REPORT

Wisconsin Department of Natural Resources

Alternate Liner Study

Submitted to:

Wisconsin Department of Natural Resources

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Executive Summary

The United States Environmental Protection Agency (USEPA) passed Subtitle D Municipal Solid Waste Landfill regulations in 1991, which created minimum standards for landfill bottom liners. The standards include two feet of compacted clay with a minimum 60 mil high-density polyethylene (HDPE) geomembrane. States then created their own standards and used the Subtitle D liner design or created a more stringent design standard. Wisconsin developed their municipal landfill liner regulations to include four feet of compacted clay with a HDPE geomembrane. This clay component is the largest of all state regulations. Wisconsin initiated this study to review other state's procedures and technical research of using geosynthetic clay liners (GCLs) in place of part of the compacted clay liner component.

The investigation began by creating a table of all 50 states with categories for their landfill liner designs included in their regulations. The table also included the location in the state regulations that these design criteria can be found and if alternate design standards are allowed. Golder Associates Inc. (Golder) filled out this matrix with readily available information for each of the states. The table was sent internally to Golder's North American waste management team to request landfill designers with experience in each state to provide comments, context, or review the table for errors and completeness.

The table with the summary of each state's landfill regulations was sent to the Wisconsin Department of Natural Resources (WDNR). Golder and WDNR agreed to compile an extensive review of all United States Environmental Protection Agency (USEPA) Region 5 states located in the Midwest, several other states in the Great Lakes region, and several states that include unique modeling or designs requirements. Golder then reached out to specific landfill designers in each state selected for review to create a comprehensive write up of the landfill regulations, typical designs used, alternate designs used, and the process for approving alternate designs.

Golder also conducted a technical review of GCL and dual composite landfill liner systems. This included conducting a review of existing landfill models such as the HELP model or diffusion transport or MODFlow to determine how designers determine the leachate head and leakage rates and anticipate contaminant migration over the lifetime of the landfill. Landfill model summaries and descriptions were reviewed by Golder's hydrogeologist.

Other areas of discussion include GCL performance during temperature gradients, freeze-thaw cycles, and calcium ion exchange between the bentonite and groundwater or landfill leachate. Golder reviewed technical publications and geosynthetic research institute data for GCLs to determine that GCLs are resilient to freeze-thaw issues. To maintain their low hydraulic conductivity and resistance to ion exchange and temperature gradients, GCLs require a high moisture content.

The study also reviewed design aspects and logistical constraints, such as cost considerations of a GCL or dual composite liner vs four feet of compacted clay, slope stability, interface shear strength issues using GCLs, additional testing requirements for source approval, CQA testing, and landfill gas drilling over thinner bottom liner.

The final section of the study provides a case study of the Seven Mile Creek Landfill feasibility application using a two-foot-thick clay liner with a GCL and HDPE geomembrane. Golder reviewed the feasibility application to determine if there was enough information provided and if the design would achieve the state's design intent for landfill bottom liners.

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1.0 INTRODUCTION

The Wisconsin Department of Natural Resources (WDNR) is reviewing proposals for alternative landfill liners and would like an evaluation of other states regulations and design considerations for alternative liners. Golder Associates Inc. (Golder) has compiled this report at the request of the WDNR. The report details the following:

- Current models used to assess landfill liner performance and contaminant migration
- Review liner conditions and design considerations for replacing all or part of a compacted clay liner (CCL) with a geosynthetic clay liner (GCL)
- Compare existing Wisconsin landfill liner requirements with dual composite liner requirements from other states
- Review current municipal solid waste (MSW) landfill liner regulations from all United States Environmental Protection Agency (USEPA) Region 5 states
- At WDNR's request, further discussion is provided for states that have similar climatological conditions to Wisconsin
- Review alternate liner design approval processes for various states
- Review the proposed alternate liner design at the Seven Mile Creek Landfill in Eau Claire, Wisconsin

2.0 CURRENT WISCONSIN REGULATIONS

The USEPA established minimum federal landfill regulations, with CFR 40 – Chapter I – Part 258.40 Subpart D of these rules establishing that MSW landfills shall utilize a composite liner which is defined as:

"Composite liner means a system consisting of two components; the upper component must consist of a minimum 30-mil flexible membrane liner (FML), and the lower component must consist of at least a two-foot layer of compacted soil with a hydraulic conductivity of no more than $1x10^{-7}$ cm/sec. FML components consisting of high-density polyethylene (HDPE) shall be at least 60-mil thick. The FML component must be installed in direct and uniform contact with the compacted soil component."

Wisconsin administrative code Chapter NR 504.06(2) establishes regulations that require a more stringent liner design than the Federal Subtitle D Wisconsin code. Chapter NR 504.06(7) notes that GCLs may not be used except in landfills which do not accept municipal solid waste unless the GCL is used as a pad between the clay component of the liner and the FML component.

2.1 Design Requirements

Wis. Admin. Code NR 504.06 details that landfills in Wisconsin shall have the following composite liner systems:

- Separation of bottom of clay and top of seasonal high groundwater level shall be minimum 10 feet except for zone of saturation landfill
- Separation of bottom of clay and top of bedrock shall be minimum 10 feet
- Minimum thickness of the clay component shall be four feet
- Slope of internal side walls shall be less than 33 percent but greater than 20 percent

- Geomembranes shall be 60 mil or thicker
- Geomembrane shall be covered with the drainage blanket within 30 days of construction

The regulation provides source testing of the clay and geomembrane and construction requirements, as discussed below in Section 2.3.1.

If the landfill is determined to be in a zone of saturation, all design elements other than the groundwater separation are still required. The facility will have to conduct an analysis of the groundwater levels and their effect on uplift, or integrity of the liner system. The analysis shall include discussion of use of an underdrain or dewatering system. The investigation shall include an extensive field program of borings and test pits on a 100-foot grid to a minimum depth of five feet.

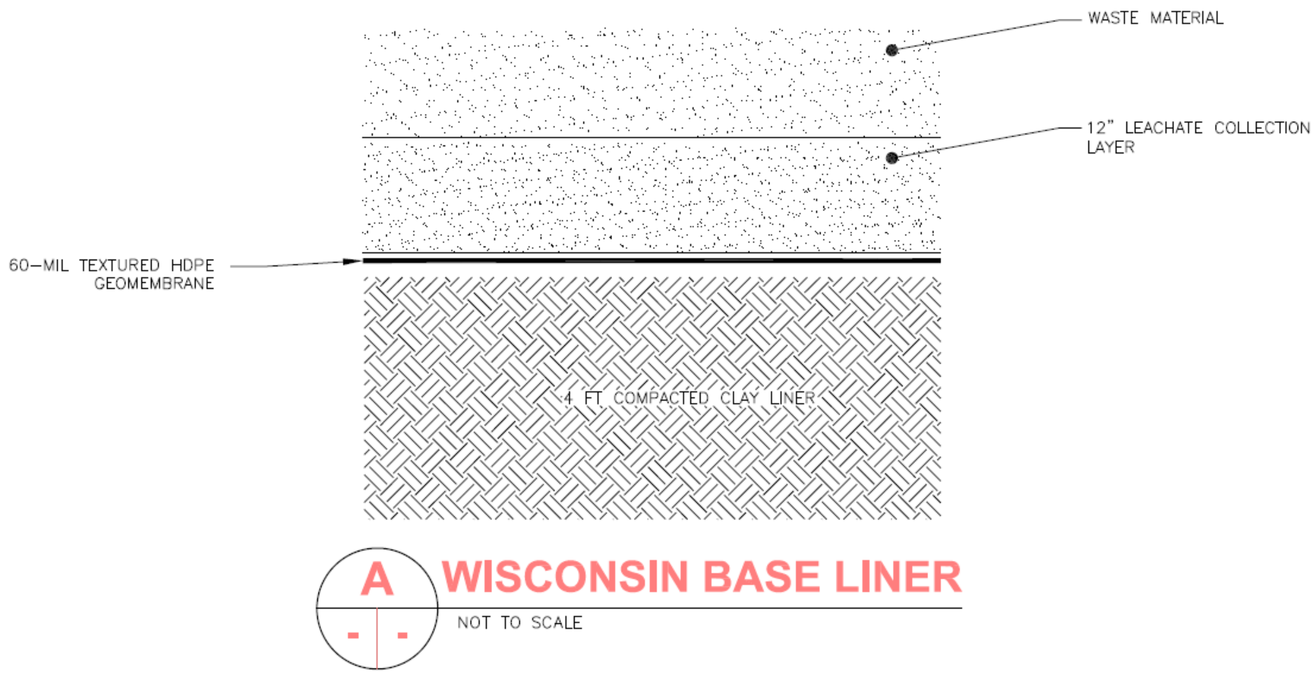

Figure 1: Wisconsin Base Liner

Note: Textured liner is shown as it was used for the cost and slope stability comparisons but is not required as part of the state's regulations.

As per Wisconsin Administrative Code Chapter NR 512.05, applications for new landfill cells must first submit a Feasibility Study to the WDNR. The Feasibility Study shall include:

- Preliminary material balance calculations
- Methods for leachate and gas controls and treatment
- Operating procedures and general filling sequence

- Description of proposed leachate, surface water, gas, air, unsaturated zone and other monitoring programs as well as a sampling plan for monitoring devices
- Stormwater controls
- Proposed final use
- Preliminary engineering plans

The Feasibility Study shall address questions and review comments from the WDNR. Once the Feasibility Study is complete, the landfill owner is responsible for creating and submitting a Plan of Operation for the new landfill. The Plan of Operation is a comprehensive document which provides detailed design components including:

- Engineering plans
- Design rationale
- Construction preparation methods
- Stormwater management
- Erosion and sediment control
- Testing schedules, techniques, and grain sizes for all soil components
- Soil borrow sources
- Groundwater and surface water monitoring levels and programs
- Daily operations
- Phased development and closure of the landfill
- Long-term care of the landfill
- Written agreements such as easements or leachate treatment
- Specifications
- Design calculations
- Slope stability assessment
- Financial responsibility analysis
- References

2.2 Wisconsin Construction Quality Assurance

While Chapter 504 provides some requirements, such as soil material particle sizes and geosynthetic panel placement, Wisconsin Chapter NR 516.04 details the documentation requirements during liner construction.

Construction of new landfill cells should be documented with a construction report certified by a professional engineer and reviewed and approved by the WDNR prior to waste placement within the new cell.

The construction documentation report includes the following:

- Observed deviations to the design
- Details of the clay component of the liner including:
  - Quality of the clay
  - Connection of the clay layers
  - Preparation of trenches, sumps, and penetrations through the clay
  - Preparation of clay for interface with geosynthetics
  - Placement of material over clay
- Elements of construction detailing leachate, gas, or stormwater collection, transport, and treatment
- Preconstruction meetings
- Preconstruction reports
- Design changes during construction
- Manufacturer details, quality control, and quality assurance of all geosynthetics
- Interface shear testing results for the composite liner
- Quality control plan
- Quality assurance plan
- Construction inspections
- Engineering plans
- Analysis and discussion of all clay work performed as per NR 516.07. Clay is tested for:
  - Dry density and moisture content on a 100-foot grid pattern for every other soil layer
  - Grain size and Atterberg limits every 5,000 cubic yards (cy)
  - Moisture and density analysis for every 5,000 cy of material placed or each source
  - One undisturbed sample per acre per one foot thickness tested for Atterberg, grain size, moisture content, and dry density
- Geosynthetics preparation and installation
- Analysis and discussion of all geomembrane work performed as per NR 516.07. Geomembranes are tested for:
  - Thickness
  - Tensile strength and elongation and yield and break

  - Density and melt flow index for each resin batch
  - Stress crack resistance
  - Trial welds peel and shear
  - Non-destructive seam testing
  - Destructive seam testing
  - Leak location survey after construction
- Analysis and discussion of all GCL work performed as per NR 516.07. GCLs are tested for:
  - Clay mass per unit area
  - Grab and peel tensile strength
  - Index flux
  - Free swell
- Analysis and discussion of all soil barrier work performed as per NR 516.07. Soil barrier layers are tested for:
  - Dry density and moisture content on a 100-foot grid pattern for every other soil layer
  - Grain size and Atterberg limits every 5,000 cy
  - Moisture and density analysis for every 5,000 cy of material placed or each source
- Analysis and discussion of all drainage blanket work performed as per NR 516.07. Drainage blanket layers are tested for:
  - Grain size distribution
  - Hydraulic conductivity, one test with field leachate
  - Moisture content and field density
  - Chemical durability testing, if requested
- Analysis and discussion of all bedding material work performed as per NR 516.07. Bedding material layers are tested for:
  - Grain size distribution
  - Chemical durability testing, if requested
- Thickness of each layer in the liner on a 100-foot grid pattern
- Discussion of leak tests
- Documentation of leachate pipe cleanout and pressure testing
- Daily construction summaries provided by the onsite engineering supervisor

- Photo log of construction works

3.0 DISCUSSION OF OTHER STATE REGULATIONS

Golder has provided a table of all 50 state regulations for landfill liners presented in Appendix A. The table includes details of state regulations for composite liners, clay components, geosynthetic components, acceptable alternate designs, and where in the state code the requirements for landfill liners can be found.

Many states have requirements that allow designers and site owners different options for the type of liner they would like to use dependent on a variety of factors such as depth to groundwater, designed leachate head, location of aquifers to landfill cell, and available materials to the site. In general, states are categorized as having one of three types of regulations.

- Acceptable for standard Subtitle D, single composite liner with two feet of clay and geomembrane – 29 states
- Modified single composite landfill requiring additional clay or more stringent soil component – nine states
- Dual composite liner system required – 12 states

It's important to note that many states have regulations for single composite liners as acceptable, but if the landfill is located adjacent to an aquifer of significance or area that is deemed environmentally at risk or doesn't have the separation from the groundwater elevation, the site may be required to install a dual composite liner system.

Also, these regulations only compare requirements at the state level. Some states such as Oregon or California have relatively simple and straightforward state requirements for landfill liners. Due to the drastically different climate regions in these states, local regulations for liners often require more stringent liner designs. This review has not incorporated those local requirements for comparison.

3.1 USEPA Region 5 States

At WDNR's request, Golder has provided an additional discussion to states within the USEPA Region 5 consisting of midwestern states that share common climatological and geological conditions to Wisconsin.

3.1.1 Minnesota

As a border state to Wisconsin, Minnesota shares similar climate, geological, and topographical conditions. The two states also share a similar landmass and population, which makes Minnesota the most similar comparison to Wisconsin of other states in the USEPA Region 5.

Minnesota has 21 active MSW landfills. The majority of the landfills are located within the southern half of the state. Seventeen of the landfill sites are county-owned landfills located in rural regions of the state. The four privately owned landfills service the Minneapolis and Saint Paul metropolitan region.

3.1.1.1 Liner Design Requirements

Landfills are regulated by Minnesota Administrative Rules Chapter 7035.2815. Landfill liners are defined in subpart 7(E):

"A natural soil barrier liner must be at least four feet thick. A synthetic membrane must be at least 60/1000 of an inch thick for an unreinforced membrane or 30/1000 of an inch thick for a reinforced membrane. A synthetic membrane must meet the specifications of the National Sanitation Foundation, Standard Number 4, Flexible

Membrane Liners, November 1983, Ann Arbor, Michigan. The synthetic membrane must be placed over a natural soil barrier liner at least two feet thick. The drainage layer must consist of at least 12 inches of suitable soil material or an equivalent synthetic material."

Landfill liners along the base of the landfill cell shall have a minimum two percent slope towards the leachate collection system, with side slopes no steeper than 50 percent.

If a facility is deemed to be located in an area where hydrologic or topographic conditions would allow rapid or unpredictable pollutant migration or impair the long-term integrity of the facility or preclude reliable monitoring, the site must take additional measures in addition to the composite liner design. Those measures include:

- A second liner with a collection system between the two liners
- An in-place, operational groundwater containment and treatment or disposal system that can be activated immediately if groundwater pollution is detected
- Another method of secondary containment backing up the liner providing additional protection equivalent to the first two options

The facility must submit an engineering report that addresses the following:

- Source and quantity of natural soils capable of meeting the requirements of the liner design
- Likelihood and consequences of failures caused by puncture; tear; creep; freeze-thaw; thermal stress; abrasion; swelling; extraction; oxidative degradation; exposure to ultraviolet radiation; acidic conditions; concentration of ions; organic constituents; pressure; and the presence of gases, rodents, microbes, and root penetration
- Composition of the drainage layer and liner including the soil gradations, percent fines, mineral composition, and solubility under acidic conditions and when in contact with solvents
- Calculations and assumptions used in choosing the particular design proposed for the facility

3.1.1.2 Construction Quality Assurance

Minnesota Administrative Rules Chapter 7035.2815 Subpart 12 describes the construction requirements for all aspects of landfill cell construction. As part of Subpart 12, Section M details the construction quality assurance (CQA) plan:

"A quality control/quality assurance program must be established for all construction projects. The program must include the tests to be completed during construction. The program also must establish the frequency of inspection and testing, the accuracy and precision standards for the tests, procedures to be followed during inspections and sample collection, and the method of documentation for all field notes including testing, pictures, and observations."

