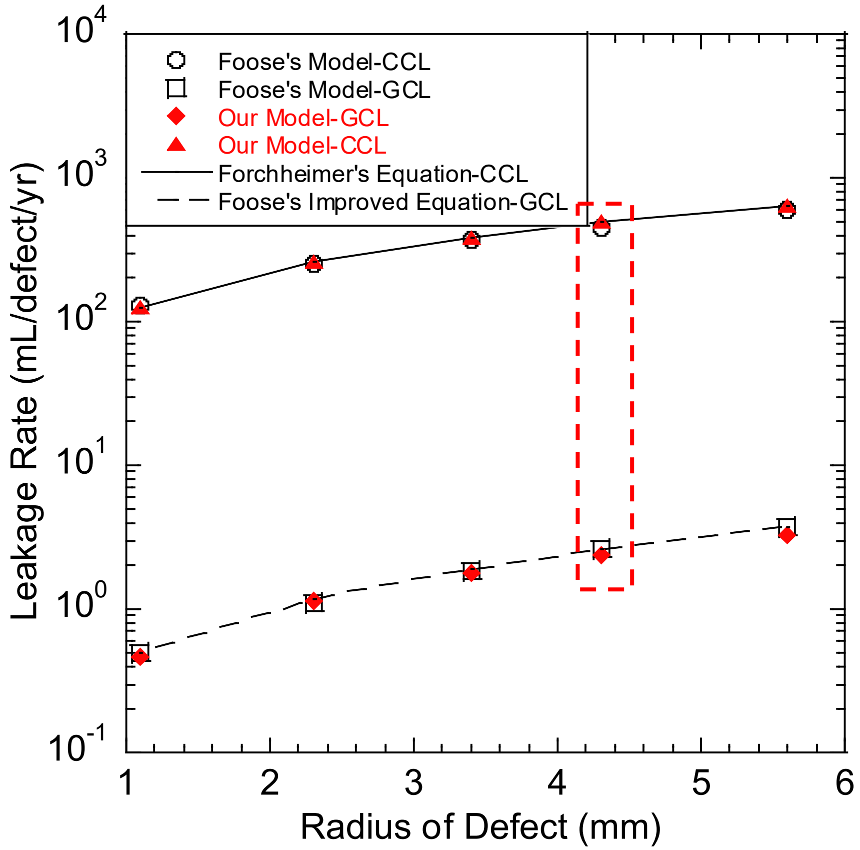
Model Setup and Calibration - EPA Composite Liner

- Area of defects was assumed to be 0.66 cm^2,
- Depth of leachate was set at 30 cm,
- length of the simulation period was 100 years.
- Assuming perfect contact.
- Calibrated with the same model conducted by Foose et al. (2001)
- Current model is 3-D and conducted by finite element approach using COMSOL Multiphysics.



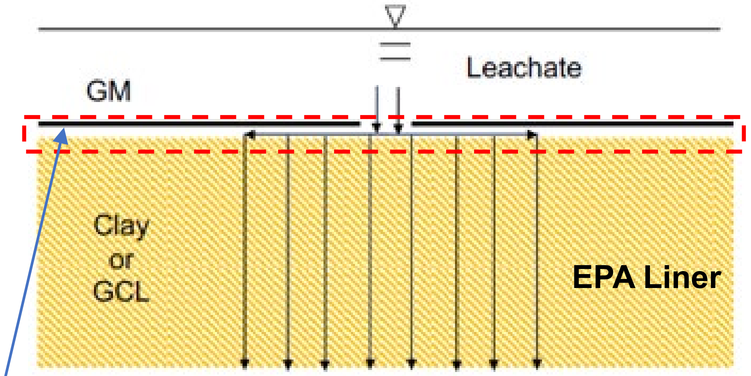
Calibration Results – Leakage Rate with Perfect Contact

Methods	Equations	Leakage Rate(mL/defect/yr)
Current model—CCL		537
Giroud's equation (Giroud, 1988)	$Q = \pi k_s h_w d$	273
Forchheimer's equation (Foose et al., 2001)	$Q = 4K_s h_t r$	523
Foose's numerical model (Foose et al., 2001)		648
Current model—GCL		2.58
Foose's improved equation (Foose et al., 2001)	$Q = F_c K_s h_t r$	1.8
Foose's numerical model (Foose et al., 2001)		2.6

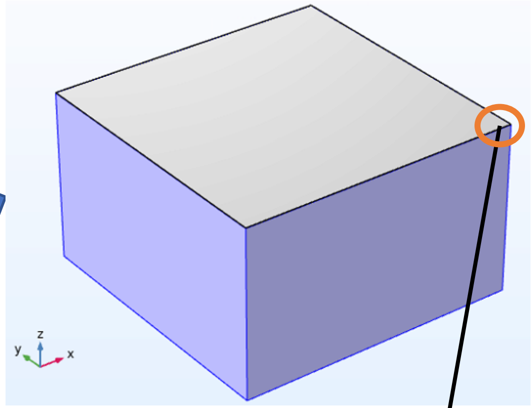


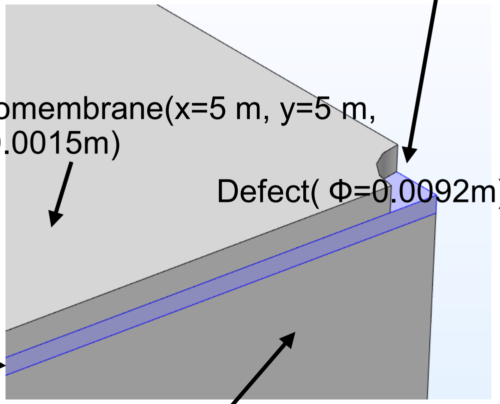
Current model shows exact same results with those of Foose et al. (2001) at perfect contact conditions.

Consideration of Contact Conditions



Imperfect Contact due to surface roughness.
Here we call it “gap”.





CCL (x=5 m, y=5 m, z=0.6 m)

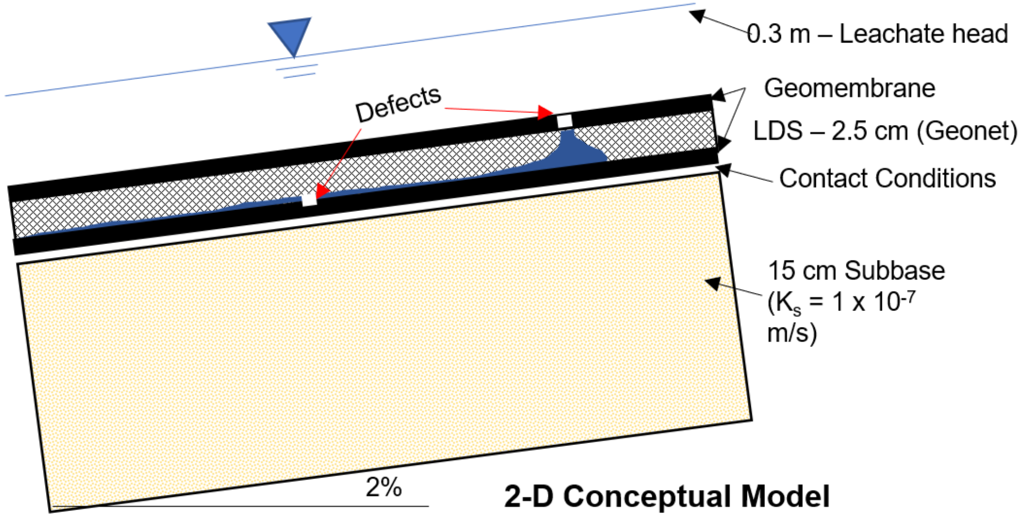
K_s=1 x 10^{-9} m/s

Gap thickness (0.0041 and 0.0092 m) from Foose’s Dissertation (1997).