As part of the plan, the following are required during liner construction:

- Notify regulatory agency prior to construction works.
- Record and document construction works for reporting to regulatory agency. Records include photos, field notes, and all test results.

- Conduct field testing for compaction, Atterberg limits, grain size distribution, lab and field permeability, and field moisture density.
- Report connection of new expansions to existing liner.
- Install flexible membranes during dry conditions. The seams joining membrane panels must be inspected as construction proceeds. Seams must be air tested and field seams must be tested for tensile strength. All flexible membranes must be protected after placement. The natural layer above and below the barrier layer must be free of roots, sharp objects, rocks, or other items that might puncture the liner.
- Survey liner and slopes during construction activity.

The Minnesota liner CQA requirements do not require a liner integrity survey to be conducted after construction to locate penetrations made during construction.

3.1.1.3 Leachate Collection Layer and Groundwater Contamination

The leachate collection layer is required to have a minimum hydraulic conductivity of $1x10^{-3}$ cm/sec minimum as per Chapter 7035.2815 Subpart 7. This layer must also cover the entire base liner and side slopes and must be capable of handling at least 95 percent of the precipitation falling on the fill area. The efficiency calculation must consider the liner thickness, liner slope, saturated hydraulic conductivity of the liner and drainage layer, drainage layer thickness, permeability of the drainage layer and liner, porosity of the drainage layer, flow distance to collection pipes, and amount of leachate to be generated and collected based on annual infiltration and groundwater inflow.

Chapter 7035.2815 Subpart 9 further details the requirements of the leachate collection system for landfills. A leachate detection system is required as stated in Subpart 9(A):

"The owner or operator must install the detection system at the lowest elevation of the fill area and throughout the fill area, as necessary, to monitor leachate build-up and for use as a part of the collection system. The detection system must be capable of monitoring leachate build-up in the fill area and consist of collection lysimeters and standpipes capable of monitoring, detecting, and collecting leachate movement through the liner. The detection system must consist of materials compatible with the leachate. The commissioner may approve a detection system without collection lysimeters or standpipes provided the owner or operator shows either to be unnecessary based on the liner system, subsurface soil conditions, ground and surface water flow patterns, depth to groundwater, and the amount of leachate generated. The detection system must be designed and constructed to monitor the effectiveness of the leachate storage area."

As part of the collection system, the following design features are required:

- Structures must be cleaned out every 500 feet of pipe, with the system capable of cleaning out the entire pipework system.
- The owner or operator must complete a water balance calculation based upon the amount of precipitation, evapotranspiration, surface runoff, soil and waste moisture storage capacity, root zone depth, surface slope, subsurface lateral drainage, and average monthly temperature. The owner or operator must derive the leachate generation rate by calculating the amount of water that percolates through the cover each month using actual data from an average weather year and a year when the precipitation exceeds the average

precipitation by at least 20 percent. The engineering design report must contain all calculations and assumptions made during the water balance calculation.

- No more than one foot of freestanding liquid over the liner system with drainage material at least one foot thick.
- Leachate flow within the drainage layer shall not be more than 100 feet.

The design requirements do not specify a distance above the uppermost aquifer the liner must be constructed. Instead, the facility must conduct a three-phase soil and rock hydrogeological evaluation. The facility must conduct multiple soil borings and take groundwater samples to identify existing conditions, then modeling for the groundwater aquifers, local stratigraphy, and all relevant field logs and laboratory results must be submitted to the regulatory agency.

The facility must determine the compliance boundary location, and then provide the contaminant migration modeling to the satisfaction of the regulatory agency that contaminant concentrations shall not exceed values provided in the regulations.

3.1.2 Michigan

Landfill liners in Michigan are regulated by Michigan Department of Environment, Great Lakes, and Energy (EGLE) Part 115, Solid Waste Management of the Natural Resources and Environmental Protection Act, 1994 PA 451, as amended (Part 115 Rules).

The state currently regulates 46 active landfills spread across both the northern and southern peninsulas based on records from the EGLE and USEPA. Of the active landfills in the state, nine are publicly owned county landfills, and the rest are privately owned.

Michigan's northern peninsula shares very similar climate to northern Wisconsin. The northern peninsula; however, has a very small population with seven relatively small in size landfills.

Michigan has two main landfill liner types, Type II and Type III. Type II is generally used for MSW, and Type III is generally for construction and demolition (C&D) debris, non-hazardous industrial waste, and single-capture landfills.

3.1.2.1 Liner Design Requirements

Landfill locations and liner elevations are determined by groundwater elevations and surface water proximity to the facility. Liner systems are required to be constructed at least 10 feet above groundwater level, or seven feet above a permanently depressed (by gravity only) groundwater level. Landfill facilities are not allowed to be constructed within 2,000 feet of the Great Lakes or Lake St. Claire, 2,000 feet of a municipal groundwater well, or 800 feet of a privately owned groundwater well.

Type II landfill liner design requirements are addressed in Part 115: R299.4421 - R299.4426.

Type II landfills can use single composite liner system in locations where a minimum 10-foot-thick natural soil barrier with maximum hydraulic conductivity of $1x10^{-7}$ cm/sec is demonstrated through a comprehensive investigation approved by EGLE. To demonstrate the presence of a natural soil barrier, the facility must provide evidence of one of the following requirements to avoid use of a dual composite liner:

- In-situ soils have a maximum hydraulic conductivity of $1x10^{-7}$ cm/sec.

- Owner or operator demonstrates a soil layer with appropriate thickness and permeability to prevent contaminant migration to the uppermost aquifer through the design life of the landfill
- Soil barrier underlain by an uppermost aquifer that is sufficiently artesian to prevent vertical migration
- Combination of hydrogeology and design that minimize percolation “at least as effectively” as the previous three options for soil barrier

Part 115, R299.4912 details the requirements of testing and sampling for evidence of an existing natural soil barrier. The regulation details testing such as particle size, Atterberg limits, and hydraulic conductivity as well as provides guidance on amount of soil boring, their locations, and spacing.

The single composite liner system for use in conjunction with the natural soil barrier can be as follows:

- Uppermost FML component in direct contact with the lower soil component. The FML shall be either 60 mil HDPE, or if not HDPE, 30 mil in thickness.
- Two feet of compacted soil with minimum $1x10^{-7}$ cm/sec or a bentonite composite liner (GCL) with appropriate thickness and permeability to show equivalence to two feet of clay.

If the facility cannot demonstrate the natural soil barrier requirements or is unmonitorable, then the landfill liner must meet the requirements of a double composite liner system consisting of top to bottom:

- Primary FML component in direct contact with the lower component. The FML shall be either 60 mil HDPE, or if not HDPE, 30 mil in thickness.
- Primary two feet of compacted soil with minimum $1x10^{-7}$ cm/sec or a bentonite composite liner (GCL) with appropriate thickness and permeability to show equivalence to two feet of clay.
- A natural (i.e., aggregate) or synthetic (i.e., geocomposite) drainage layer to act as the secondary collection layer (or leak detection layer if the unit is unmonitorable).
- Secondary FML component in direct contact with the lower component. The FML shall be either 60 mil HDPE, or if not HDPE, 30 mil in thickness.
- Secondary two feet of compacted soil with minimum $1x10^{-7}$ cm/sec or a bentonite composite liner (GCL) with appropriate thickness and permeability to show equivalence to two feet of clay.

The uppermost composite liner is allowed to remove the soil component of the liner on the side slopes if the design has grades greater than 20 percent. The two composite liners are required to be separated by a leak detection layer.

3.1.2.2 Construction Quality Assurance

Part 115, R299.4916 provides details of the required CQA Plan that shall be included for landfill liner construction and final certification. Prior to start of construction, the facility is responsible for creation of a CQA Plan. The CQA Plan shall include details of key personnel, sampling and testing locations and frequencies, acceptance criteria, and corrective measures.

Part 115, R299.4913 details the requirements of the soil liner component of the composite liner systems. R299.1917 details the construction records of the soil liner component. The section provides source material testing requirements, and details of how to construct the clay liner. A CQA officer is responsible for observing:

- Compacted lift thicknesses of six inches or less
- Ninety percent modified proctor density or 95 percent standard proctor density of compacted lifts with appropriate relative moisture content
- Integration or scarifying of lifts
- No frozen material during placement of clay
- Inspection of clay prior to covering with a FML, ensuring the clay hasn't been desiccated by adverse weather or has large angular particles, directing the contractor to areas that require removal or reworking
- Testing the compacted clay using nuclear moisture and density method ASTM D6938 and in-situ Shelby tubes permeability testing using ASTM D 1587

A facility may use alternate methods for placement of compacted material, which will require equivalency testing and construction of a test pad, with the approval of EGLE.

Part 115, R299.4915 details the requirements of the FML component of the composite liner system. R299.1918 details the construction records of the FML component. The sections provide source material testing requirements and details to construct the FML liner. A CQA officer is responsible for observing:

- Grading and preparation of the foundation for the FML
- Storage of the geosynthetic material in a safe location
- Deployment of the panels to reduce stress and damage to the material
- Welding seams of the panels done in accordance with design specifications and CQA Plan
- Repairs to the FML
- Construction and backfill of the anchor trench
- After being constructed, the FML is covered within 30 days

Part 115, R299.4919 details the requirements of the leachate collection system component of the liner system. The section provides source material testing requirements and details how to construct the leachate collection system. A CQA officer is responsible for observing:

- Observations and testing of pipes, geosynthetics, and drainage material included in the leachate collection system
- Observation that pipes, geosynthetics, and drainage material are placed in accordance with design, specifications, and CQA Plan
- Tests to verify hydraulic conductivity
- Survey of pipe and drainage material grades
- Testing of sump and leachate removal equipment

R299.4921 provides requirements of the final CQA certification report once the construction of the new cell is finished. The certification report will include:

- All relevant construction records for each aspect of the liner construction
- CQA officer and engineer's certification
- Daily activity log for each day of construction works

Landfill liner CQA does not require leak location survey upon completion of the liner system construction.

3.1.2.3 Leachate Drainage Layer and Groundwater Contamination

The leachate collection and removal system is detailed in Part 115: R299.4423. The design goals of the leachate collection system are as follows:

- Maintain less than one foot of leachate head on top of the primary (uppermost) liner
- Extend over the entire primary (uppermost) liner
- Be chemically resistant to expected leachate concentrations
- Minimize clogging through post closure period
- Drain leachate to designed, adequate-sized, sumps

The standards specify requirements of each part of the drainage layer, including the drainage material and pipework, to meet the design goals. The requirements of the drainage material are:

- Minimum one foot thick with minimum hydraulic conductivity of 1×10^{-2} cm/sec. The material may have a lower hydraulic conductivity of 1×10^{-3} cm/sec if it is placed in conjuncture with a geosynthetic with a one cm/sec hydraulic conductivity
- Free of organic material and less than five percent fines by weight
- Minimum slope of two percent in direction perpendicular to the pipework
- Free of angular stones that may puncture or damage the primary (uppermost) liner unless a cushion geotextile is used to protect the liner

The drainage layer shall provide puncture protection to the liner from waste. To do this, the drainage layer may be increased to two feet thick with a minimum hydraulic conductivity of $1\text{x}10^{-4}$ cm/sec. Otherwise, the design may use a cushion geotextile or limit the type of waste placed within the first five feet above the liner system.

Requirements of the leachate pipework are:

- Wall thickness to withstand expected pressure loads
- Diameter capable of transporting expected leachate collection
- Slope of one percent drainage layer flow to the sumps; design must prove the pipe will maintain grade after settlement
- Sufficient manholes and cleanout risers to conduct proper maintenance and cleaning of pipework

- Not spaced more than 50 feet from the high point of the drainage layer, unless calculations can prove a longer effective length
- Pipework shall utilize a filter layer which utilizes one of the following:
  - Cohesionless soil with max particle size of three inches and less than five percent fines by weight
  - Geotextile filter capable of passing expected flow

For unmonitorable or non-natural soil barrier sites, the design must include a secondary collection system (leak detection layer for unmonitorable units) between the primary (uppermost) and secondary (lowermost) liners. R299.4424 provides the design considerations of this layer:

- Be capable of detecting, collecting, and removing accumulation of hazardous constituents that have traveled through the primary (uppermost) liner during the active and post closure periods of the landfill
- Have a slope of one percent or greater after settlement
- Be a granular material 12 inches thick and a minimum hydraulic conductivity of 1×10^{-2} cm/sec or greater or shall be a geosynthetic 100 mil thick with a minimum hydraulic conductivity of 1 cm/sec. The site may propose an alternative option utilizing soil and geosynethtic having a combination of a hydraulic transmissivity of 5×10^{-4} m2/sec
- Composed of material compatible with expected leachate concentrations
- Designed to minimize clogging during active and post closure life
- Utilizes sumps and pumps that are designed to prevent liquids from collecting in the leak detection layer

Leak detection systems are permitted with a response flow rate. A landfill which uses compacted clay is generally permitted 200 gallons per acre per day for their leak detection layer. A liner which utilizes an option other than compacted clay (i.e., GCL) is generally permitted 25 gallons per acre per day for their leak detection layer. The larger permitted pumping rate for clay is from the natural groundwater or consolidation of the clay material.

Additionally, if the landfill liner leak detection layer collects leachate below a certain limit, the facility may be eligible for reduced monitoring requirements for groundwater.

3.1.3 Illinois

Landfill regulations for the state of Illinois are located in Administrative Code Title 35: Environmental Protection Subtitle G: Waste Disposal, Chapter I: Pollution Control Board, Subchapter i: Solid Waste and Special Waste Hauling, Part 811 Standards for new Solid Waste Landfills.

The state currently regulates 35 active landfills spread across the entire state based on records from the Illinois Environmental Protection Agency (IEPA) and USEPA. The state regulates both privately owned sites as well as local publicly owned landfills. There are several dozen former landfill facilities currently in post closure care period as well as 33 landfills that were abandoned without proper closure construction or containment works.

The northern half of the state shares similar climate regions with Wisconsin, while the state's southern region is slightly warmer with less snowfall and freeze-thaw conditions than found in Wisconsin.

3.1.3.1 Liner Design Requirements

Section 811.306 of the administrative code detail the requirements of new landfill liner design. Illinois notes two standards for liners. Compacted earth liner standards detail that a liner shall be minimum 1.52 meters thick (five feet) and have a maximum hydraulic conductivity of $1x10^{-7}$ cm/sec. The soil material used to construct the liner should be compatible with the concentration and amount of contaminant likely to be generated within the facility.

The requirements state that alternative liner designs that consist of a geomembrane component may be used in place of the compacted earth liner design. The geomembrane shall be 60 mil thick with a compacted earth component no less than three feet thick. Experience with liner designs in Illinois indicate that all new liners incorporate a composite system and do not use the compacted earth liner. Additionally, it is unlikely the compacted earth liner will meet the requirements of the groundwater modeling discussed below.

Illinois does not specify liner or side slope grades or separation between landfill liner and groundwater. Instead, the state utilizes the groundwater contaminant transport modeling discussed below to determine appropriate design constraints to limit leachate percolation or migration.

3.1.3.2 Construction Quality Assurance

Section 811 Subpart E details CQA requirements of landfill construction. The subpart is divided into nine sections, with each detailing a different aspect of CQA requirements or defining roles or testing procedures.

The site shall engage a third-party contractor, which is a registered professional engineer in the state of Illinois to conduct the CQA works. The CQA officer shall be responsible for overseeing all inspections, tests, and other works relevant to the construction of the landfill cell which include:

- Subgrade and foundation compaction
- Placement of compacted earth liner
- Geomembrane installation
- Installation of any slurry walls or trenches
- Installation of leachate drainage and collection system
- Application of final cover
- Installation of gas collection and control system
- Construction of ponds, ditches, lagoons, or berms

The CQA officer shall be present for all work unless the facility designates a CQA officer-in-absentia to carry out responsibilities. The CQA officer shall still assume all responsibility of the regulatory requirements. The responsibilities include documentation of daily summary reports, daily inspection records, photographic logs of construction progress, and acceptance reports for final certification that construction was completed in accordance with the design.

The main CQA requirements during liner construction are further detailed for compacted earth liners, geomembranes, and leachate collection system construction. The compacted earth liner CQA requirements include:

- Oversight of construction of test liner for each borrow source with minimum three lifts of compacted earthen material; the test liner shall be tested for hydraulic conductivity, particle size, water content, and density
- Oversight of actual earthen compacted liner to conclude material, equipment, and methods are in accord with the test liner
- Testing of density, water content, and permeability of each successive lift
- Use of methods to bond lifts
- Checking for liner strength on sidewalls
- Contractor protects earth material to prevent drying or desiccation and that construction only takes place during favorable weather
- Ensure material placed is not frozen or placed on top of frozen material
- Observe any damage to liner sections during construction

CQA geosynthetics installation requirements include:

- Inspection of bedding material for undesirable objects
- Inspection of anchor trench
- Placement of material is in line with CQA placement plan
- Repairs to all tears, rips, punctures, or damage
- Adequate construction and testing of all seams

Lastly, the leachate collection system CQA requirements include:

- Verify pipe sizes, material, perforations, placement, and grades are in accordance with the design
- Verify soil drainage material and filter material are adequate for gradation specification and design plans
- Inspect prefabricated materials for defective manufacturing and conformity with design specifications

3.1.3.3 Leachate Drainage Layer and Groundwater Contamination

Requirements of the leachate drainage and collection systems are detailed in Sections 811.307 and 811.308. The system shall include:

- Maintaining a leachate head of one foot or less with a drainage layer at least one foot thick and a hydraulic conductivity equal to or greater than 1×10^{-3} cm/sec. The drainage system shall be capable of maintaining these heads during the months with highest average precipitation and highest groundwater seasonal groundwater levels. Modeling shall assume airspace is filled with a final cover system in place.
- Design shall maintain laminar flow through the drainage layer.
- Materials used in the drainage and collection system shall be chemically compatible with the type and amount of leachate likely to be encountered.

- Drainage layer shall incorporate a geotextile filter material to prevent clogging and obstruction of fine materials.
- Collection pipes shall be designed for open channel flow and be of a cross section which allows cleaning and be designed to support the maximum loads imposed by the overlaying materials.
- Pipe designs shall include drainage gravel or filter fabric material to minimize clogging.
- System shall include sufficient manholes and cleanouts to provide cleaning and maintenance of the system throughout the design period.
- Leachate shall drain freely from the collection pipes. If sumps are used, the leachate level shall be maintained below the invert of the collection pipes.

As part of the design, the site is required to conduct contaminant transport modeling. The model shall estimate the amount of leachate percolation from the designed liner system. The site is also required to test for the concentrations of contaminants within the leachate or from similar waste and use these values to create a contaminant transport model for groundwater modeling. As discussed in Section 4.0, these assessments would include conducting a Hydrologic Evaluation of Landfill Performance (HELP) model assessment and MODFLOW analysis for groundwater transport.

Illinois provides standards for the contaminant transport model. The site must use well-documented and theoretically sound numerical solutions to calculate the contaminant transport. The model must be calibrated using site-specific information such as in-situ soils, groundwater levels, and background groundwater concentrations. All site-specific data should be supported by laboratory analysis and test results.

Lastly, a sensitivity analysis and mass balance analysis shall be conducted on the model to determine the model's response to changes in values of the model parameters, error tolerances, and numerically assigned space and time discretization. The mass balance analysis shall provide evidence to verify the model's physical validity.

3.1.4 Indiana

Indiana currently regulates 29 active landfill sites spread across the entire state based on records from the Indiana Department of Environmental Management (IDEM) and USEPA. Only six of the active landfills are publicly-owned county landfills with the rest owned by private entities.

The state shares very similar conditions to Illinois. The northern half of the state nearby to Lake Michigan shares similar climate to Wisconsin, while the state's southern region is slightly warmer with less snowfall and freeze-thaw conditions than found in Wisconsin.

Landfill regulations for the state of Indiana are located in State Administrative Code 329 Section 10-17 – Municipal Solid Waste Landfill Liner Systems; Design, Construction, and CQA/CQC Requirements. This section of the administrative code is divided into 18 sections but focuses on nine main topics:

- Landfill subgrade
- Liner soil component
- Liner geomembrane component
- Drainage layer

- Geosynthetic clay component
- Protective cover
- Optional drainage layer
- Alternative liner designs
- Municipal solid waste liner systems

3.1.4.1 Liner Design Requirements

Indiana's landfill liner regulations are dependent on the landfill location and depth to groundwater. If the bottom of the liner is located more than 10 feet above the top of the uppermost aquifer or if the landfill is located outside an "aquifer of significance," the landfill liner shall consist of:

- Three feet of compacted soil with a maximum hydraulic conductivity of 1×10^{-7} cm/sec
- Geomembrane, 60 mil if HDPE, 30 mil otherwise
- Drainage layer
- Protective cover layer

If the landfill is located within 10 feet of the upper most aquifer or above an "aquifer of significance," the landfill liner must consist of:

- Two feet of compacted soil with a maximum hydraulic conductivity of 1×10^{-6} cm/sec as a separation layer from the groundwater and under liner drainage layer
- Under liner drainage layer
- Three feet of compacted soil with a maximum hydraulic conductivity of 1×10^{-7} cm/sec
- Geomembrane, 60 mil if HDPE, 30 mil otherwise
- Drainage layer
- Protective cover layer

Sump areas of the landfill cell must include the following:

- The sump liner must extend 10 feet beyond the edge of the sump
- Two feet of compacted soil with a maximum hydraulic conductivity of 1×10^{-6} cm/sec as a separation layer from the groundwater and leak detection layer
- Leak detection layer
- Three feet of compacted soil with a maximum hydraulic conductivity of 1×10^{-7} cm/sec
- Geomembrane, 60 mil if HDPE, 30 mil otherwise
- Geosynthetic clay liner

- Geomembrane, 60 mil if HDPE, 30 mil otherwise
- Drainage layer
- Protective cover layer

Liners must be graded at a minimum of two percent toward the leachate drainage collection system. Soil component designs must include components to address uplift from hydrostatic components, control of freeze/thaw cycles and wet/dry cycles, and any other components requested by the IDEM.

GCL's used in the sump area are not specified for type or quality. The decision of quality is left to the design engineer.

3.1.4.2 Construction Quality Assurance

Indiana regulations divide CQA components for each component of the liner. In addition to requiring the landfill cell designer to provide a construction plan; the requirements provide specific tests, methods, and procedures required as part of the plan. Indiana's CQA requirements provide some of the most specific of any state in Region 5.

An onsite CQA official is responsible for supervision of each of the following aspects of the construction. For subgrade material and preparation, prior to placement of any new material, the subgrade material shall be tested for moisture and density and inspected by the CQA officer.

Regulations detail specific soil component tests and frequencies for both source material and onsite sampling including:

- Grain size
- Moisture
- Atterberg
- Density
- Conductivity

Additionally, a test pad must be constructed for each borrow source material used for the soil component of the liner system.

The geomembrane component of the liner shall have full-time CQA observation during installation. Regulations detail specific requirement for all aspects of the design including:

- Source testing requirements
- Review of manufacturer's quality control documentation
- Subbase inspection
- Panel placement requirements
- Anchor trench inspection and construction
- Trial welds

- Seaming instructions
- Repair instructions
- Seam testing for extrusion and fusion welding

Drainage layer and protective cover material CQA depends on if the design uses a soil or geosynthetic material for each layer. Regulations for geosynthetic material list between 10 and 21 tests required for source material for geotextiles, geonets, or geocomposites. Soil material used for the drainage layer requires material size testing and chemical components testing for carbonate content and pH to ensure the drainage material is not damaged or destroyed through the design life by the leachate's chemical composition.

3.1.4.3 Leachate Drainage Layer and Groundwater Contamination

Drainage material above the geomembrane needs to be either a coarse-grained soil component or geosynthetic component. If the drainage material is soil, it must be free of organic material, be a minimum 12 inches thick, and have a minimum hydraulic conductivity of $1x10^{-2}$ cm/sec. If the drainage layer is a geosynthetic, it must be compatible with the leachate within the landfill, must not be compromised by a compressive load, and have a minimum transmissivity of 3×10^{-5} m^2/s. Regulations also provide requirements for filter geotextiles if they are included in the drainage layer design. The geotextile requirements detail permeability, soil particle retention, constructability, and resistance to physical and chemical conditions within the bottom of the landfill liner.

Design of the leachate collection pipes included in the landfill cell must include:

- A minimum six inches in diameter and a slope of one percent toward collection structures
- Chemical properties that are not adversely affected by the leachate concentrations within the landfill
- Structural strength to withstand pressures applied by all subsequent layers placed on top of them
- The length of the pipes must be capable of being cleaned out with available equipment

Protective cover material must be placed over the leachate drainage layer. There are three soil options and one geosynthetic option for the protective cover layer.

- A soil material that brings the thickness of the combined drainage layer and cover layer to 30 inches
- Eighteen inches of bottom ash or foundry sand if the drainage material is sand
- Thirty inches of bottom ash or foundry sand if the drainage material is a geosynthetic

Soil materials must be free of organic material and meet soil classification and grain size requirements allowing a majority sand or gravel material.

The regulations allow the use of a cushion geotextile for use as an alternative geosynthetic protective cover. The cushion geotextile must be minimum 16 oz per square yard and covered with 12 inches of well or poorly graded gravel material.

3.1.5 Ohio

Landfill liners in Ohio are regulated by Ohio Administrative Code 3745-27-08 Sanitary Landfill Facility Construction. Landfill locations and general permitting are regulated by Ohio Administrative Code 3745-27-07 Additional criteria for approval of sanitary landfill facility permit to install applications.

The state currently regulates 38 active landfills spread across the state based on records from the Ohio Environmental Protection Agency (Ohio EPA) and the USEPA. Of the active landfills in the state, 12 are publicly-owned county landfills and the rest are privately owned.

Ohio shares similarities with Wisconsin being a midwestern and Great Lakes state but is likely the least similar state to Wisconsin in the USEPA Region 5. The majority of Ohio has similar precipitation but average temperatures approximately 10 degrees warmer than Wisconsin.

3.1.5.1 Liner Design Requirements

Prior to finalizing the design of the landfill liner, the liner has limitations for location and elevations in relation to groundwater aquifers:

- Landfill footprint or subsurface pipework shall not be placed within a mining operation's former sand or gravel pit unless the deposit has been completely removed
- Landfill footprint or subsurface pipework shall not be placed within a former limestone or sandstone quarry
- Landfill footprint or subsurface pipework shall not be placed above any location deemed by the Safe Drinking Water Act to be a sole source aquifer
- Extents of waste or subsurface pipework shall not be placed above an unconsolidated aquifer system capable of sustaining a yield of one hundred gallons per minute for a 24-hour period
- The bottom elevation of the liner or leachate storage shall not be within 15 feet of the uppermost aquifer after accounting for consolidation

The regulations also provide setbacks for extent of waste from underground mines, public drinking water sources, private drinking wells, surface waters, domiciles, property lines, and natural areas such as state parks or protected forests.

The general design criteria for the landfill liner are:

- To serve as a barrier to prevent discharge of leachate to ground or surface waters
- To have a two percent slope in all areas except those with flow paths altered by leachate pipes
- Maximum slope is based on compaction equipment limitations and slope stability calculations

The regulation detailing liner constraints and construction, OAC 3745-27-08, states that, at a minimum, a landfill liner shall consist of:

- A prepared in-situ foundation
- Three-foot recompacted soil liner or two-foot recompacted soil liner below a geosynthetic clay liner; soil material shall have a maximum permeability of $1x10^{-7}$ cm/sec.
- Flexible membrane liner at least 60 mil thick HDPE

Ohio EPA allows for the use of a GCL through the requirement in the September 17, 1997 Ohio EPA Memorandum titled "Advisory on Structural Integrity Considerations for Incorporating Geosynthetic Clay Liners In Solid Waste Landfill Facility Design." This document includes reference to regulatory considerations in OAC

2745-27-06(C)(4)(j) for use of GCL with requirements for fluid migration and bentonite mass per unit area. Additionally, the GCL must be considered as part of the geotechnical analysis requirements and calculations per the Ohio EPA's Geotechnical Resource Group "Geotechnical and Stability Analyses for Ohio Waste Containment Facilities" (GoegRG) Manual, dated September 14, 2004. Requirements include performing conformance testing for internal shear testing of the GCL as well as interface shear testing with the surrounding liner materials for use in a geotechnical slope stability model with resulting minimum factors of safety (FSs) of greater than 1.3 for post-peak (residual) static stability and greater than 1.1 for post-peak seismic stability. GCLs used may be reinforced or reinforced per the design slope requirements and resulting FSs.

The same standard (OAC 2745-27-08) identifies that the minimum required for a leachate collection and control system shall constitute:

- Leachate collection layer
- Leachate collection pipes
- Filter layer
- Sump
- Leachate conveyance apparatus

3.1.5.2 Construction Quality Assurance

For each aspect of the liner design, the regulations detail construction requirements including source material testing, construction tests (i.e., density or proof rolling), strength requirements, and construction methods.

For the in-situ foundation, the material shall be free of debris and foreign matter and contain no solid waste. It shall not have grade changes that may damage the liner. A CQA officer shall be responsible for proof rolling the material prior to placement of subsequent layers. The material shall be resistant to corrosion and have adequate bearing capacity.

Structural fill or clay liner material have similar requirements as in-situ foundation except any material from a borrow source requires pre-construction source material testing in the form of a test pad and frequent quality assurance (QA) testing for a variety of factors not limited to density, Atterberg, moisture content, permeability, and grain size. The material shall be observed during placement for lift thickness, lift compaction, and damage from freeze/thaw or wet/dry cycles.

If the design includes a GCL, it shall be negligibly permeable to fluid migration. It shall have a bentonite mass per unit area of at least one pound per square foot. Representative samples and test results of the GCL shall be submitted to the Ohio EPA not later than seven days prior to use onsite. While placing GCL, the CQA officer shall ensure it is installed in accordance with manufacturer's requirements, with appropriate overlap and seaming, and is placed on clay without sharp edges or protrusions.

FML requirements that shall be recorded as part of the CQA include:

- Chemically and physically resistive to corrosion using ASTM 9090
- Interface shear testing
- Installer qualifications

- Continuous seaming to account for negligible defects
- Cleaned for deleterious material
- Trial welds of welding equipment
- Non-destructive testing of all seams
- Destructive testing on limited seams
- Dipole Leak Location Testing conducted after completion of liner

OAC 3745-27-08(H) lays out the requirements of a CQA report to be prepared and signed by a registered professional engineer in the state of Ohio and submitted to the Ohio EPA and Board of Health. The report is required to include:

- Narrative section that identifies components of the design and includes summary of the design and construction specifications, as well as a summary of how construction was impacted by weather or other limitations
- List of alterations to the design over the course of construction including alterations approved by Ohio EPA, alterations needing approval by Ohio EPA, and list of alterations that do not require approval
- Results of all tests conducted as part of the quality control plan including testing procedures, frequency, location, and parameters
- Results of all surveys conducted as part of construction including extent and thicknesses of each element of the liner system
- Record drawings showing as-built plan views and details of all aspects of the liner system
- Qualification of testing personnel
- Documentation of any oil or gas wells identified within the limits of solid waste and evidence they have been plugged or contained appropriately
- Detailed drawing package of survey control points showing coordinates
- Notarized statement that, to the best of the knowledge of the owner or operator, the certification report is true, accurate, and contains all information in accordance with this rule and the quality assurance/quality control plan
- Copies of daily construction logs to be made available to the Ohio EPA upon request

3.1.5.3 Leachate Drainage Layer and Groundwater Contamination

The general design requirements of the leachate collection system are to:

- Incorporate adequate measures to remove leachate from the landfill
- Ensure that materials used are protective of the FML or include a cushion geotextile
- Designed to withstand expected pressures and loads

- Designed to minimize clogging
- Ensure materials are physically and chemically resistant to expected leachate concentrations
- Limit leachate head to one foot above the FML
- Have at least a 0.5 percent grade for collection pipes in all areas after accounting for consolidation

OAC 3745-27-08(D)(12) gives specific design constraints for the leachate collection layer:

- Shall be at least one foot thick with less than five percent fines by weight and a minimum hydraulic conductivity of 1.0×10^{-2} cm/sec.
- Maximum five percent carbonate content by weight
- Shall have testing for source and onsite quality control testing for grain size, permeability, and carbonate content
- Shall not be placed on FML with wrinkles over four inches

If a geocomposite is used in place of drainage aggregate, the design shall provide the following:

- Provide evidence the geocomposite shall limit leachate head below one foot on top of the liner system
- Twelve inches of permeable material shall be placed on top of the composite to provide protection of the FML
- Quality control testing for transmissivity of the geocomposite during construction

Leachate collection pipes shall:

- Be embedded in the drainage layer
- Provide access for cleanout devices that are protected from settlement
- Have lengths and configurations that do not inhibit cleanout devices
- Have sealed joints to prevent separation
- Have sealants and means of cleaning access resistant to solid waste and leachate contaminants

A filter layer designed to minimize clogging of the leachate collection layer shall be installed above the drainage material.