Calculated K_g = 6 x 10^{-6} to 1 x 10^{-4} m/s based on the good and poor contact conditions using Giroud (1997)’s equation.

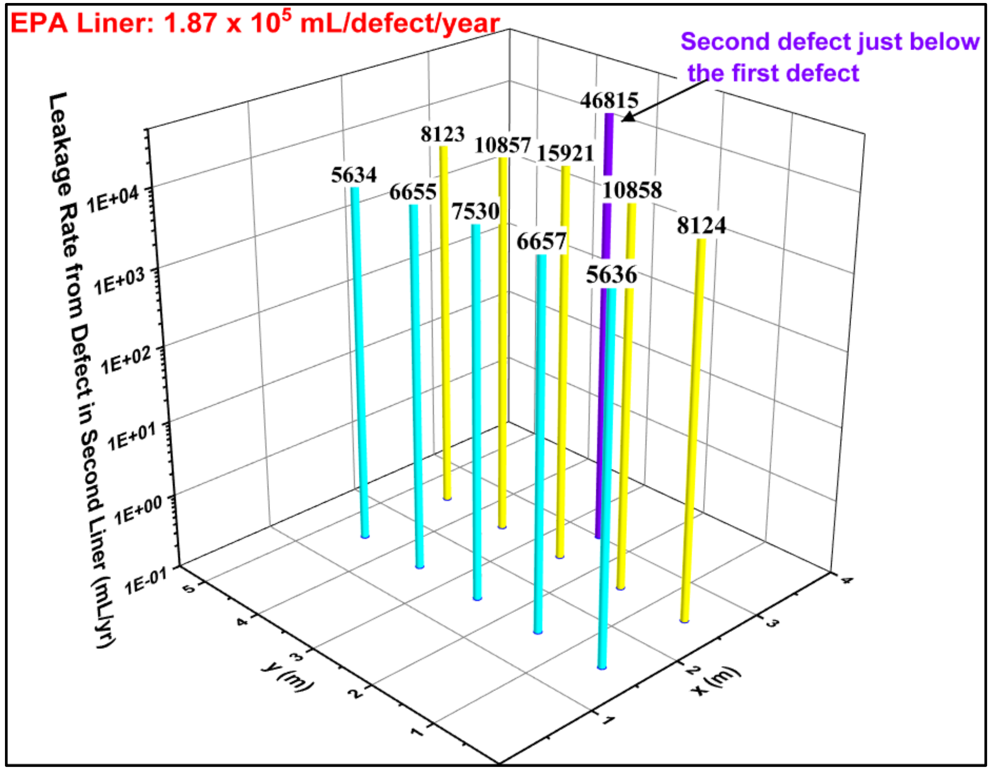
Numerical Modelling of Leakage through the Florida Double Liner

- Area of defects was assumed to be 0.66 cm^2,
- Depth of leachate was set at 30 cm,
- length of the simulation period was 100 years.
- Applying good and poor contacts.
- The leachate in the LDS can drain to the leakage detection sump.
- Current model is 3-D with domain size 5 m x 5 m.

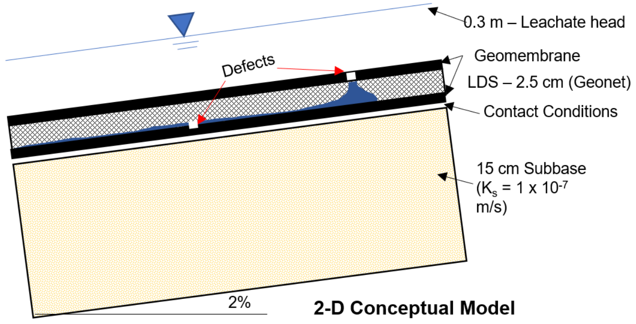


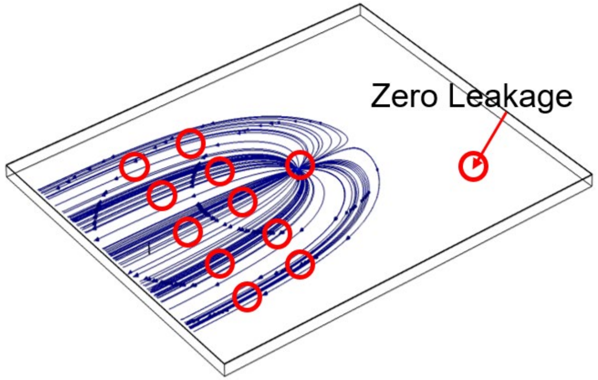
2-D Conceptual Model

Leakage Rate of the Double Liner with Subgrade Soil (Good Contact)



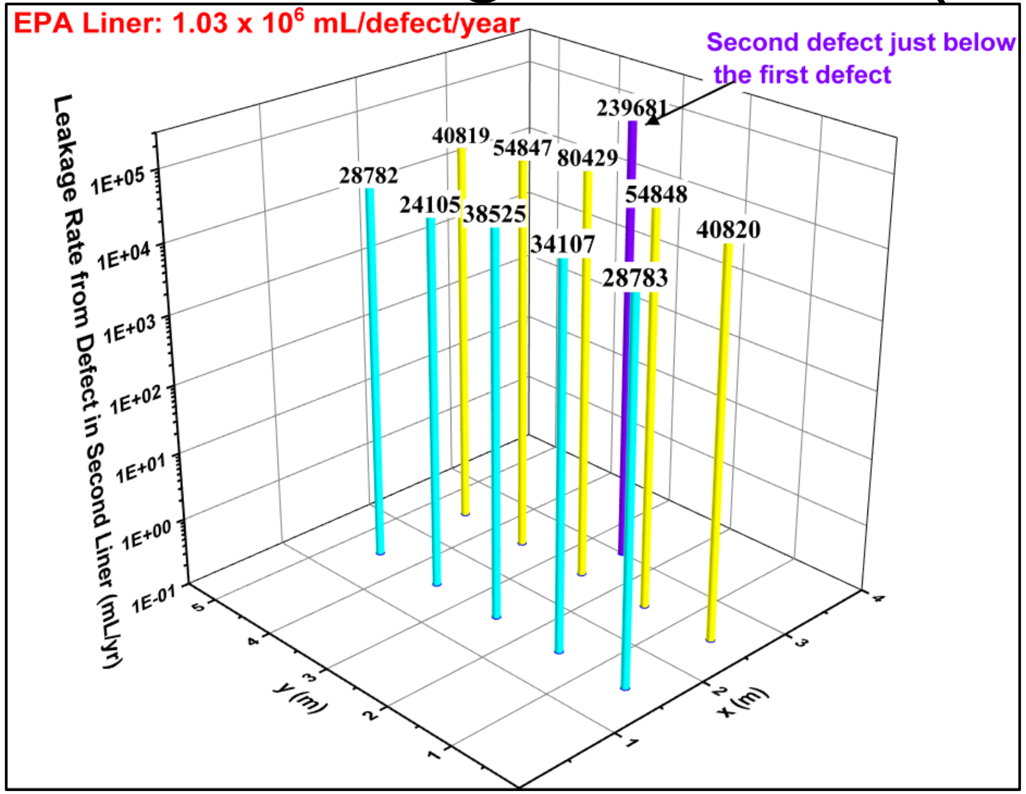
Double Liner with Good Contact

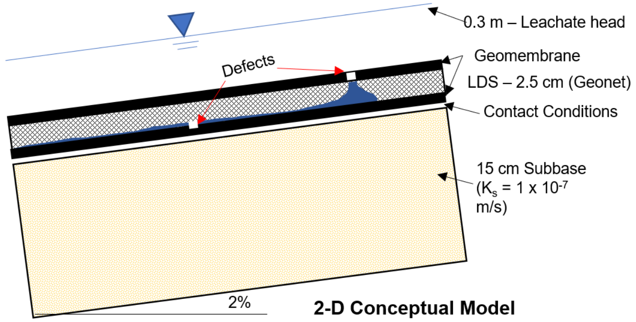


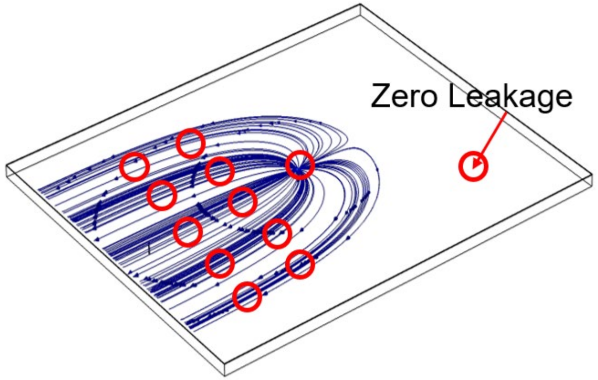


The leakage rate of double liner is at least 4 times lower than that of the EPA liner.

Leakage Rate of the Double Liner with Subgrade Soil (Poor Contact)





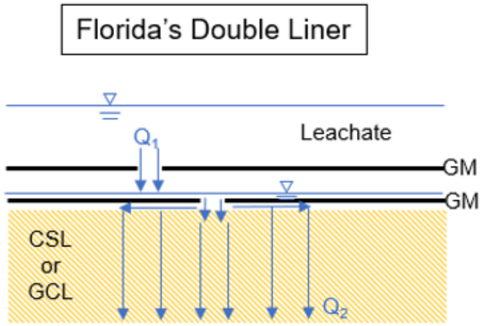


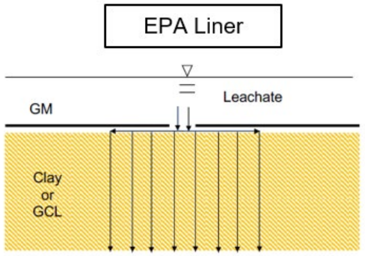
Double Liner with Poor Contact

The leakage rate of double liner is at least 4 times lower than that of the EPA liner.

Comparison of the numerical modelling of leakage through the Florida and EPA's lining systems

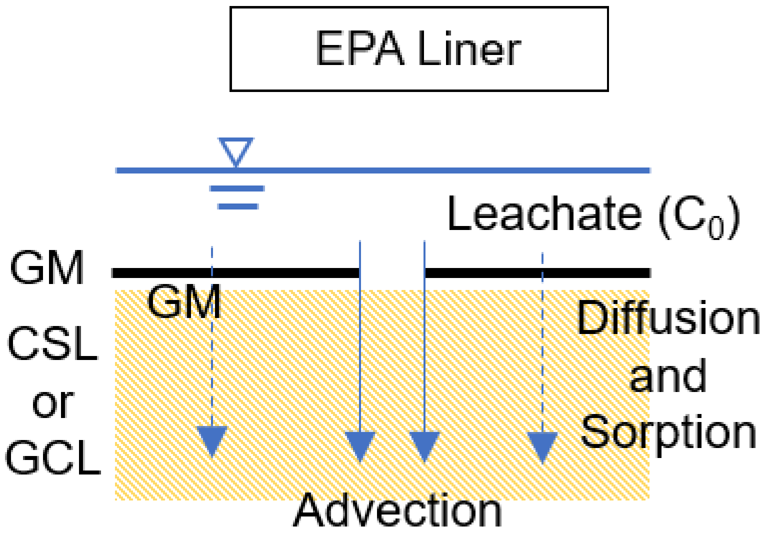
Liner Type	Leakage rate (Q2) range (mL/year)
FL Double liner (with subbase soil); good contact	**0 – 4.7x10^4**
FL Double liner (with subbase soil); poor contact	**0 - 2.4x10^5**
EPA Liner (GM+CCL); good contact	1.9x10^5
EPA Liner (GM+CCL); poor contact	1.0x10^6

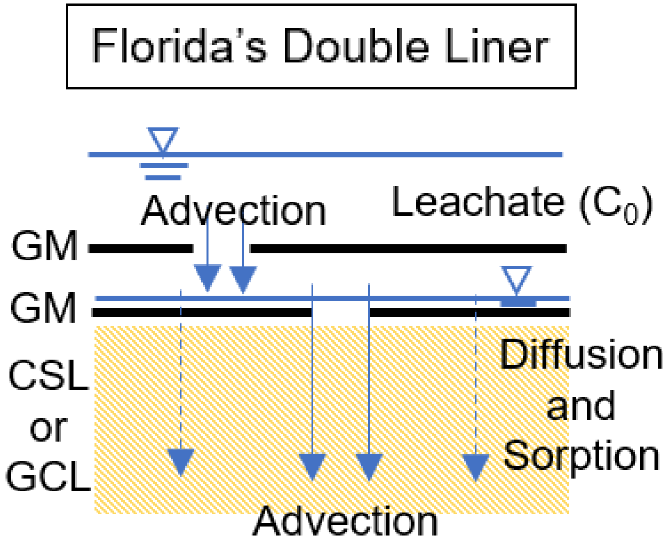




Conclusion: The Florida double lining system is equivalent to the EPA composite lining system based on leakage rate.

Mass Transport through the Liner





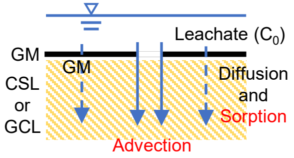
$$R\frac{\partial C_r}{\partial t} = \frac{\partial\left(D^*_{ij}\frac{\partial C_r}{\partial x_i}\right)}{\partial x_i} - \frac{\partial (v_{siC} C_r)}{\partial x_i}$$

R = retardation factor; C_r = resident concentration of solute in the pore water; t = time; x_i = distance along the respective Cartesian coordinate; D^*_{ij}= effective diffusion coefficient tensor; and v_{siC} and v_{siD} = seepage velocity in the direction x_i of composite liner and double liner.