Sumps shall be resistant to leachate concentrations and contaminants and be fitted with high level alarms.

3.2 Other States for Discussion

In addition to the USEPA Region 5 states, the WDNR requested that Golder detail other states including New York and Pennsylvania.

3.2.1 New York

Landfills in New York are regulated by New York Code Rules and Regulations, Title 6, Chapter IV, Subchapter B, Part 363 (6 CRR-NY §363).

The state currently regulates 27 active MSW landfills as per the New York State Department of Environmental Conservation (NYSDEC) and USEPA.

New York was chosen as a state for review by the WDNR due to its somewhat similar climate and proximity to the Great Lakes. The average rainfall across the state is slightly higher than Wisconsin. The eastern half of the state experiences slightly warmer temperatures with a longer growing season than Wisconsin.

3.2.1.1 Landfill Liner Requirements

6 CRR-NY §363-6.6 requires that landfill liner systems consist of (from bottom to top):

- Minimum two-foot-thick compacted soil layer with maximum hydraulic conductivity of 1x10^{-7} cm/sec
- 60-mil thick HDPE geomembrane liner
- Cushion geotextile
- Secondary leachate collection system consisting of a geocomposite drainage layer and 12 inches of drainage stone (slopes less than 10 percent only)
- GCL required as part of primary composite on slopes less than 10 percent
- 60-mil thick HDPE geomembrane liner
- Cushion geotextile
- Minimum 24-inch thick primary leachate collection system

The bottom of the liner system shall be at minimum 10 feet above bedrock. The subgrade below the liner system shall consist of in-situ soil layer or select fill consisting of low permeability soils with silty and clayey characteristics. The material must be capable of attenuating and absorbing contaminants. The bottom of liner must also be at least five feet above the seasonal high groundwater level. If the bottom liner is lower than five feet above the season high groundwater level, then a groundwater suppression system must be constructed.

3.2.1.2 Construction Quality Assurance

New York State landfill liner CQA is regulated by 6 CRR-NY §363-6.19 Construction certification. The requirements detail:

The certification required in Section 360.16(j) of this Title must include a report prepared by the project engineer which demonstrates that the landfill was constructed in accordance with the department-approved engineering design and permit requirements, and the report must include the following:

(a) at a minimum, all CQA and CQC testing as required in this Subpart. It must include documentation of any failed test results and results of all retesting performed, descriptions of procedures used to correct improperly installed, damaged, or irregular material, and electrical resistivity leak location survey data and reports;

(b) record drawings noting any deviation from the approved engineering plans;

(c) a comprehensive narrative including, but not limited to, daily reports from the project engineer and a series of color photographs of major project features;

(d) a certification that the primary liner system leakage rate was below 20 gallons per acre per day using a rolling average for 30 consecutive days:

> *(1) during the primary liner leakage rate evaluation period, at least one inch of rain or equivalent must be introduced into the cell. Data verifying acceptable primary liner performance, including precipitation or the introduction of water to the cell must be provided in the construction certification report; and*
>
> *(2) the liner performance evaluation period may not be conducted under frozen ground conditions;*

(e) certification that an electrical resistivity leak location evaluation, and/or other geomembrane liner integrity evaluation as approved by the department was conducted on both the primary and secondary liners in accordance with the provisions of section 363-6.8(c)(3)(vii) of this Subpart.

As noted in Section (a), the certification report requires documentation of all testing conducted as part of the construction works. The regulations for each section of the liner detail what tests are required for that section.

3.2.1.3 Leachate Drainage Layers

The primary leachate collection layer located above the primary (upper) liner shall have the following design:

- Designed to maintain no more than 12 inches of leachate head, except during 24-hour, 25-year storm events and except in sump areas
- Primary leachate collection layer shall be minimum two feet thick
- On slopes 10 percent or less, the lower 12 inches must have a hydraulic conductivity of 1 cm/sec or greater and the upper 12 inches must have a hydraulic conductivity of 0.1 cm/sec or greater
- On slopes greater than 10 percent, the drainage layer must have a hydraulic conductivity of 0.1 cm/sec or greater

The secondary leachate collection layer located between the composite liners shall have the following design:

- The system must be capable of removing 1,000 gallons of leachate per acre per day with a maximum detection time of 24 hours
- On slopes 10 percent or less, a geosynthetic drainage layer and a minimum of one foot of soil drainage material with a hydraulic conductivity of 0.1 centimeter per second or greater and a maximum leachate depth (head) of one inch
- On slopes greater than 10 percent, system may be constructed of a geosynthetic drainage layer system designed to meet the hydraulic and mechanical needs of the landfill with a head that does not exceed the thickness of the confined drainage layer

The following are design components of the leachate collection systems:

- Drainage aggregate material shall be less than five percent fines, no more than 15 percent calcium carbonate
- Drainage aggregate shall be graded no less than two percent

- Leachate collection pipes shall be minimum eight inches in diameter for primary pipes and minimum six inches for secondary pipes; pipes shall have adequate structural strength for expected loads and be chemically compatible with expected leachate composition
- Leachate pipes shall have a minimum grade of one percent
- Pipes shall be designed to allow for access for cameras and cleaning equipment
- Pipes outside liner shall be double-walled
- Geosynthetic drainage materials shall be designed for chemical compatibility with leachate and accounted for creep, transmissivity, and clogging with a FS of 3

3.2.2 Pennsylvania

Pennsylvania is the northernmost state in USEPA Region 3. The region also includes Virginia, West Virginia, Maryland, and Delaware. Pennsylvania landfills are regulated by Pennsylvania Code Title 25 Chapter 273 – Municipal Solid Waste Landfills (25 PA Code §273). The state was selected by the WDNR for comparison with Wisconsin and other USEPA Region 5 states due to its proximity to the Great Lakes as well as its somewhat similar freeze and thaw cycles as Wisconsin.

The state currently regulates 43 active landfill sites as per the Pennsylvania Department of Environmental Protection (PADEP) and USEPA. The landfills are mostly located within the southern half of the state close to the Pittsburgh and Philadelphia metro areas on the western and eastern sides of the state, respectively. Of the active landfills, only eight are publicly owned.

3.2.2.1 Liner Design Requirements

As per 25 PA Code §273.251, a liner system shall include the following elements:

- Six-inch-thick subbase layer with maximum hydraulic conductivity of $1x10^{-5}$ cm/sec*
- Secondary (lower) liner
- Leachate detection system
- Primary (upper) liner
- Protective cover and leachate collection layer

*Note that, based on Golder's experience, the subbase layer is usually replaced with a GCL, which has been approved by PADEP at multiple sites in Pennsylvania.

Either the primary or secondary liner shall be constructed as a composite liner.

Other general limitations of the liner design include:

- Bottom of a subbase may not be in contact with a seasonal high groundwater table or perched water table. Drainage and pumping systems may be used, but only if they do not adversely affect public or private water supply.
- Eight feet of separation between bottom of subbase and regional groundwater table in an unconfined aquifer. The unconfined aquifer may not be artificially lowered.

- In a confined aquifer, at least eight feet shall be maintained between the bottom of the subbase of the liner system and the top of the confining layer or the shallowest level below the bottom of the subbase where groundwater occurs as a result of upward leakage from natural or preexisting causes. The integrity of the confining layer may not be compromised by excavation.
- Slopes shall be minimum two percent and maximum 33 percent after settlement.

The secondary and primary liner are regulated with the exact same requirements, except that only one of the two is required to be a composite liner. The design requirements include:

- Be no more permeable than 1 x 10^{-7} cm/sec based on laboratory and field testing.
- Be installed according to manufacturer's specifications under the supervision of an authorized representative of the manufacturer if the liner is synthetic. An approved quality assurance and quality control plan shall be implemented in the field during the installation of the liner.
- Be designed, installed, and maintained according to a quality assurance and quality control plan approved by the Department if the liner is remolded clay.
- Be inspected for uniformity, damage, and imperfections during construction and installation.

Whichever of the two liners is the composite liner, the design shall include:

- An upper component made of a manufactured geosynthetic liner which is 60 mil thick if HDPE, 30 mil if other material
- A composite component two feet thick made of earthen material except that the composite component may be no more permeable than 1.0 x 10^{-7} cm/sec. based on laboratory and field testing
- The two components of the composite liner shall be designed, constructed, and maintained to provide a compression connection or direct, continuous, and uniform contact between them.

3.2.2.2 Construction Quality Assurance

As per 25 PA Code §273.161, the facility is responsible for submission of a quality control plan to the PADEP prior to construction of the liner. The plan must include:

- Description of the testing procedures and construction methods to be used
- Description of the manner the protective cover and liner system will be maintained and protected in unfilled portions in the initial life of the new cell
- Protection from weather
- Sampling plan for every component of the liner system including sample size; methods for determining locations, frequency, and acceptance criteria; and method for ensuring that corrective measures are implemented
- Plan for documenting compliance with the quality control plan

3.2.2.3 Leachate Drainage Layers

The secondary leachate detection layer between the two liners shall:

- Rapidly detect and collect liquid entering the leachate detection zone and rapidly transmit the liquid to the leachate treatment system
- Withstand chemical attack from waste or leachate
- Withstand anticipated loads, stresses, and disturbances from overlying waste, waste cover materials, and equipment operation
- Function without clogging
- Prevent the liner from cracking, tearing, stretching, or otherwise losing its physical integrity
- Cover the bottom and sidewalls of the facility
- Be at least 12 inches thick
- Contain no material exceeding 0.5 inches in particle size
- Create a flow zone between the secondary liner and the primary liner equal to or more permeable than 1 x 10^{-2} cm/sec based on a laboratory and field testing
- Contain a perforated piping system capable of detecting and intercepting liquid within the leachate detection zone and conveying the liquid to a collection sump for storage, processing, or disposal. The sump shall be separate from the leachate collection sump and shall be of a sufficient size to transmit leachate that is generated.
- The piping system shall also meet the following:
  - The slope, size, and spacing of the piping system shall assure that liquids drain from the leachate detection zone
  - The pipes shall be installed primarily perpendicular to the flow and shall have a minimum post settlement grade of at least two percent
  - The minimum diameter of the perforated pipe shall be four inches with a wall thickness of Schedule-80 or greater, as specified by ASTM or equivalent
  - The pipes shall be cleaned and maintained, as necessary
  - The leachate detection zone shall have a minimum bottom slope of two percent
  - Contain stone or aggregates without sharp edges

The protective cover and primary leachate collection system shall:

- Protect the primary liner from physical damage from stresses and disturbances from overlying wastes, waste cover materials, and equipment operation
- Protect the leachate collection system within the protective cover from stresses and disturbances from overlying wastes, waste cover materials, and equipment operation
- Allow the continuous and free flow of leachate into the leachate collection system within the protective cover

- Cover the bottom and sidewalls of the disposal area
- Ensure that free flowing liquids and leachate will drain continuously from the protective cover to the leachate treatment system without ponding or accumulating on the liner
- Ensure that the depth of leachate on or above the primary liner does not exceed one foot
- Withstand chemical attack from leachate
- Function without clogging
- Protective cover shall be comprised of clean earth material that contains no aggregate, rocks, debris, plant material, or other solid material larger than one-half-inch in diameter and no material with sharp edges
- Minimal hydraulic conductivity of 1 x 10^{-2} cm/sec based on field testing and shall allow the free flow of liquids and leachate passing through or generated by solid waste
- At least 18 inches in thickness
- The leachate collection system shall include a perforated piping system which is capable of intercepting free flowing liquids and leachate within the protective cover and conveying them to a collection sump for storage, processing, or disposal. The collection sump shall be of sufficient size to transmit leachate that is generated and shall be capable of automatic and continuous functioning.
- The perforated piping system shall be sloped, sized, and spaced to assure that free flowing liquids and leachate will drain continuously from the protective cover to the collection sump or point.
- The minimum diameter of the perforated pipes shall be six inches with a wall thickness of Schedule-80 or greater, as specified by ASTM or equivalent
- The leachate collection system shall contain stones or aggregates
- The pipes shall be installed primarily perpendicular to the flow and shall have a post-settlement grade of at least two percent
- The leachate collection system shall be cleaned and maintained, as necessary
- The leachate collection system shall have a minimum bottom slope of two percent

3.3 Alternate Liner Approvals Methods

In addition to the landfill liner requirements, this report has reviewed the process for approving alternate liner designs than those detailed in state code or regulations. As per WDNR request, this section has reviewed the process for submitting, reviewing, and approving alternate designs for landfill bottom liners for each of the USEPA Region 5 states.

3.3.1 USEPA Region 5 States

3.3.1.1 Wisconsin

Wisconsin Chapter NR 512.05 discusses the requirements of the Feasibility Study of a new landfill cell. The requirements include the following concerning alternate liner designs:

Applicants proposing an alternative design to the requirements contained in ss. NR 504.05, 504.06, 504.07, 504.08 and shall 504.09 include an analysis that predicts whether the proposed landfill will meet or exceed the performance standards of s. NR 504.04(4) (d) regarding groundwater quality.

The performance standards referenced in NR 504.04(4)(d) state the following:

(4) PERFORMANCE STANDARDS. No person may establish, construct, operate, maintain or permit the use of property for a landfill if there is a reasonable probability that the landfill will cause:

(a) A significant adverse impact on wetlands as provided in ch. NR 103.

(b) A take of an endangered or threatened species in accordance with s. 29.604, Stats.

(c) A detrimental effect on any surface water.

(d) A detrimental effect on groundwater quality or will cause or exacerbate an attainment or exceedance of any preventive action limit or enforcement standard at a point of standards application as defined in ch. NR 140. For the purposes of design the point of standards application is defined by s. NR 140.22(1).

(e) The migration and concentration of explosive gases in any landfill structures excluding the leachate collection system or gas control or recovery system components in excess of 25% of the lower explosive limit for such gases at any time. The migration and concentration of explosive gases in the soils outside of the limits of filling within 200 feet of the landfill property boundary or beyond the landfill property boundary in excess of the lower explosive limit for such gases at any time. The migration and concentration of explosive gases in the air outside of the limits of filling within 200 feet of the landfill boundary or beyond the landfill property boundary in excess of the lower explosive limit for such gases at any time.

(f) The emission of any hazardous air contaminant exceeding the limitations for those substances contained in s. NR 445.07.

Feasibility reports submitted to the WDNR should address that the proposed alternate design meets or exceeds each of these performance standards. If the WDNR accepts the alternate design, the approval shall be granted under Chapter NR 500.08(4) which states:

Exemptions from the requirements of chs NR 500 to 538 may be granted in writing by the department in special cases except as otherwise provided.

The department shall consider the application for:

- Population of the area being served
- Amount of waste generated
- Geologic and hydrogeologic conditions of the facility
- Design of the facility
- Operational history of the facility
- Physical and chemical characteristics of the waste
- Any other information which may be appropriate

3.3.1.2 Minnesota

Minnesota landfill regulations 7035.2815, 7(K) states the following concerning use of alternate liner designs:

An alternative liner system design may be used when approved by the commissioner. The commissioner's approval shall be based on the ability of the proposed liner system to control leachate migration, meet performance standards, and protect human health and the environment.