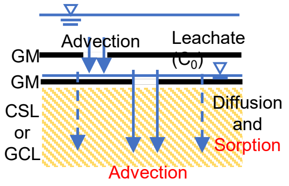
Mass Transport Calculation

Demonstrate *mass discharge* from base of alternative liner no more than conventional liner – *effective in managing contaminants*.

Numerical Modelling of Mass Transport through the Florida Double Liner



$$R\frac{\partial C_r}{\partial t}=\frac{\partial\left(D_{ij}^{*}\frac{\partial C_r}{\partial x_i}\right)}{\partial x_i}-\frac{\partial(v_{siC}C_r)}{\partial x_i}$$



$$R\frac{\partial C_r}{\partial t}=\frac{\partial\left(D_{ij}^{*}\frac{\partial C_r}{\partial x_i}\right)}{\partial x_i}-\frac{\partial(v_{siD}C_r)}{\partial x_i}$$

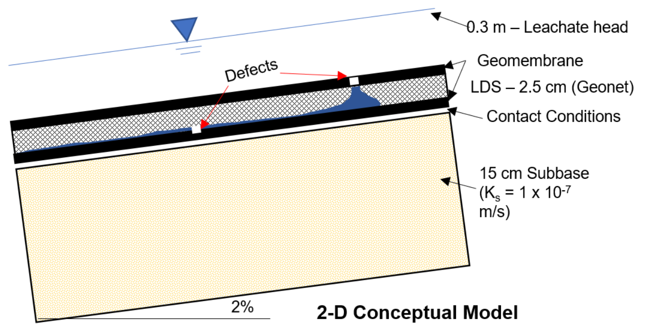
Mass Transport

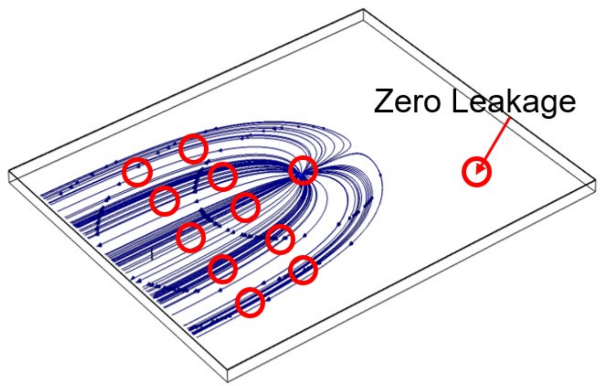
Demonstrate *mass discharge* from base of alternative liner no more than conventional liner – *effective in managing contaminants*.

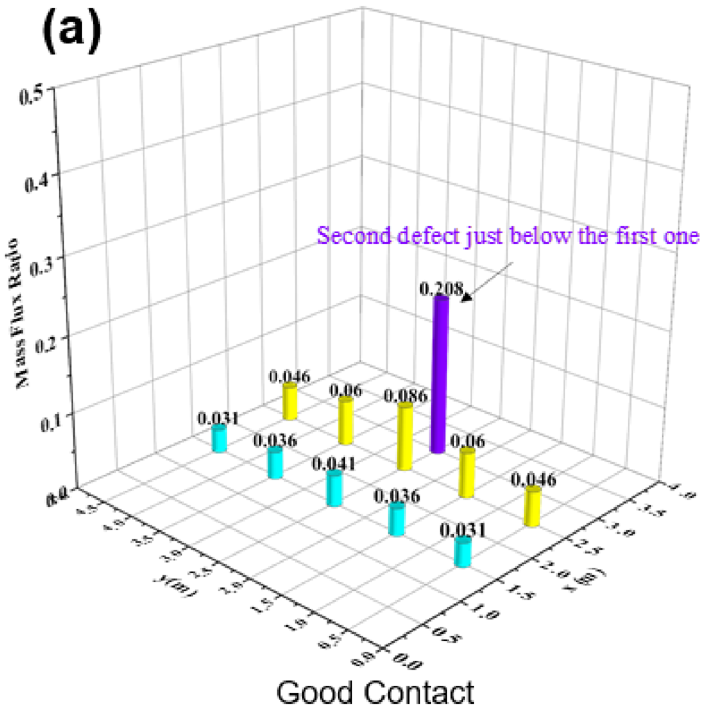
R = retardation factor; C_r = resident concentration of solute in the pore water;
t = time; x_i = distance along the respective Cartesian coordinate; D^*_{ij}= effective diffusion coefficient tensor; and v_{siC} and v_{siD} = seepage velocity in the direction x_i of composite liner and double liner.

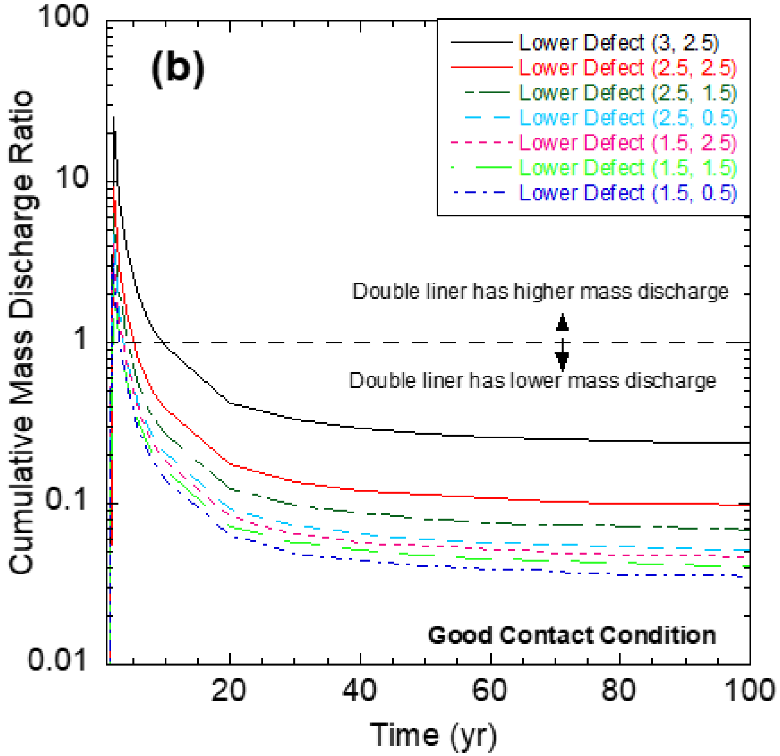
- Model domain, properties, defect, leachate head are same with the leakage model.
- Advection, sorption, and diffusion were considered.
- A source concentration of 100 ug/L Cadmium (Cd) was used in the leachate above the defect. The using of Cd is purely for mass transport comparison due to its well-documented transport phenomenon through EPA composite liner.
- Additional evaluation of Se, Cr, and As adopted the same methodology and are currently under evaluation.

Mass Transport through the Florida Double Liner and EPA Liner









- Mass Flux Ratio = Mass Flux of Double Liner at Steady State / Mass Flux of EPA Liner at Steady State
- Cumulative Mass Discharge Ratio = Cumulative Mass Discharge of Double Liner over time / Cumulative Mass Discharge of EPA Liner over time.

Conclusions

- The equivalency of the Florida double liner to EPA composite liner was assessed based on field leakage data of landfills with the double liner system, and the use of a numerical model to analyze leakage rate. The Florida double liner performs better than EPA's GM-CCL composite lining system.

- Based on the numerical simulation, the leakage rate of the Florida double liner depends on the relative locations of the defects on the primary and secondary GMs. The maximum leakage rate occurs when two defects are vertically aligned.

- The mass transport of inorganic metal elements from the double-liner is calculated to be lower than that of the EPA liner.

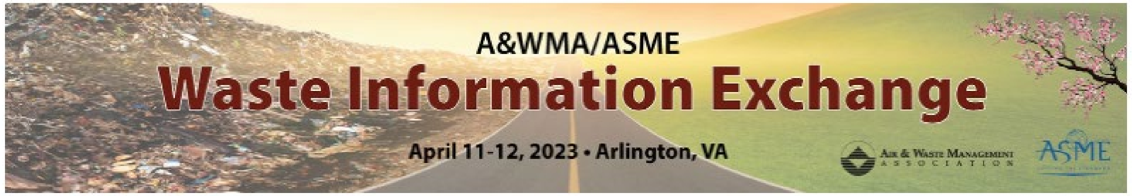
- It should be noted that initial modeling was performed using concentration of Cd higher than observed in coal ash leachate. A mass transport study using an actual concentration of inorganic metal elements (including Se, As, and Cr) in CCP leachate are currently ongoing.

Presentations and Outreach

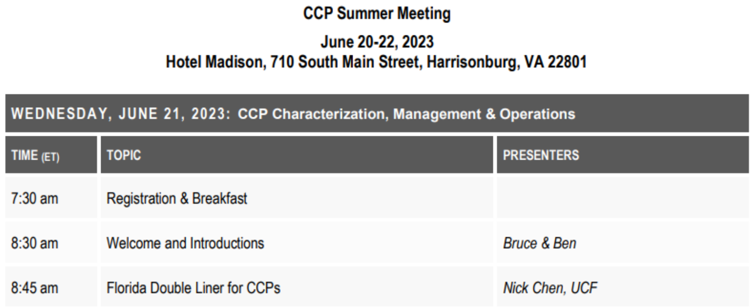
Conferences Presentation (September, 2022) - ICLRS

Conference Presentation (April, 2023) - AWMA

Waste Information Exchange



Conference Presentation (June, 2023) - EPRI



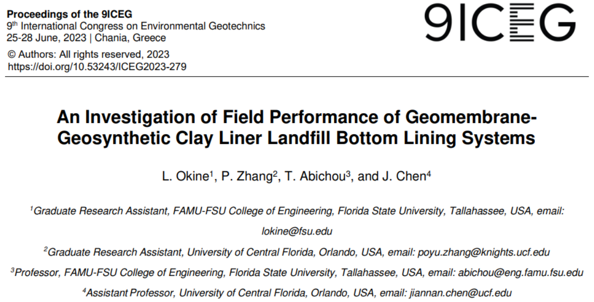
CCP Summer Meeting

June 20-22, 2023

Hotel Madison, 710 South Main Street, Harrisonburg, VA 22801

WEDNESDAY, JUNE 21, 2023: CCP Characterization, Management & Operations		
TIME (ET)	TOPIC	PRESENTERS
7:30 am	Registration & Breakfast	
8:30 am	Welcome and Introductions	*Bruce & Ben*
8:45 am	Florida Double Liner for CCPs	*Nick Chen, UCF*

Conference Presentation (June, 2023) - EPRI



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9ICEG

An Investigation of Field Performance of Geomembrane-Geosynthetic Clay Liner Landfill Bottom Lining Systems

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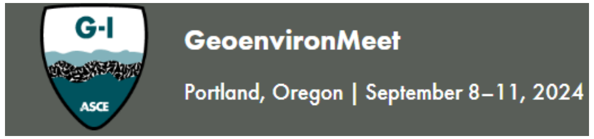
Upcoming Conference Presentation (2024)



Final Hinkley Report and Meeting Recordings

https://sites.google.com/view/fl-double-liner-system/home

Thank you very much !

Technical Awareness Group (TAG) and Advisory Board

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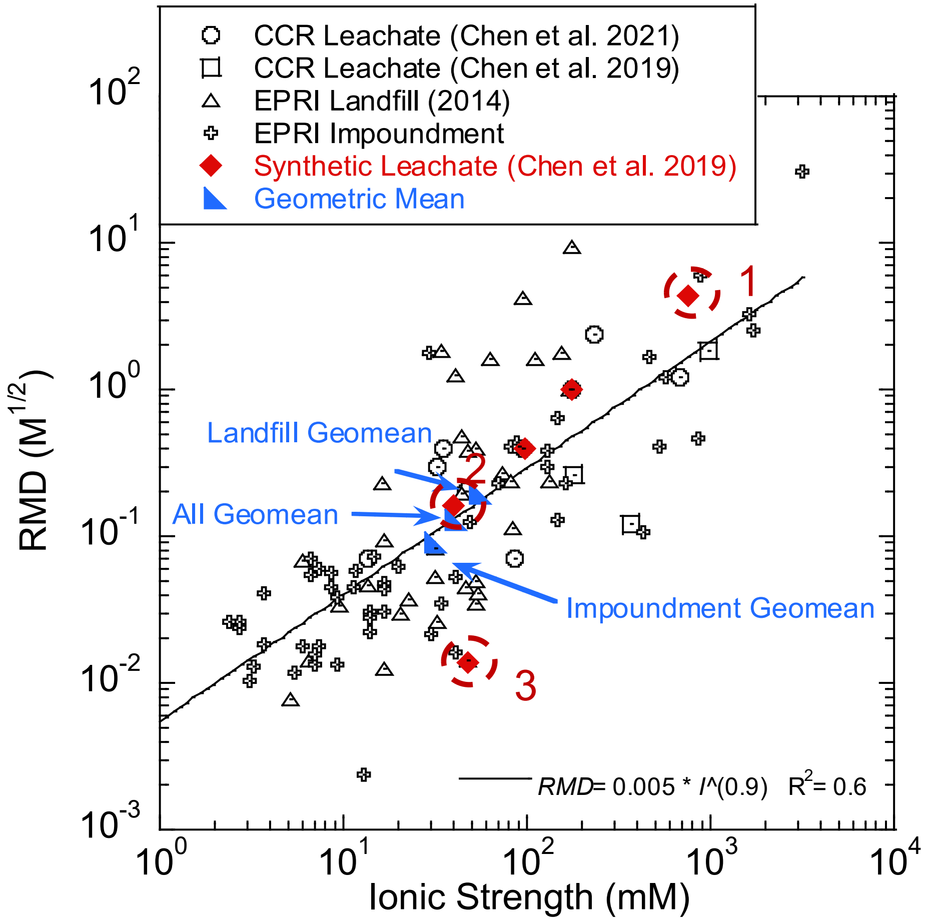
Characterize the Chemistry of CCR Leachate