Alternate designs have been based on site-specific requirements and reviewed on an individual basis for landfill liners. Designs have been reviewed with the facility providing liner percolation information, groundwater modeling, and equivalency calculations for use.

Some landfills have requested to use GCLs on side slopes in place of some compacted clay with approval from the state regulators. The use of GCL on side slopes considers the aspect of the liner having little to no leachate head on steeper grades than the base cell while providing equivalent hydraulic conductivity and leachate migration protection.

3.3.1.3 Michigan

EGLE Part 115 Rules allow for a demonstration of equivalency or improvement to the prescribed composite liner and leachate collection system requirements for proposed alternatives. The proposed alternatives must have supporting calculations, testing, and demonstrations to allow for the Department to approve the alternate. EGLE's Operational Memorandum 115-18 provides guidance on when alternate designs require full EGLE approval.

R299.4102(c)(ii)(C) allows the Department to approve alternate soil or GCL components of a composite liner system.

R299.4422 allows the facility to propose an alternate leakage control design (composite liner with natural soil barrier or double composite liner without):

(3)(c)(iii) An alternate system which is approved by the director and which prevents the migration of hazardous substances at least as effectively as the other options specified in this subrule.

R299.4423 allows the facility to propose an alternative leachate drainage system and states the following:

(5) The owner and operator of a type II landfill may propose the use of an alternative drainage system design for a primary leachate collection system if the owner and operator can demonstrate, using mounding calculations and data on liner slope, drainage layer permeability, and flow length, that the alternative system will limit the head on the liner to the same extent as the design specified in subrule (3) of this rule and protect the liner system from waste, ultraviolet light, and other deleterious effects.

R299.4424 allows the Facility to propose an alternative material for the leak detection layer and states the following:

(3) The director shall approve alternative materials to those specified in subrule (2) of this rule if the owner and operator demonstrate that the alternate design is capable of detecting a primary liner leak at least as effectively.

Based on Golder's experience, sites which require dual composite liner designs will often propose a liner design with two GCLs and geomembranes separated by a geocomposite.

3.3.1.4 Illinois

Illinois Section 811.306(g) states:

The owner or operator may utilize liner configurations other than those specified in this Section, special construction techniques and admixtures provided that:

(1) The alternative technology or material provides equivalent, or superior, performance to the requirements of this Section;

(2) The technology or material has been successfully utilized in at least one application similar to the proposed application; and

(3) Methods for manufacturing quality control and construction quality assurance can be implemented.

Illinois does not define "equivalent or superior," which appears to be open for interpretation. Section 811.317 requires the site to conduct a groundwater contaminant transport model previously discussed. The alternate design should provide contaminant containment value greater than the standard design provided in Section 811.306 of the state code.

3.3.1.5 Indiana

Indiana State Code Section 329: 10-17-15 determines the alternate liner design requirements for approval.

(a) The commissioner shall approve alternative liner designs or construction technologies if they are demonstrated, to the satisfaction of the commissioner, to provide at least equivalent protection to public health and the environment as the following:

> *(1) Subgrade design and construction, as specified under section 3 of this rule.*
>
> *(2) Soil liner design and construction, as specified under sections 4 and 5 of this rule.*
>
> *(3) Geomembrane liner design and construction, as specified under sections 6 and 7 of this rule.*
>
> *(4) Drainage layer or leachate collection pipe design and construction, as specified under sections 8 and 9 of this rule.*
>
> *(5) Geosynthetic clay liner design and construction, as specified under section 10 of this rule.*
>
> *(6) Protective cover design and construction, as specified under sections 11 and 12 of this rule.*
>
> *(7) Optional drainage layer filter design and construction, as specified under sections 13 and 14 of this rule.*

While not going into specifics of the term equivalency, the code requires the design to provide assurances that it meets or exceeds each section of the liner component requirements. Therefore, the facility is responsible for showing equivalence for each of the seven sections shown above.

3.3.1.6 Ohio

To accommodate advances in technology, the OAC 3745-27 rules allow alternative materials and thicknesses if the landfill design demonstrates equivalency or improvements and the alternates meet the geotechnical and performance standards in the rule. In general, the facility undergoes a review of the landfill design to demonstrate it is consistent with current design standards every 10 years.

3.3.2 New York

New York State's alternative liner requirements are detailed in Section 363-6.21 Equivalent design standards and use of waste as construction and operational material:

(a) An applicant may propose an equivalent design for any landfill component through the submission of documentation substantiating the alternative component's ability to perform in the same manner as the component specified in this Part. Equivalency determinations are not subject to the variance requirements of section 360.10 of this Title.

(b) When the equivalent design involves the substitution of waste for components of the facility's liner or final cover system, and where it can be demonstrated that these substitutions are below the uppermost barrier layer of the final cover and above the primary composite liner, equivalency determinations are not subject to the variance requirements of section 360.10 of this Title or beneficial use requirements of section 360.12 of this Title.

> *(1) Equivalent design applications for the use of waste tire-derived aggregate in a leachate collection and removal system or gas venting layer must:*
>
> > *(i) address procedures for receipt of waste tires or waste tire-derived aggregate and onsite processing or storage;*
> >
> > *(ii) treat the waste tire-derived aggregate as conventional construction material and comply with the landfill's design and the applicable soil drainage layer provisions of section 363-6.10 of this Subpart. This must include specifications for gradation analysis and permeability testing for both CQA and CQC;*
> >
> > *(iii) specify that the waste tires or waste tire-derived aggregate are free of soil, petroleum products or other contaminants;*
> >
> > *(iv) specify that waste tires must be processed in a manner to keep exposed wires to no more than three inches;*
> >
> > *(v) specify that waste tires or waste tire-derived aggregate that were exposed to fire are not processed for use under this paragraph;*
> >
> > *(vi) specify that the leachate collection and removal system or gas venting layer must incorporate an appropriately specified 12-inch layer of soil or stone between any geomembrane or GCL and a waste tire-derived aggregate layer; and*
> >
> > *(vii) demonstrate that the final thickness of the waste tire-derived aggregate layer after compression will be a minimum of 24 inches.*

Section 360.10 of the New York code details the procedures to seek approval for variance request by a site. As stated in the alternate liner requirements, Section 360.10 is not applicable to alternate liner designs.

3.3.3 Pennsylvania

Pennsylvania Code Chapter 271.231. Equivalency review procedure details requirements for review and approval of alternate landfill designs. The section states:

(a) In approving a permit application under this article, the Department may authorize, in writing, alternatives to the design requirements in this article only if, and only to the extent that, specific sections in this article expressly state that alternatives may be authorized under this section.

(b) A person requesting an alternative under this section shall submit a request to the Department, in writing. The request shall:

(1) Identify the specific regulation for which an equivalency alternative is being sought.

(2) Demonstrate, through supporting technical documentation, justification and quality control procedures, that the requested alternative to the design requirements in a section of the regulations will, for the life of operations at the facility, achieve the performance standards in that section, and will do so in a manner that is equivalent or superior to the design requirements in that section.

(c) No equivalency alternative will be approved unless the application affirmatively demonstrates that the following conditions are met:

(1) The request is complete and accurate and the requirements of this section have been complied with.

(2) The proposed alternative will, for the life of operations at the facility, achieve the performance standards in the section of regulations for which the alternative to the design requirements in that section is sought, and will do so in a manner that is equivalent or superior to the design requirements in that section.

(3) The proposed alternative will not cause pollution to the air, water or other natural resources of this Commonwealth, and will not harm or endanger public health, safety or welfare.

(d) In lieu of approving an equivalency alternative for the entire facility, the Department may approve an equivalency alternative for part of a site as provided in Subchapter F (relating to demonstration facilities).

(e) If an alternative design is approved through a major permit modification, the Department may approve the applicability of the alternative design to another applicant through a minor permit modification.

Based on Golder’s experience, the following are typical alternate liner system designs in Pennsylvania:

- Substitution of six-inch-thick low permeability subbase with a GCL
- Substitution of 12-inch-thick secondary leachate detection layer with drainage geocomposite having a transmissivity that is equivalent or better than a 12-inch-thick layer with 1 x 10^{-2} cm/sec permeability
- Elimination or reduction in extent of piping system in the secondary leachate detection system
- The requirement that the primary leachate collection pipes be installed primarily perpendicular to the flow is usually satisfied with a single collection pipe in each disposal cell by demonstrating the collection system is capable of conveying the leachate to the collection sump within an equivalent or faster time than the prescribed system using pipes and the minimum required permeability

3.3.4 Florida

Florida landfill liner regulations are determined in Rule: 62-701.400. The state’s liner requirements include a dual composite liner separated by a leak detection system. However, the composite liner design may vary depending on other factors of the design. Table 1, below shows the thickness of the soil component of the composite liner as is required depending on the leachate head and hydraulic conductivity of the suggested soil used for the liner. If the design achieves a smaller leachate head and uses a soil with a lower hydraulic conductivity, the thickness of the soil may be reduced to as low as one foot.

Table 1: Florida Minimum Thickness of Lower Component of Composite Liner (Feet)

Maximum Design Hydraulic Head (inches)	Maximum Hydraulic Conductivity		
	$1x10^{-7}$ cm/sec	$5x10^{-8}$ cm/sec	$1x10^{-8}$ cm/sec
1	2.0	1.0	1.0
6	2.5	1.5	1.0
12	3.0	2.0	1.0

In addition to reducing the thickness of the soil component of the composite liner, the regulations also state:

A geosynthetic clay liner (GCL) with a hydraulic conductivity not greater than 1x10-7 cm/sec may be used in place of the six-inch thick subbase layer provided it is placed on a prepared subgrade which will not damage the GCL.

Due to Florida's relatively low elevations, high groundwater, and generally sandy soils; the use of a dual composite liner is used in place of a clay heavy single composite. Allowing for use of a GCL in place of the soil components allows landfills flexibility in design to account for these challenging design constraints. In Golder's experience, common landfill base liners will often consist of six inches of compacted subbase material with a GCL, 60 mil HDPE geomembrane with a second HDPE geomembrane separated by a drainage layer.

3.3.5 North Carolina

North Carolina liner regulations are detailed in Administrative Code Title 15A, Chapter 13B, Section 1624. The state provides three options for landfill base liner designs. Those options are quoted from the regulations below:

(*i*) *A composite liner utilizing a compacted clay liner (CCL). The composite liner is one*

liner that consists of two components; a geomembrane liner installed above and in direct and uniform contact with a compacted clay liner with a minimum thickness of 24 inches (0.61 m) and a permeability of no more than 1.0 X 10^{-7} cm/sec. The composite liner shall be designed and constructed in accordance with Subparagraphs (b)(8) and (10) of this Rule.

(ii) A composite liner utilizing a geosynthetic clay liner (GCL). The composite liner is one liner that consists of three components: a geomembrane liner installed above and in uniform contact with a GCL overlying a compacted clay liner with a minimum thickness of 18 inches (0.46 m) and a permeability of no more than 1.0 X 10^{-5} cm/sec. The composite liner shall be designed and constructed in accordance with Subparagraphs (b)(8), (9), and (10) of this Rule.

(iii) A composite liner utilizing two geomembrane liners. The composite liner consists of three components; two geomembrane liners each with an overlying leachate drainage system designed to reduce the maximum predicted head acting on the lower membrane liner to less than one inch. The lower membrane liner shall overlie a compacted clay

liner with a minimum thickness of 12 inches (0.31m) and a permeability of no more than 1.0 X 10^{-5} cm/sec. The composite liner system shall be designed and constructed in accordance with Subparagraphs (b)(8) and (10) of this Rule.

The options essentially allow the facility to use a standard subtitle D liner with two feet of clay. The other options allow for use of a more permeable clay provided the design includes a less permeable substitute as well. For option 2, this means a GCL replaces six inches of clay, while the remaining 18 inches of clay may have a high permeability. For option 3, this means the design may use a second geomembrane to replace one foot of clay with the remaining one foot of clay with a higher permeability.

In addition to the three options for liner design, the state also provides a mechanism for alternate liner designs as quoted below:

An alternative base liner. An alternative base liner system may be approved by the Division if the owner or operator demonstrates through a two-phase modeling approach that the alternative liner design meets the following criteria:

(I) the rate of leakage through the alternative liner system will be less than or equal to the composite liner system defined in Subparts (b)(1)(A)(i) of this Rule; and

(II) the design will ensure that concentration values listed in Table 1 will not be exceeded in the uppermost aquifer at the relevant point of compliance as established in Rule .1631(a)(2) of this Section.

The alternate design approach allows the facility to conduct groundwater modeling using the point of compliance method within Resource Conservation and Recovery Act (RCRA) Subtitle D to provide equivalency for contaminant concentrations.

3.3.6 Maine

Maine's Department of Environmental Protection Chapter 401, 06-096 Landfill Siting, Design and Operation, provides the state's requirements for landfills. Subsection 2(E) of this regulation provides the state's minimal requirements for alternate designs proposed by a facility:

Alternatives to the minimum design standards and requirements of section 2(D) may be proposed by the applicant. A variance request pursuant to the provisions of 06-096 CMR ch. 400, section 13 is not required for proposals which meet the requirements of this paragraph. The applicant shall submit the following documentation to clearly and convincingly demonstrate technical equivalency of the proposed alternative:

(1) A discussion of the benefits of the proposed alternative technology.

(2) A discussion of the risks and drawbacks of the proposed alternative technology.

(3) An assessment of similar applications of the proposed alternative technology.

(4) A demonstration that the alternative technology will provide equal or superior performance to the component it is proposed to replace, or that its inclusion within a system will result in equal or superior performance of that system.

(5) An assessment of the feasibility of constructing the proposed alternative, including the ability to provide an adequate level of quality assurance and quality control. A demonstration of the feasibility of construction may be required.

(6) An assessment of the likelihood that the proposed alternative will perform as designed through landfill operations, closure, and post-closure periods.

In addition to these alternate design requirements, each facility has other options for liner design regulations. The state requires sites to conduct a six-year groundwater time of travel performance model for each new cell. As part of this modeling, the regulations include an “Improvement Allowance System” that allows the designer to include offsets to their models if certain design features or operational plans are included in their permit application. These design features are shown below in Table 1 from Subsection 1(D)2 of the state’s regulations.

Table 1

Improvement Allowance Description		**Offset**
1a.	Addition and monitoring of a leak detection system underlain by a 40 mil HDPE liner beneath the primary liner system **OR**	2
1b.	Addition of composite liner(s) and a leak detection system	3
2.	Artificial creation and maintenance of groundwater discharge conditions into the facility structures	1
3.	Creation of a contingency plan including necessary action trigger levels and remedial action funding mechanisms	2
4.	Creation of an innovative performance monitoring program and/or creation of an intensive environmental monitoring program exceeding the standards of 06-096 CMR ch. 405	To be determined, but no more than 2
5.	For the expansion of an existing facility only and in conjunction with at least the addition of a composite liner and leak detection system, the addition of engineered systems that will improve existing ground and/or surface water quality conditions	To be determined, but no more than 2

If the facility voluntarily includes additional design features into their liner, the modeling requirement of the design is offset an additional two to three years from the six-year standard.

4.0 MODELING METHODS AND CONTAMINANT MIGRATION

The HELP model was developed by the USEPA in the 1980s. The most recent version of the model is version 4 released in 2020. It is a two-dimensional hydrologic model that measures movement or accumulation of water through vertical layers of a landfill. The model incorporates runoff, snow melt, infiltration, vegetation, evapotranspiration, drainage, and leachate collection to estimate hydraulic conductivity of the landfill liner as well as effectiveness of each part of the liner. The model is one of the main tools of a landfill design engineer to determine the performance of a landfill liner to contain leachate.

MODFLOW is a groundwater flow modeling program developed by the United States Geological Survey (USGS). MODFLOW is used to determine groundwater gradients, flow velocities, and potential for contamination migration through subsurface strata. The most recent version of the model is MODFLOW 6 released in 2017.

The two models work in conjunction to determine the hydraulic conductivity of the landfill liner and transportation of landfill contaminants exposed to groundwater and determine the accumulation of those contaminants once they have left the landfill's liner. As part of the design process, the HELP model is the main tool used to estimate the effectiveness of different aspects of the liner, such as collection pipe spacing, thickness of material, or alternate material options.

4.1 HELP Model

Each version of the HELP model has been refined to allow for improvements to the process. The HELP model estimates average rainfall and/or subsurface infiltration to the liner system and uses it to determine how much infiltration is shed from the cover, evaporates, or percolates into the waste. The model does not attempt to estimate maximum capacity or efficiency of specific layers but instead shows volumes or percolation rates for how much water can be expected to fall onto the landfill and where that water will end up depending on the aspects of the design.