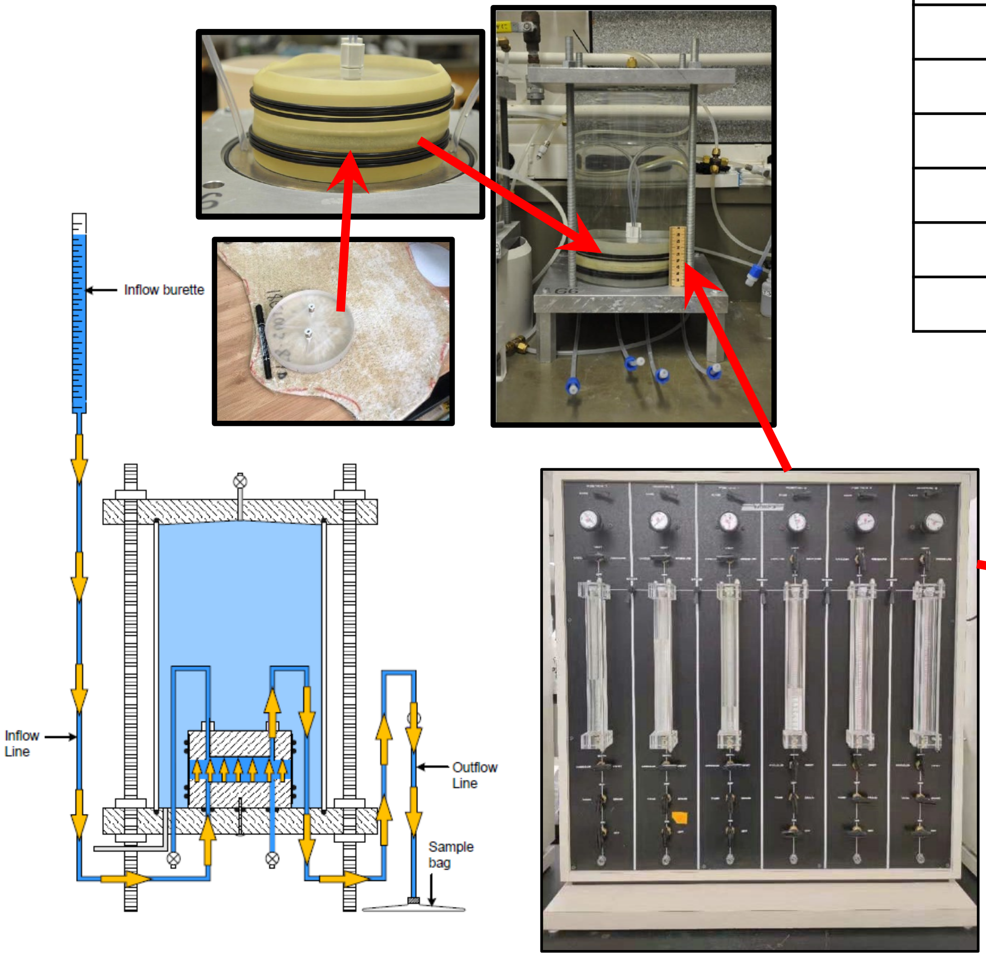
Leachate Chemistry

Cation or Anion(mg/L)	HSL	AL	DL
Ca	154.6	505	616
Mg	3186.4	10.1	24.3
Na	12500	16	29.9
K	5470	93	11.7
Cl	22000	2.7	29.1
SO4	16000	1397	1612.8
pH	6.6	6.2	6.2
Ionic Strength(mM)	1255.3	56.7	67.6
Electric Conductivity (ms/cm)	70.9	2.3	2.5
RMD (M1/2)	1.86	0.027	0.012

Note: HSL-high strength of CCR Landfill Leachate, AL-average CCR Landfill Leachate, and DL-divalent CCR Landfill Leachate

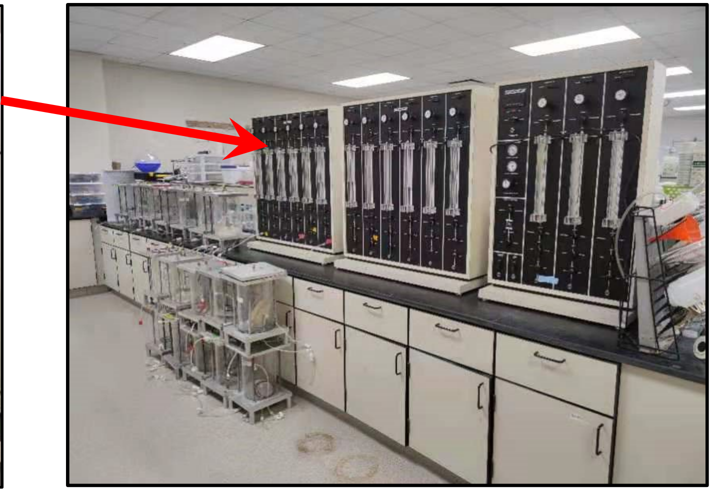
Compatibility and Leakage Rate of Liner Materials to CCR

Flexible-wall Permeameter



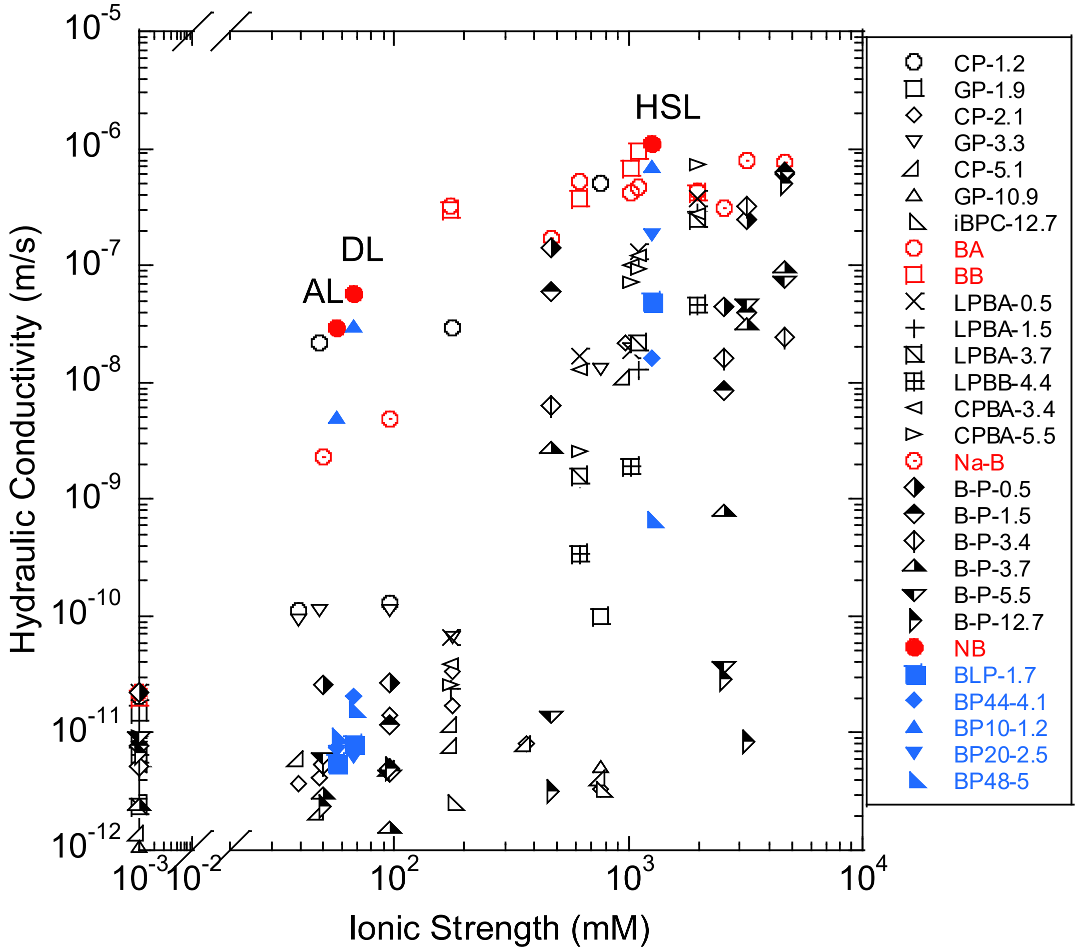
No.	GCLs Evaluated in this Study
1	NB (Na-B GCL)
2	BLP-1.7
3	BP10-1.2
4	BP20-2.5
5	BP44-4.1
6	BP48-5

Pressure Control System



Using the falling headwater and constant tailwater methods in ASTM D5084 and ASTM D6766.

Hydraulic conductivity vs. Ionic strength



Data of **NB, BLP-1.7, BP44-4.1, BP10-1.2, BP20-2.5, BP48-5** are from our study.

Data of **CP-1.2, GP-1.9, CP-2.1, Gp-3.3, CP-5.1, GP-10.9, iBPC-12.7** are from Chen et. al.(2019)

Data of **BA, BB, LPBA-0.5, LPBA-1.5, LPBA-3.7, LPBB-4.4, CPBA-3.4, CPBA-5.5** are from Wireko, et. al.(2021)

Data of **Na-B, B-P-0.5, B-P-1.5, B-P-3.4, B-P-3.7, B-P-5.5, B-P-12.7** are from Zainab, et. al.(2021)

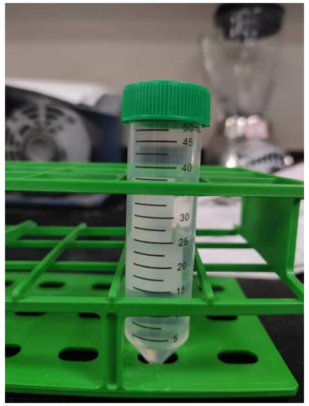
- Hydraulic conductivity of the GCLs were used in the determination of leakage rate and mass transport of double liner with GCLs.
- When use 1 x 10^{-9} m/s as the hydraulic conductivity of GCL in the double liner system, the leakage rate (1.9 to 8.5 x 10^{4} mL/year) was calculated to be lower than that of the EPA liner (1.8 x 10^{5} to 1.1 x 10^{6} mL/year).

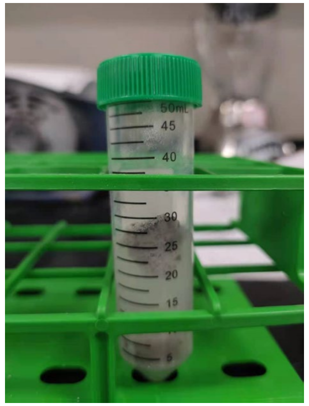
Sorption of the Bentonite and Bentonite with Polymer

The sorption isotherm is critical for mass transport of GCLs.

Dry Bentonite from GCLs

Cd Solution(4000 mg/L)

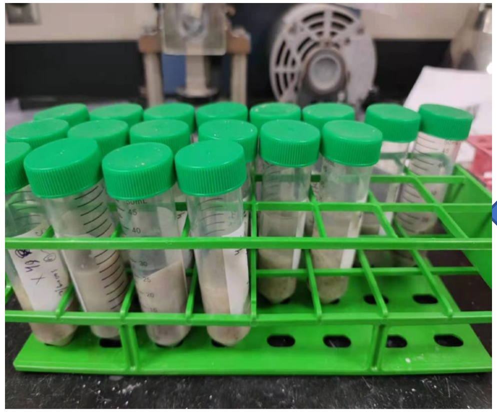




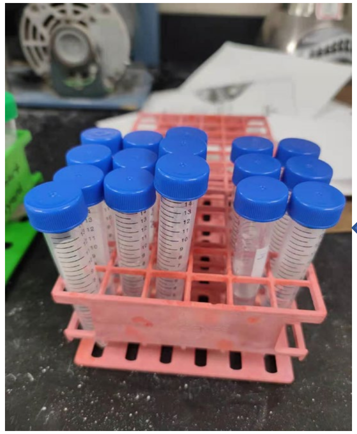
Mixed and Rotated

After Rotation

After Centrifugation



Separate the Solution and Soil



Collect the supernatant and add 1% HNO_3 to Preserve

Sorption isotherm of Cd on GCL- Langmuir Model

$$q_e = \frac{q_m * b * C_e}{1 + b * C_e}$$

b— equilibrium constant (L/mg) related to the free energy of adsorption

q_m— monolayer adsorption capacity of the adsorbent (mg/g)