There have been multiple studies that have measured the effectiveness and accuracy of the HELP model against actual field conditions (Berger, 2015). Berger (2015) also notes that previous versions of the HELP model were found to overestimate runoff in colder climates by underestimating freeze and thaw dates and similarly underpredicting runoff in warm humid climates. Newer versions of the model have been updated to allow for variations to the growing season to more accurately model runoff.

The newest version of the HELP model (V4.0) was released in October 2020, and simulations and research comparing the effectiveness of the model against real world conditions have not been published yet. USEPA notes within the HELP model manual: *"Modeling procedures are based on many simplifying assumptions. Generally, these assumptions are reasonable and consistent with the objectives of the model when applied to standard landfill designs. However, some of these assumptions may not account for unusual designs."*

4.1.1 HELP Model Inputs

Model inputs are divided into four sections: General Information, Weather, Runoff Curve Number, and Soil Design.

4.1.1.1 General Information

The general information section of the model includes the following:

- Site name
- Site location – address and longitude and latitude coordinates
- Units – US standard units or metric units
- Years to run simulation (40 years for Wisconsin post closure period)
- Landfill area

- Initial moisture of the facility
- Percent of the landfill area subject to runoff
- Water and snow storage above the landfill

4.1.1.2 Weather

Weather data for the facility requires inputs for the following:

- Precipitation
- Temperature
- Solar radiation
- Wind speed and humidity
- Growing season length
- Leaf area index
- Evaporative zone depth

There are multiple ways to input weather data for the facility's model. The facility can input their numbers if they have an onsite weather station or records of historical weather, which will allow the model to incorporate onsite actual historical data to predict future events.

In the absence of historical data, the model allows the facility to import National Oceanic and Atmospheric Association (NOAA) data to use for the historical data.

The third option is for the model to simulate weather data based on the built-in synthetic weather generation (WGEN) function. This function is based on a routine developed by the United States Department of Agriculture (USDA) and incorporates weather parameters from 13,000 points across the country. Using site location, the generator provides estimates for weather inputs. The data required to conduct this simulation is provided for download by the USEPA.

Items such as the growing season lengths, leaf area index, and evaporative zone depth can be input based on site-specific knowledge. If the facility doesn't have that information, growing season length can be found on resources from NOAA or USDA. The HELP model manual provides references to USEPA maps showing average leaf area index and evaporation zone depths based on geographic region.

4.1.1.3 Runoff Curve Number

The runoff curve is a unitless number used in the calculations to help determine the amount of water that will be directed off the landfill surface and the amount of water that will infiltrate within the landfill body. This number can be calculated or input three ways. The first is for the facility to calculate the number on their own and input directly into the model. This is a number the facility may have on hand from design of their stormwater containment systems; and therefore, requires no additional input.

The second method for determining the runoff curve number is for the facility to enter the estimated curve number as well as the slope grade and length of the landfill cell. The model will then calculate a modified number to use as part of the model.

The third method for determining the runoff curve is to allow the HELP model to calculate the number. This requires the facility to input slope grade and length of the landfill cell and the type of vegetative cover of the cell. There are five default values for vegetative cover that extend from bare ground to excellent grass.

4.1.1.4 Soil and Design

The soil and design section of the HELP model allows the designer to build a cross section of the entire landfill cell. The model has inputs for seven types of landfill layers:

- Final cover soil
- Vertical percolation layer
- Lateral drainage layer
- Barrier soil liner
- Waste
- Geomembrane liner
- Geosynthetic drainage net

Each layer allows for different inputs to help refine the ability of each layer to hold, contain, or transport water through the landfill. If the designer does not have the site-specific information for material or does not know the exact geosynthetic product that will be used, the model can provide default values for the layer based on industry established averages.

The final cover soil layer is for defining the type of cover material on the uppermost layer of the model. It allows inputs for soil type and thickness. If known, the designer may include values for wilting point, hydraulic conductivity, and porosity for the material used in the final cover. A vertical percolation layer is used for drainage aggregate or fill material that does not contain a pipe collection network. It contains all the same inputs as the final cover layer.

The lateral drainage layer is intended for the leachate collection layer above the geomembrane. This layer has similar inputs for soil as the vertical percolation layer but also includes inputs for the pipe collection network. The pipe inputs include the grade, drainage length which is determined by the pipe spacings, and if the leachate is recirculated and to what layer the recirculated material is deposited. The geosynethtic drainage net layer has similar inputs as the lateral drainage layer. The main difference is that it has a smaller thickness but otherwise is consistent.

Barrier soil layer is mainly used for a clay liner and has all the same inputs as the other soil layers. This layer would also be used for inserting a GCL. Since a GCL is a bentonite layer with geosynthetics on either side, the HELP model will assume the thickness of the bentonite within the GCL as a soil barrier. Current Wisconsin regulations for clay liner compaction allow for the bottom lift of clay in the compacted clay component to not be compacted. To account for this layer, the barrier soil layer may look to divide the clay thickness into two different layers: a bottom layer with a higher hydraulic conductivity due to the compaction requirements and a upper layer with the standard hydraulic conductivity for compacted clay.

The waste layer allows an individual to pick default waste values for different types of waste including MSW, fly ash, bottom ash, and copper slag. If the designer knows the waste profile of the landfill, the model allows manual input for items such as the hydraulic conductivity and porosity.

The final layer, geomembrane liner, is for input of the geomembrane. The inputs for the membrane are for hydraulic conductivity, pinholes per acre, installation defects per acre, condition of the contact between the liner and the lower layer, and transmissivity of the geotextile, if applicable. The inputs also allow for differentiating the type of geomembrane material: HDPE, linear low-density polyethylene (LLDPE), polyvinyl chloride (PVC), or other material.

4.1.2 Wisconsin Standard Liner Performance Modeling

As part of this report, a HELP model was created using basic assumptions to develop a base level of performance of the Wisconsin Chapter 504 liner. The following assumptions were used for inputs into this model:

- 40 years of simulation for Wisconsin post closure period
- Site location of Eau Claire, Wisconsin
- Site area of 10 acres with 80 percent subject to runoff at 33 percent side slopes 150 feet in length
- Weather data simulated for Eau Claire, Wisconsin using USDA weather procedure within HELP model
- Historical relative humidity taken from NOAA monthly averages
- Growing season from May 7 through October 6
- Maximum leaf index and evaporative zone depth taken from USEPA maps for northern Wisconsin
- Intermediate cover of one foot of loamy sand with good grass cover used for cover material to provide conservative estimate of infiltration
- Standard HELP values for hydraulic conductivity used for each layer of the strata
- Assume 50 feet of waste material above bottom liner
- Liner design consists of one foot of drainage aggregate, 60 mil HPDE, four feet of clay
- Model did not incorporate geotextiles or geocomposites
- Leachate pipe spacing of 130 feet with a bottom slope of two percent
- Assume good CQA overall; geomembrane has two pinholes per acre, two installation defects per acre, and excellent contact with clay layer
- Ten feet below bottom of liner to top of groundwater table

Based on these assumptions, the model ran for 40 years without a final cover to maximize water infiltration. Results of the model are presented in Table 2, below. The long form results for each year are presented in Appendix B.

Table 2: HELP Model Results - Standard Wisconsin Landfill Liner

Description	Annual Averages (per acre per year)	40-year Peak (24-hour period)
Percolation through Clay (cubic feet)	1.9569	0.5663
Head on top of Geomembrane (inches)	0.0887	0.9299

The HELP model results indicate that 1.9569 ft^3 (14.6 gallons) per acre per year of leachate will percolate through the liner. The maximum year modeled had 3.3789 ft^3 (25.3 gallons) of leachate percolate through the liner per acre per year. Leachate head on top of the geomembrane is considered negligible at less than one inch of head for the entire 40-year period. The model calculated minimal percolation through the liner system. These small numbers are not indicative of a larger landfill, as the model only assumed a 10-acre cell with 50 feet of waste. As noted in the assumptions, the model assumed a good connection between the liner and clay, good CQA with a small number of penetrations per acre, and good grass coverage over the majority of the landfill. Adjustments to each of these items would have resulted in a larger percolation estimate. The main objective of this HELP model was for comparison with alternate liner options discussed in later sections.

Adjustments for thickness of layers, such as barrier layers in clay and the geomembrane, help to limit percolation rates. However, the model anticipates leakage rates using anticipated rainfalls and the amount of water that percolates through the waste mass and onto the liner. If the landfill is located in a dry climate, has a final cover, or is designed with steep side slopes shedding the majority of the rainfall; the model will not assume maximum head on top of the liner. Because rainfall is the largest source of water exposure to the landfill, the most efficient way to limit percolation from the liner is to provide other means of collecting and disposing of the water prior to it reaching the liner. This includes adjusting runoff for cover material, reducing pipe spacings for leachate collection, or adjusting grades for the bottom liner to help transport leachate from off the liner.

4.2 Percolation through Liner System

As mentioned, the HELP model is used to calculate estimated percolation through the liner based on anticipated rainfall and site-specific conditions. It does not allow an estimate of maximum flow through a liner based on leachate head or system capacity. For estimations of percolation flow through a liner system based on leachate head, often manual calculations are used.

Based on Giroud et al (1989) and Qian (2002), penetrations through the geomembrane can use Bernoulli’s equation to estimate flow through each penetration assuming the number of penetrations or manufacturer or installation defects per acre will allow an estimate of flow through the geomembrane per acre. The percolation through the geomembrane is the sum of all flow through penetrations.

To calculate the flow through a clay liner, Darcy’s Law can be used (Qian, 2002). This equation does not work for a composite liner, as it requires saturation of soils above the liner and does not account for the geomembrane. Those equations are as follows:

Bernoulli Equation

$$Q = C_b \times a \times (2 \times g \times h)^{0.5}$$

where: Q = flow rate through the geomembrane, cubic centimeters per second (cm^3/sec);

C_b = flow coefficient, approximately 0.6 for a circular hole

a = area of defect in geomembrane, approximate for circular hole (cm^2)

g = acceleration due to gravity, 981 centimeters per seconds squared (cm/sec^2)

h = liquid head above geomembrane (cm)

Darcy's Law

$$Q = k_s \times i \times A$$

where: Q= flow rate through the compacted clay liner, cm^3/sec

ks= hydraulic conductivity of the soil, cm/sec

i= hydraulic gradient (cm/cm)

A= area over which flow occurs, cm^2

For saturated soil with no soil suction, the hydraulic gradient is given by:

$$i = (h + D)/D$$

where: i= hydraulic gradient (cm/cm)

h= head over the soil liner (cm)

D= thickness of the soil liner (cm)

Alternately, Giroud et al (1989) and Foose, et al (2001) created another empirical formula to determine percolation through a composite liner.

$$\boldsymbol{Q = C\left[1 + \frac{1}{10}\left(\frac{d_L}{t_L}\right)^{0.95}\right] a^{0.1} d_L^{0.9} K_s^{0.74}}$$

Q= Flow rate per hole in geomembrane

a= Area of hole in geomembrane

d_L= Depth of leachate

t_L= Thickness of liner

C= Contact Factor (0.21)

k_s= hydraulic conductivity of the soil, cm/sec

This equation allows for estimation of pinhole flow through the liner using assumed depths of leachate head over the liner.

4.3 Diffusion through Liner System

The second indicator of liner performance, other than percolation rates, is diffusion rate. With well-constructed composite liners, diffusion can be a method of contaminant migration through a liner system. (Foose, et al, 1999) It is possible for contaminants to transport or diffuse through intact geomembranes (Park and Nibras, 1993). While typical percolation rates are limited to locations with punctures or defects within a liner system, diffusion of contaminants takes place over the entire surface area of the liner.

Transport of contaminants through a landfill liner system are influenced by the thickness of liner materials, the properties of the materials, and the concentration of the contaminant. Hashimoto, et al (1964) developed contaminant transport models for mass transport of a non-decaying solute in saturated soils.

$$(\partial C\_z)/\partial t = (D * \partial\text{^}2\ C\_s)/(R\partial Z\text{^}2\ )$$

C_s = the concentration of the contaminant

z = the distance along the direction of diffusion

t = elapsed time

R = the retardation factor which is based on the clay-water partition coefficient, the dry density and porosity of the clay.

D = the effective diffusion coefficient

This mass transport equation provides an estimate for the concentration of the contaminant over time and as it transports through the liner. Based on this empirical equation, to help reduce the diffusion factor, the design engineer can alter the material used or provide for a thicker liner system. Diffusion rates are not dependent on water percolating through the layers of the landfill or liner system. Using a more dense, finer, more compact soil will help to reduce diffusion; but if the liner and base soils are in dry conditions, the thickness is the most significant factor in reducing transport.

4.4 Numerical Groundwater Flow and Solute Transport Modeling Overview

Numerical modeling is commonly conducted for landfill sites to support engineering or corrective action design. Examples of commonly evaluated conditions include:

- Groundwater flow through a clay liner and unsaturated natural formation
- Saturated groundwater flow in one or more hydrostratigraphic units (e.g., waste mass, overburden, bedrock), both horizontally and vertically
- Estimation of aquifer recharge variables, including precipitation recharge and point source recharge from facility-related sources and associated activities
- Migration of leachate-impacted groundwater from the landfill

- Leachate transport mitigation measures

Groundwater flow modeling is typically performed using one of the MODFLOW finite difference codes (e.g., MODFLOW-2005, MODFLOW-NWT, MODFLOW-USG, MODFLOW 6, or MODFLOW SURFACT). Once the groundwater flow model is calibrated, the MODPATH particle tracking software is typically used to evaluate potential lateral and vertical groundwater flow paths. More detailed solute transport analyses are typically conducted using MT3DMS or a similar transport code. The following sections provide a brief overview of how groundwater flow, particle track, and solute transport models are implemented to support the decision-making process.

4.4.1 Groundwater Flow Modeling

The typical elements of a numerical groundwater model include the model grid, model layers, boundary conditions, sources and sinks, and aquifer parameters. The model grid consists of varying numbers of rows, columns, and layers. The primary axis of the model grid is typically oriented parallel to the inferred groundwater flow direction. The grid cell size in the XY direction is normally variable, with cell sizes ranging from very small (e.g., 5 feet x 5 feet in the vicinity of a sump) to very large (e.g., 1,000 feet x 1,000 feet) in outlying areas of the model domain. Grid cell size in the vertical direction is also variable and is typically based on a variety of data sources, including digital terrain models, stratigraphic data, and as-built drawings of site features (e.g., liner base grades). Model layers are typically divided into layers to represent site features (e.g., landfill waste mass and landfill liner) and geologic units, including aquifers and aquitards.

A variety of model boundary conditions (BCs) are used to simulate features at a landfill site. Examples of commonly used BCs include:

- Constant head boundaries – rivers and lakes
- Drain boundaries – creeks, sumps, blanket and toe drains, wetlands
- General head boundaries – rivers
- Lake boundaries – lakes and ponds
- River boundaries – rivers, lakes, and streams
- Stream boundaries – streams

More than one type of BC may be used to represent similar features based on the modeling objectives. For example, river cells may be used to simulate a perennial creek; while drain cells may be used for an ephemeral creek. Examples of other features that may be implemented in a landfill groundwater flow model include:

- **Landfill liner** – The liner can be represented as an explicit model layer, or, if the liner is assumed to be impermeable, it can be represented as a no flow boundary. Individual liner cells may be activated to represent postulated liner breach locations for the purposes of the transport modeling.
- **Landfill Waste Mass** – The waste mass can be represented as an explicit model layer(s) or it can be set as inactive if flow above the liner is not included in the model simulations.
- **Outlying Areas** – Model cells outside the active model boundary can be set as inactive.

- **Model bottom** – The model bottom is assumed to be a no flow boundary. The model bottom should be sufficiently deep to avoid edge effects.

Climatic conditions are typically simulated using the recharge (R) and evapotranspiration (ET) terms. Recharge and ET can be included separately or combined into a single term and can vary over time or represent time-averaged conditions, depending on the modeling objectives. Zones are used to represent spatial variation of R and ET (e.g., pervious vs. impervious surfaces or different types of ground cover). Initial R and ET values are typically obtained from nearby weather station data or site-specific HELP modeling and are later adjusted during model calibration.