NB:
b=0.0012, q_m=55.7, R^2=0.961

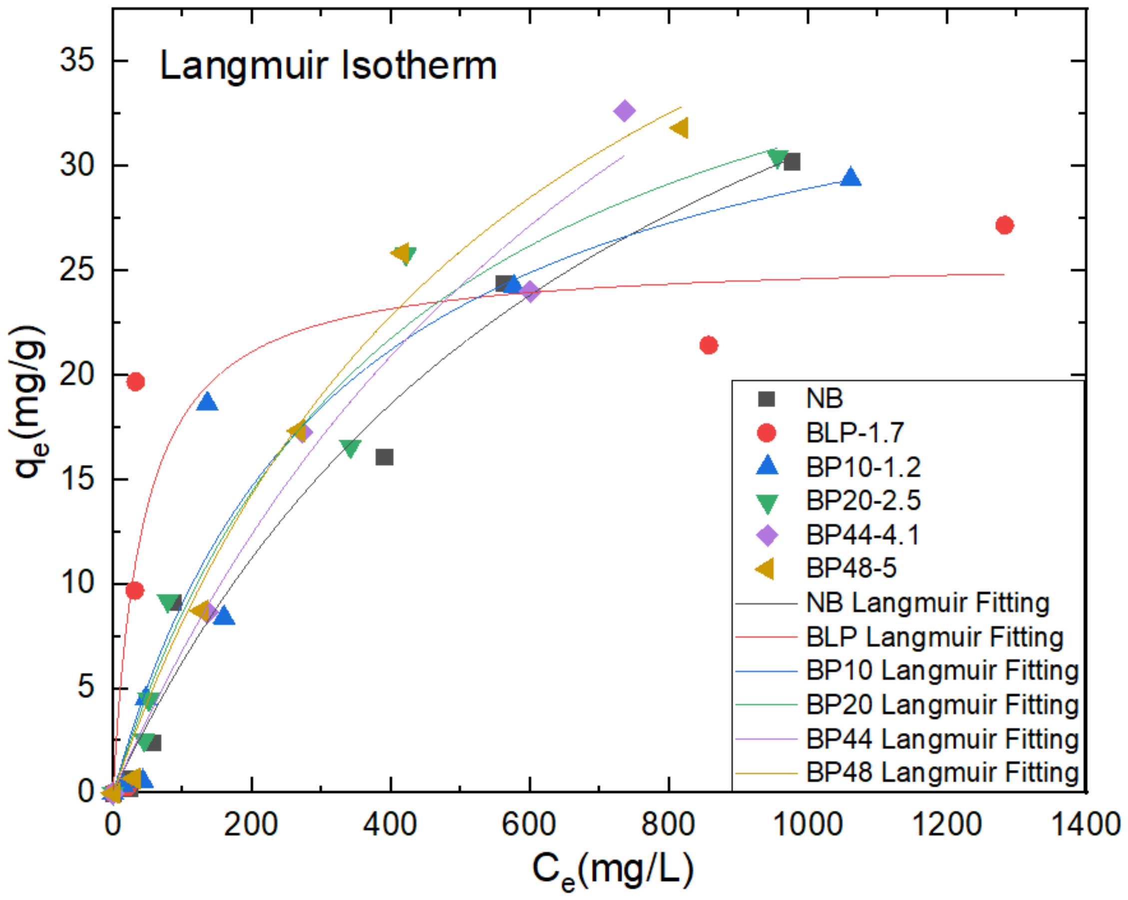
BLP:
b=0.023, q_m=25.6, R^2=0.648

BP10:
b=0.0031, q_m=38.3, R^2=0.889

BP20:
b=0.0023, q_m=45.4, R^2=0.915

BP44:
b=0.0011, q_m=67, R^2=0.946

BP48:
b=0.0017, q_m=56.5, R^2=0.979



Sorption Isotherm of Cd on GCL - Freundlich Model

$$q_e = K_F * C_e^{1/n}$$

K_F ($mg^{1-n} L^n g^{-1}$) and n (dimensionless) are the Freundlich adsorption isotherm constants

NB:
n=1.45, K_F=0.27, R^2=0.952

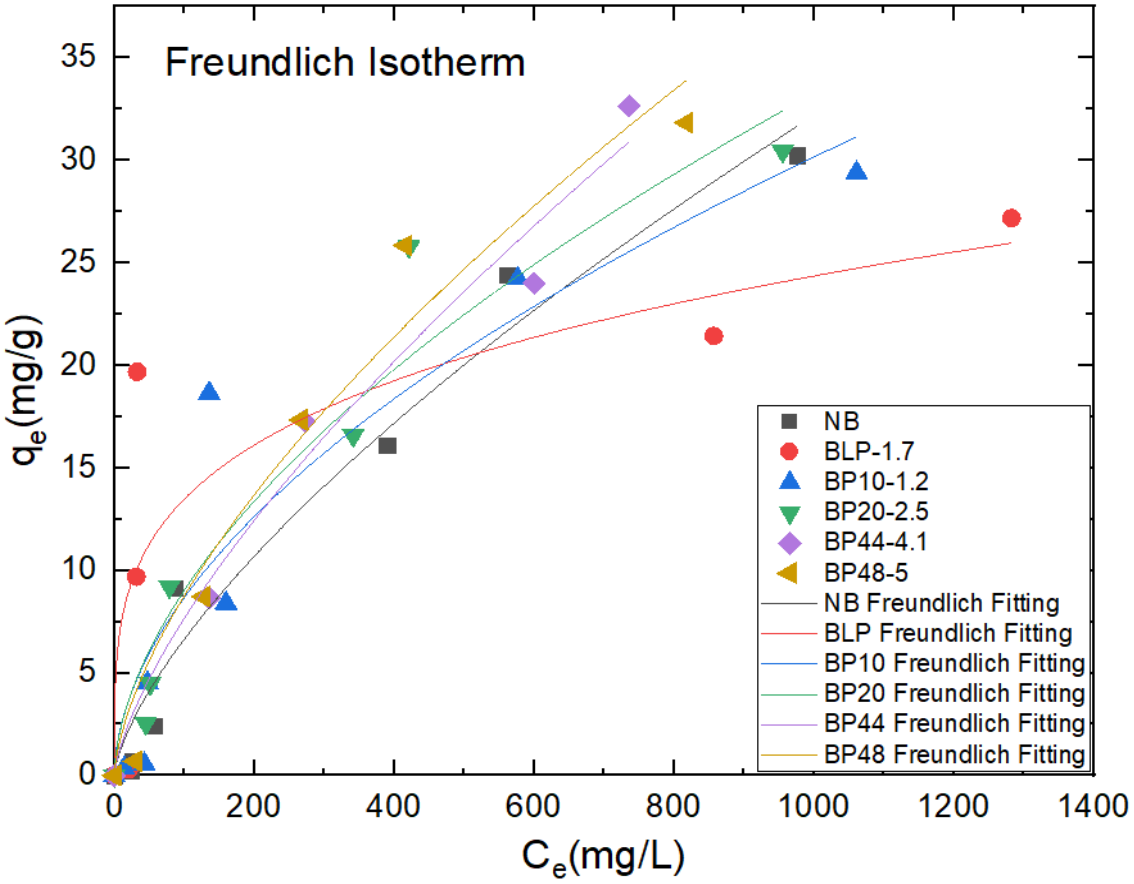
BLP:
n=3.9, K_F=4.14, R^2=0.614

BP10:
n=1.85, K_F=0.718, R^2=0.855

BP20:
n=1.76, K_F=0.654, R^2=0.894

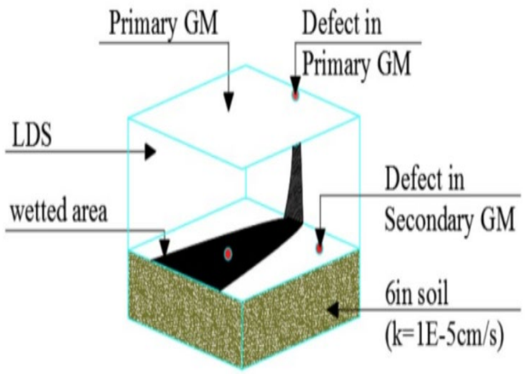
BP44:
n=1.43, K_F=0.308, R^2=0.952

BP48:
n=1.55, K_F=0.453, R^2=0.947



Statistical analysis of leakage through the Florida Double lining system

- For the FL double lining system, leakage to the subsurface occurs when the defect in the secondary GM is in the wetted area.
- The defects in the primary and secondary GMs were randomly placed in a statistical analysis conducted.
- 100, 000 simulations were conducted



Area of defect=1 cm^2