Local differences in aquifer properties (e.g., hydraulic conductivity, specific yield, and specific storage) are typically accounted for by creating several zones within the model based on site-specific geologic data. Parameter values are initially set based on field measurements or literature estimates and are later adjusted during model calibration.

4.4.2 Model Calibration

Flow models should be calibrated before using them for decision making. Flow model calibration consists of successive refinement of the model input data from initial assumptions and estimates to improve the fit between observed and model-predicted results. Models are calibrated through trial-and-error or automated (e.g., PEST) adjustment of model parameter values within reasonable ranges based on available site-specific data and literature references.

A sensitivity analysis is typically performed on the calibrated model to assess the model's sensitivity to changes in aquifer parameter values. This procedure is important because model calibration is an inherently non-unique process, meaning that multiple combinations of parameter values can yield similar solutions. Reduction of uncertainty is considered important for estimation of aquifer parameters, including hydraulic conductivity of aquifers and aquitards, the degree of interconnection between aquifers, anisotropic conditions, and a variety of other factors.

4.4.3 Particle Tracking

Particle tracking simulations using MODPATH are typically performed to evaluate potential groundwater and contaminant flow paths. MODPATH calculates three dimensional pathlines based upon cell-by-cell flow output from MODFLOW. Particles can be simulated in forward mode (i.e., particles released beneath the landfill and tracked downgradient toward the property boundary) or reverse mode (i.e., particles released at a pumping well and tracked upgradient to evaluate a capture zone). Particle tracking is typically performed for a duration of 30 or 100 years, depending on the modeling objectives.

4.4.4 Solute Transport Modeling

Solute fate and transport modeling using MT3DMS is often coupled with MODFLOW modeling to evaluate solute concentrations over time in groundwater. An example application for a landfill site would be to evaluate the transport and relative concentrations of chloride based on a hypothetical failure of a HDPE liner.

MT3DMS solute transport models simulate advective transport and dispersion. Dispersion describes how a solute spreads through groundwater incorporating mechanical mixing and chemical diffusion of the solute as it moves through groundwater pores. Chemical diffusion is a molecular based process describing the tendency of solutes within areas of high concentration moving to areas of low concentration. Mechanical dispersion is considered the dominant transport process in coarser grained material (e.g., sands); while transport through the clays is expected to be diffusion dominated.

5.0 ALTERNATE LINER TYPES REVIEWED

In addition to establishing minimum standards for composite liners, RCRA Subtitle D also provides a provision which allows use of an alternate liner as long as the liner provides equivalence to the Subtitle D composite liner. The term equivalency is not specifically defined. Instead, Subtitle D provides a performance standard stating that:

"In accordance with a design approved by the Director of an approved State or as specified in §258.40(e) for unapproved States. The design must ensure that the concentration values listed in Table 1 of this section will not be exceeded in the uppermost aquifer at the relevant point of compliance, as specified by the Director of an approved State under paragraph (d) of this section,"

The standard then provides multiple criteria to select the point of compliance. The criteria include, but are not limited to groundwater flow direction, hydrogeologic characteristics, and drinking water source locations. This method determines that the landfill liner shall limit concentration values below given limits at a point of compliance downgradient of the landfill.

States are then allowed to follow this point of compliance regulation or define their own more stringent requirements or concentrations values to assume equivalent liner protections for a landfill. Some states have adopted the point of compliance modeling as a requirement for all landfill designs, such as Illinois. Other states have requested point of compliance modeling for any design that uses alternate design techniques to prove the alternate design is equivalent or greater. To conduct point of compliance modeling, the designers will determine the potential for contaminants to travel through the landfill liners using diffusion transport or HELP models, and then use MODFLOW to determine the concentration of those contaminants at the designated point of compliance to determine if the liner design is adequate.

As part of the review Golder has discussed two alternate liner types with the WDNR. These include GCL replacement for two feet of CCL and the use of a dual composite liner which incorporates a GCL in place of clay.

5.1 GCL Substitute for Compacted Clay Liner

A GCL composite liner is one that uses a bentonite pad 5.0 to 6.5 mm thick installed directly below a FML. The GCL is often used in place of a certain thickness of clay which is determined using equivalency calculations. The GCL layer is capable of creating a similar or higher hydraulic conductivity as compacted clay. In addition to its permeability properties, the GCL also has a swell index once it hydrates. The swelling allows the GCL to fill voids, imperfections, or penetrations within the FML (like pinholes) reducing the risk of contaminants percolating through the liner system. The GCL also provides a cushion to the FML to prevent stress on the FML.

GCLs have been used across the United States and internationally for decades as components of landfill liners or containment cells. Facilities without local clay borrow sources prefer GCL use in landfill liners to avoid restrictive costs of hauling clay. The GCL may also provide additional airspace to the landfill cell depending on permit conditions, limiting the thickness of the liner system.

When replacing compacted clay with a GCL, states have taken unique approaches when accounting for how much clay is eligible for replacement. In some instances, such as Ohio discussed above, the regulations allow GCL to replace no more than one foot of compacted clay. In other states, such as Florida, a GCL may be used to replace the entire thickness of clay. In addition to the varying thickness of clay replaced, other states may require the GCL to have a larger amount of bentonite to replace certain thickness of clay. In these instances of using a GCL with more bentonite, the GCL may not be allowed on side slopes due to the slope stability risks. In general terms, GCL is often used to replace between one and two feet of clay in states which allow GCL replacement.

Discussion listed in Section 5.1 will focus on a design that includes two feet of compacted clay liner overlaid with a GCL, overlaid with a FML. A cross section of the design has been provided in Figure 2:

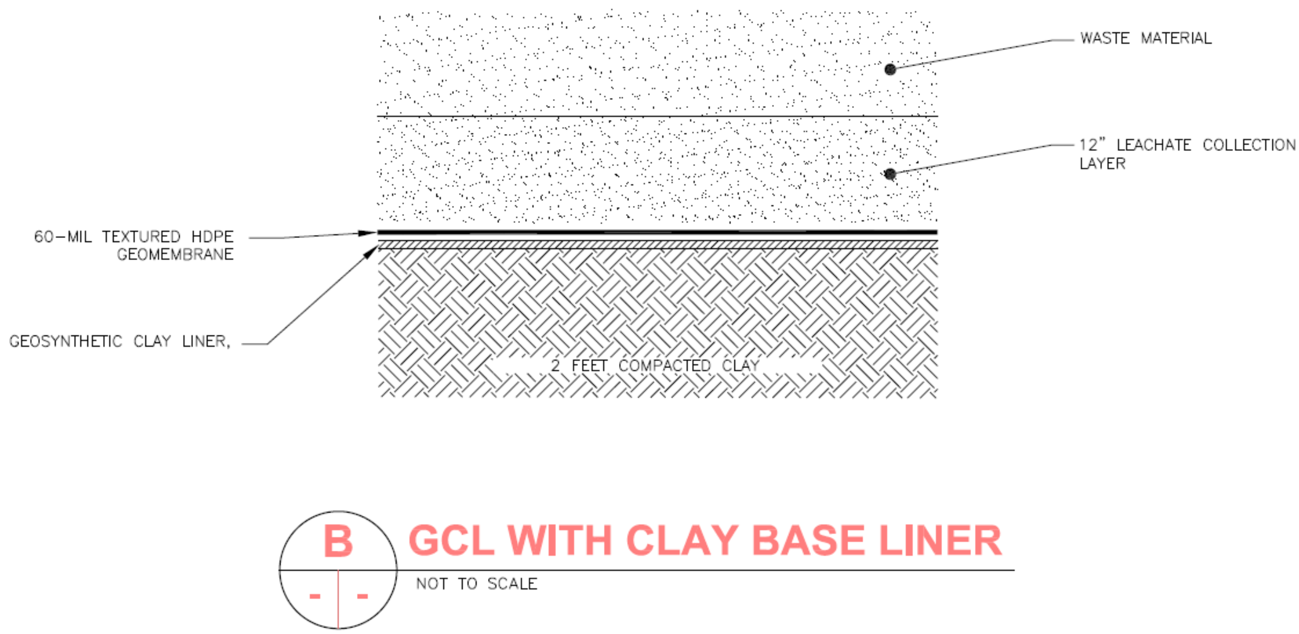

Figure 2: GCL with two feet of Clay Base Liner

5.1.1 Construction and Operation Costs

A typical cost estimate was developed for Wisconsin liner construction for an assumed one acre of landfill bottom liner. Costs presented were created based on similar unit rates from projects within the previous two years. The table, assumptions, and cost estimates are presented in Appendix C Table 1.

Wisconsin has extensive clay resources along its western border, southern region, and eastern region. Landfills located within the central or northern regions of the state may not be able to locally source clay that achieves the permeability and plasticity requirements of the state regulations. These sites may be required to transport clay from other areas to construct their liner systems, as per Wisconsin Chapter 504 requirements. A second cost estimate is presented in Appendix C Table 2. All construction costs are based on an assumed construction of one acre of liner.

Sites that must import clay material from sources over one hour from the site will pay substantially more for construction than landfills that are able to locally source clay material.

Appendix C Table 3 provides a cost estimate and assumptions for liner construction works for an assumed one acre of landfill bottom liner using the GCL substitution for two feet of compacted clay. Costs presented were created based on similar unit rates from projects within the previous two years.

When compared to the cost of transporting four feet of clay from an offsite source over an hour away, the GCL replacement may save the facility approximately $100,000 per acre of construction of new landfill liner. If the facility has an onsite source of clay, the savings for GCL replacement may be closer to approximately $10,000 per acre.

Construction costs are not used for assessment of a landfill liner system during the design and approval process by the WDNR. However, the cost of construction is a main determination to the feasibility of a site to construct an expansion cell using the existing Wisconsin clay liner design or attempt to suggest a new alternate liner option for approval.

5.1.2 Construction Quality Assurance

The CQA requirements for the GCL replacement alternative liner require source material and construction testing for the three components: CCL, GCL, and FML. The differences between the requirements of the Wisconsin Chapter 504 liner and the GCL alternative are the source material tests required for the GCL and frequency of compaction and proctor testing for the CCL.

Prior to GCL being shipped to site, the supplier will provide material source testing for the GCL. Source material tests include, but are not limited to:

- Bentonite swell index
- Bentonite fluid loss
- Bentonite mass per area
- Grab strength
- Pell strength
- Index flux
- Hydraulic conductivity
- Hydrated internal sheer stress

Using a GCL over the CCL creates a better connection between the FML and lower layers. The GCL acts as a protective layer for the FML, creating a pad that will cushion sharp edges, cracks, or gullies within the clay. Using the GCL helps to improve the contact with the FML and below strata by swelling and helps to limit voids, gaps, and leachate migration pathways to the clay. The use of GCL does not remove the burden of inspecting the final CCL surface for debris, cracks, or gullies. If the upper layer of the compacted clay includes large particle sizes, cracks or gullies, the GCL can be damaged or punctured, reducing its effectiveness and increasing the hydraulic conductivity of the composite liner. While a GCL has healing capabilities for small punctures or penetrations, large punctures or penetrations will result in more leakage than a traditional clay liner due to the GCL being thinner than the clay layer.

Wisconsin regulations do not require the initial one-foot lift of clay to achieve the same compaction requirements of the top three feet of the compacted clay. Additionally, not all lifts in the compacted clay are tested for compaction. Using a reduced thickness GCL substitute design would require that all lifts of clay achieve compaction requirements. The initial lift of clay may require a bridging layer placed above subgrade in order to achieve compaction if the in-situ subgrade material is either too saturated or does not provide a stable surface to place clay material.

Prior to placement of the GCL panels, the clay material should be at optimum moisture to initiate the hydration of the bentonite within the GCL. Moisture within the clay is important to maintain the GCL integrity and self-healing effects.

If a liner leak location survey is going to be conducted on the geomembrane above a GCL, a wire will need to be installed across the entire GCL system such that it touches each GCL panel. The wire will then need to have a small tag accessible from below the liner which is connected to the dipole equipment to close the circuit necessary to conduct the testing. If the wire is not in place, the GCL will act as an insulator, which will obstruct results from the survey. The alternative option to the testing is to use a leak location liner with a conductive coating.

5.1.3 Slope Stability

Evaluation of the relative slope stability of a GCL with two feet of clay base liner was performed by creating a typical landfill scenario. A model was developed using a landfill cross section with typical design geometry and construction, such as a 3:1 final side slope, one foot of cover material over waste material over a liner system. Typical material parameters used to define the assumed materials are summarized in Table 3.

Table 3: Slope Stability Material Parameters

Material Name	Unit Weight (lbs/ft^3)	Saturated Unit Weight (lbs/ft^3)	Strength Type	Cohesion (psf)	Phi (deg)
Temporary Sand Cover	110	115	Mohr-Coulomb	0	28
Waste	90	-	Mohr-Coulomb	300	33
Textured GM/Clay Interface	125	-	Mohr-Coulomb	0	18
Compacted Clay	130	140	Mohr-Coulomb	1000	0
GCL Internal Interface	125	-	Mohr-Coulomb	0	16
Granular Drainage Layer	120	125	Mohr-Coulomb	0	38
Native Medium Dense Sand	125	130	Mohr-Coulomb	0	30
Native Sandstone	160	165	Mohr-Coulomb	360,000	0

The model was used to evaluate the slope stability of a four-foot compacted clay liner with a textured geomembrane to provide results that can be expected from such a liner system. The model was also used to evaluate the slope stability of a GCL with two feet of clay base liner. The slope stability analysis was performed to compare the relative stability between a GCL with two feet of clay base and a four-foot compacted clay liner with textured geomembrane. Methodology used to run the stability analysis remained the same for both liner systems, as did all aspects of the model except the liner systems themselves. Further details on the model and results from both scenarios are presented below.

The static stability of the GCL with two feet of clay base liner was evaluated using the computer program SLIDE2 Version 9.014 (Rocscience, 2021). Generalized limit equilibrium method of stability analysis developed by Morgenstern and Price (Abramson, et al, 2002) was utilized for the analysis. Block and circular search patterns were utilized to find failure surfaces that resulted in the minimum calculated FS. Block search patterns were also utilized to search for slip surfaces within suspected weak interfaces, for this case within the GCL. The lowest FSs were obtained for circular failure. Both failure directions (left to right and right to left) were utilized to find failure surfaces that resulted in the minimum FS. The lowest FS were obtained with the right to left failure direction (3:1 exterior landfill slope); therefore, discussion and results are only presented for the right to left failure direction. A seismic coefficient was not used for this analysis account for seismic loading. Groundwater was assumed to be below the liner elevation and assumed native dense sand.

Results from the stability analysis are found in Table 4, below. Both liner systems were modeled to occur at the interface with the lowest friction angle. The liner with four feet of compacted clay with textured HDPE has a critical interface at the HDPE/clay interface. The assumed friction angle at that interface was derived from the Geosynthetic Research Institute (GRI) database and was assumed to be 18 degrees. If the design used a smooth HDPE liner, the HDPE and GCL interface would be the lowest friction angle. The critical interface for the GCL with two feet of clay base was the internal shear strength of the GCL and was assumed to have a 16-degree friction angle as reported by GRI. The difference in calculated FS is largely due to the difference in friction angle. Site-specific slope stability modeling should be completed for use in practice, but due to the similarities in liner interface strength parameters, the slope stability results can be expected to be similar as well.

Table 4: Slope Stability Results

Analysis	Method	Calculated FoS Value	Figure
Four feet Compacted Clay with Textured HDPE	Non-Circular	4.25	B1
GCL with two feet of Clay Base	Non-Circular	3.98	B3

5.1.4 Groundwater Impact and Permeability

When comparing equivalency of liner types for their ability to contain leachate and contaminants, the alternate design will need to show equivalent or greater protection for both percolation and diffusion. Comparing just percolation or diffusion alone is not enough to provide assurances that the alternate liner system will provide equivalent environmental protections.

To show equivalent hydraulic conductivity protection, the design should show HELP model results for the standard Wisconsin NR 504 liner as well as the alternate liner, in this case the use of GCL in place of two feet of clay. HELP model results for the alternate landfill liner are included in Appendix B. A discussion of landfill liner percolation with the alternative liner is discussed further in later sections.

In addition to the HELP model, Daniel and Koerner (1993) developed a methodology to determine a hydraulic conductivity equivalency between compacted clay and a GCL.

$$k_{GCL} = k_{clay}\left(\frac{t_{GCL}}{t_{Clay}}\right)\left(\frac{h + t_{Clay}}{h + t_{GCL}}\right)$$

k_{GCL} = GCL saturated hydraulic conductivity (cm/sec)

k_{Clay} = Compacted clay saturated hydraulic conductivity (cm/sec)

t_{GCL} = Thickness of GCL (cm)

t_{Clay} = Thickness of compacted clay (cm)

h = Hydraulic head on top of liner (1 foot or 30.48 cm)

Using this equation, a design can calculate the minimum required hydraulic conductivity of a GCL to achieve the same hydraulic conductivity of the replaced clay liner component.

When comparing diffusion of alternate liner types, Foose, et al (1999) determined that a GCL substitution for two feet of clay as part of a subtitle D composite liner resulted in increased contaminant diffusion through the landfill liner; and thus, poorer containment. Based on the calculations for determining equivalency, Foose, et al (1999) determined that placing additional compacted material below the GCL created protections that ultimately established an equivalent or greater protection over a RCRA subtitle D liner.

Thickness of the liner system is the most effective means to reduce diffusion transport. Diffusion transport is not dependent on water or leachate leakage through the liner system but is driven by a high concentration of a contaminant travelling to an area of a lower concentration of a contaminant. Since the goal of the liner is to prevent contaminants from reaching groundwater, it is important to not only compare the thickness of the liner design but to also compare the separation between the leachate collection layer and the top of the uppermost aquifer. This means to reduce diffusion transport, adding material to increase the thickness between the waste body and groundwater is the easiest way to reduce diffusion transport even if the material added does not have a low hydraulic conductivity.

If the facility is short of clay material but has a large separation between the liner and groundwater table, the diffusion may be negligible, with the dry compacted soil below the liner acting as another strata of the liner system. The point of compliance equivalency is a measurement of groundwater at a location outside of the waste body. Therefore, the design engineer should present equivalency of the concentration values at this predetermined location and not at a location directly below the landfill liner.

Foose, et al (1999) note that placing compacted soil beneath the GCL can help to reduce the diffusion, even if the compacted soils aren’t clay material. The main point of adding this material is to provide additional distance between the leachate containment and groundwater levels. Their findings indicate that placing towo feet of compacted soil below the GCL can provide either equivalent or greater protection from diffusion over the design life of the liner system.

5.1.4.1 HELP MODEL

A HELP model of the GCL alternate liner was conducted for comparison with the initial Wisconsin NR 504 liner. All assumptions from the HELP model discussed in Section 4.1.1 are consistent with the following changes:

- Two feet of the clay component has been replaced with a GCL with hydraulic conductivity of 3 x 10^{-9} cm/sec
- The bottom of liner was still considered to be 10 feet above groundwater with the liner being two feet thinner

Results of the GCL alternate liner are presented in Table 5, below.

Table 5: GCL Alternate Liner HELP Model

Description	Annual Average (per Acre per Year)	40 Year Peak (24-hour period)
Percolation through Clay (cubic feet)	0.1965	0.5615
Head on top of Geomembrane (inches)	0.0887	0.9299

The HELP model results show that the predicted percolation through a GCL alternative liner is lower than the standard Wisconsin liner by a factor of 10.

5.1.5 Integrity and Resistance to Degradation

The temperatures due to decomposition of waste within a landfill have the potential to increase contaminate transport and accelerate aging of the geomembrane and desiccation of mineral layers (Southern, J.M, Rowe, K.R. 2005). The desiccation of the mineral layers is caused by thermal layers within the landfill liner and the movement of moisture from warmer gradients to cooler gradients. Assuming the geomembrane creates a vapor barrier from the hot waste body and the cooler under liner soils, vapor shall be sucked from the GCL into the lower layers of the liner (Southern and Rowe, 2005).

The two main factors in thermal gradient that affected the desiccation of the GCL are the temperature differences and the initial moisture of the subgrade material below the GCL. While the temperatures are not easily adjusted at the bottom of a landfill cell, the moisture content of the underlaying soil is controllable during construction. Southern and Rowe (2005) noted that the GCLs in their thermal gradient experiment that had sublayers moisture above optimum experiences much less desiccation than those with optimum to dry moisture soil.

In certain chemical environments, the sodium ions in bentonite can be replaced with cations dissolved in the water that comes into contact with the GCL. This process has been referred to as ion exchange. This type of exchange can reduce the amount of water held within the bentonite and decrease the material's swell and increase the material's porosity and hydraulic conductivity. The main source of ion exchange issues within a GCL come from exposure to calcium and magnesium (Jo, et al, 2001). Landfill leachate or fly ash usually have high concentrations of both of these elements. While it is possible for ion exchange to happen with exposure with other elements, it is not as prevalent.

Kolstad, et al (2004) developed an empirical method to determine if the GCL is likely compatible with a leachate concentration at a landfill. The method compares the ratio of the hydraulic conductivity of a GCL hydrated with clean water vs leachate to the ionic strength of the leachate (estimated from the total dissolved solids and specific conductance) and ratio of the monovalent ions to the square root of the divalent ions. The method requires site-specific testing of the leachate at the site. If this method indicates the ion exchange will be detrimental to the GCL, the designer may consider using laboratory test methods for determining the compatibility of the GCL with the leachate.

ASTM Method D6141 is a bentonite screening test that compares the quality of the bentonite swell and ion exchange of the GCL using clean water sources and a sample of the landfill leachate sources. The test is conducted for relatively short periods up to two days. For long-term testing of the chemical compatibility of GCL, ASTM D6766 is used. This test is essentially the same as a hydraulic conductivity tests, but samples of the leachate from the landfill are used as the hydration source.

A GCL installed below a geomembrane will absorb all of its moisture from the subgrade soil below it. Depending on the composition of the soil, the GCL can undergo ion exchange of sodium for calcium or magnesium with ions found in the soil. Bradshaw, et al (2013) noted that GCLs exhumed after several years still showing moisture content over 50 percent did not experience any noticeable increase in hydraulic conductivity. GCLs exhumed with a moisture content below 50 percent showed a measurable increase in hydraulic conductivity. If the GCL is sufficiently hydrated within the first 30 days and has an appropriate confining pressure applied, the GCL will maintain its hydraulic conductivity and swell.

To ensure the GCL does not lose moisture and swell through ion exchange, the subgrade material should be at optimum moisture as determined by onsite density testing prior to installation of the GCL. In addition, the subsequent layers of the geomembrane and leachate drainage layer should be installed on top of a GCL as soon as reasonably possible to maintain the GCL design integrity (Bradshaw, et al, 2013).

Additional considerations should be made for a GCL or bottom liner construction within a zone of saturation. This would be conducted in the same manner as the leachate testing described above. As with construction of a compacted clay liner within a zone of saturation, the water level during construction will also create a risk to damage the liner’s integrity. Construction of clay in wet conditions requires lime stabilization, dewatering, or bridging layers. A GCL that swells prior to a confining pressure will create issues for bentonite squeeze out and compromise the GCL’s hydraulic conductivity integrity. Designers and construction efforts should ensure the GCL is not prematurely hydrated if placed in a zone of saturation.

5.1.6 Other Environmental Impacts

Numerous studies have indicated that compacted clay will experience an increase in hydraulic conductivity after multiple freeze and thaw cycles. Moisture within the soil material will freeze and create ice lenses. After thawing, the lenses provide migration pathways for the moisture and can result in increased hydraulic conductivity on the order of magnitude one to three times. (Benson, et al, 1995).

Kraus, et al (1997) reviewed GCL in freeze-thaw in controlled laboratory conditions as well as in field test pad conditions. The experiment also reviewed the hydraulic conductivity of a sand and bentonite mixture in addition to the GCL panels. Both the GCL panels and the sand bentonite mixtures experienced little to no increase in hydraulic conductivity after freeze and thaw conditions. Examining cross sections of the frozen bentonite and sand mixtures and GCL panels, the experiment noted that frozen lenses appeared in the sand mixture but not in the GCL panel. However, after thawing, neither showed signs of desiccation as the bentonite’s healing effect swelled back to repair any cracks created by the frozen moisture. Kraus, et al (1997) recommended further study be done to examine the long-term effects of freeze-thaw on bentonite and GCLs.

Podgorney and Bennett (2006) measured multiple GCL samples at a variety of pressures for up to 150 freeze-thaw cycles over a three-month period in laboratory conditions. The results of Podgorney and Bennett (2006) concluded that the GCLs experienced no significant increase in hydraulic conductivity. The GCL maintained its design integrity after 150 freeze-thaws.

While noting that the GCL component of the composite liner will maintain its integrity during freeze-thaw conditions, the reduced clay component is susceptible to increases in hydraulic conductivity during freeze-thaw cycles. If the top two feet of a four-foot-thick compacted clay liner increases in hydraulic conductivity, it would be assumed that the two feet of clay in a GCL substitute liner would also experience similar increase in hydraulic conductivity. If the GCL component of the liner maintains its hydraulic conductivity and was designed using the Daniel and Koerner (1993) methodology to have a lower hydraulic conductivity than the equivalent clay thickness, then the GCL composite liner would maintain a lower hydraulic conductivity than the compacted clay composite liner after freeze-thaw cycles.

There are two GCL categories: unreinforced and reinforced. The unreinforced GCLs are essentially just bentonite laid between two geotextiles. The bentonite can move freely, creating issues for slope stability from the internal friction angle of the bentonite. Unreinforced GCLs are not used often within landfill liners and only on flat sections of a landfill cell and never on slopes.

Reinforced GCLs have a nonwoven geotextile that is needle-punched through the bentonite and sandwich layers of the other geotextile. This reinforced geotextile needle-punched through the GCL provides additional slope stability and helps to keep bentonite in place on side slopes. Almost all GCLs included in landfill liner designs are reinforced GCLs.

5.1.7 Impact on Other Liner Components

A facility that uses a GCL substitution liner will have little effect on the operation of routine events at the facility. The main aspects are for long-term considerations or construction items from other landfill systems. This includes drilling of vertical gas wells. The thinner landfill liner would be more susceptible for the landfill gas drilling rig to puncture the entire composite liner than a standard Wisconsin NR 504 liner. Using four feet of clay, the drainage material and clay component would be thicker than the bucket auger used to drill vertical gas wells. Therefore, the driller would encounter the sand, gravel of the drainage aggregate, or the clay of the liner in at least one bucket before puncturing through to the bottom of the clay.

The alternative liner design would be approximately three feet from the top of the drainage aggregate to the bottom of the clay. This is roughly equivalent to one load of the bucket auger; and therefore, would pose a larger risk as the driller could accidentally puncture through the entire liner system. The risk of puncturing the liner can be mitigated by using a thicker drainage aggregate layer or placing other geosynthetics above the drainage aggregate that can act as a filter or a warning layer to the driller.

The designer may also request a tighter survey grid. The tighter grid during construction of the liner will reduce areas of fluctuating elevation between survey points. It will provide a more accurate representation of the landfill gas drilling elevations and their proximity to the liner.

The last option for mitigating risk to the liner from drilling vertical landfill gas wells is to use caisson gas wells. These wells are placed during construction of the leachate system. The bottom of the wells can be placed above the leachate pipe to freely drain gas condensate and help drain the landfill liquids. As waste is placed and the elevation of the landfill mas increases, a caisson around the top of the well is raised and new sections of the well are welded to the top. Caissons require careful operation during waste placement but do not require any drilling and pose no risk to the liner while providing additional benefits to landfill drainage and leachate management.

5.1.8 Summary of Design Impacts

If an alternate design for replacement of compacted clay utilizes a GCL, the design will need to account for the following items:

- Assurances of gas well drilling over a thinner liner to avoid future drilling through the liner
- Conducting a leak location survey with a GCL beneath the geomembrane
- Leachate compatibility with GCL bentonite to avoid ion exchange desiccation
- Slope stability analysis to account for the geosynthetic-to-geosynthetic interface shear and internal bentonite friction angle
- More stringent CQA on the smaller clay component of the liner
- Thickness of the liner to avoid diffusion transport to groundwater
- Saturation of the soil prematurely hydrating the GCL
- Review of manufacturer quality assurance protocols and testing
- Review of CQA for GCL testing requirements
- Ensuring the design includes the correct type of GCL (i.e., reinforced or unreinforced)

5.2 Dual Composite Liners

Dual composite liners are required in a variety of states or often utilized when a site has high groundwater. They include two composite liners usually separated by a leak detection layer capable of pumping leachate out of the upper composite. Dual composite liners provide a second layer of leachate drainage and collection as well as a second layer of geomembrane that protects groundwater from leachate and protects the upper composite liner from high groundwater infiltration. As part of the review below, the following design of a dual composite liner was considered:

- 10 feet of loamy sand above the groundwater table
- GCL layer
- HDPE geomembrane 60 mil thick
- One foot leak detection layer of gravel
- GCL layer
- HDPE geomembrane 60 mil thick
- One-foot-thick leachate drainage layer

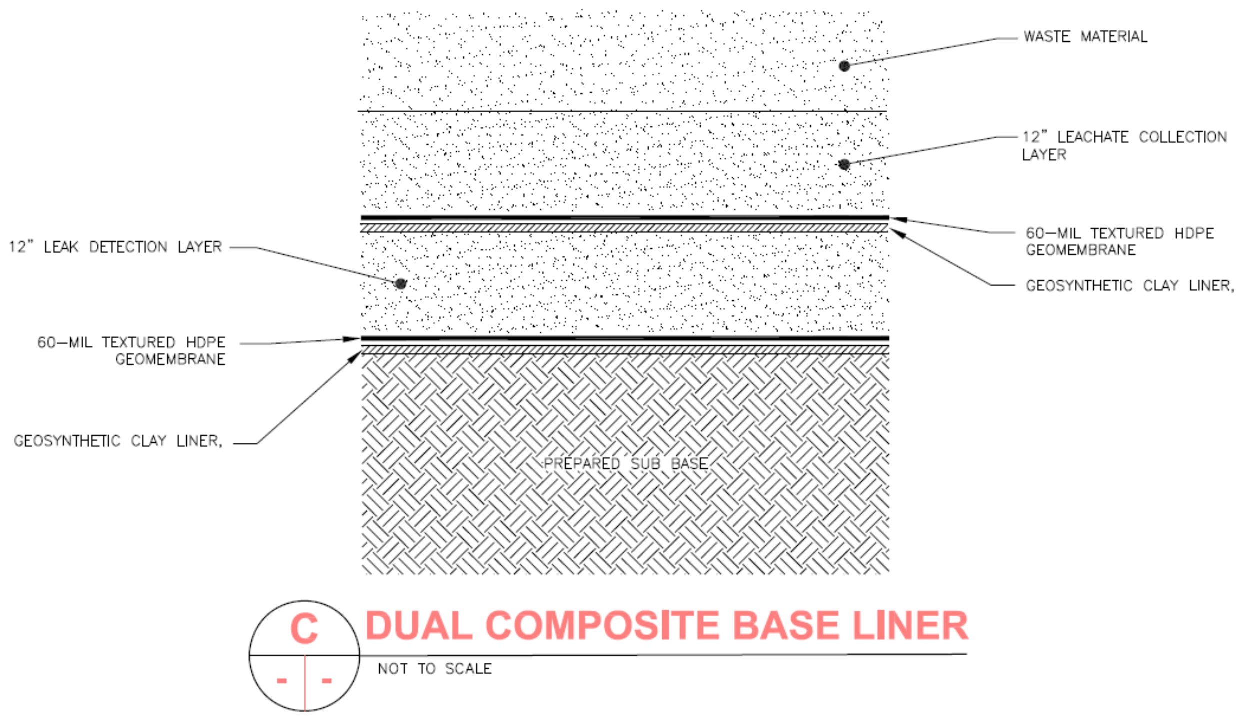

Figure 3: Dual Composite Base Liner

5.2.1 Construction and Operation Costs

A typical cost estimate was developed for a dual composite liner for an assumed one acre of landfill bottom liner. Costs presented were created based on similar unit rates from projects within the previous two years. The table, assumptions, and cost estimates are presented in Appendix C Table 4.

Using a dual composite liner to substitute for all clay material, the dual composite is more cost-effective than transporting all clay material to the site. The standard four feet of clay sourced onsite was the most cost-effective option at $143,118.80 per acre. The dual composite liner, which uses no clay, is the next cost-effective option at $217,509.60 per acre. The GCL substitute for two feet of clay was the next option at $252,486.80 per acre, and the most expensive option was transporting the clay in from an offsite source one hour or more away with a cost of $356,724.00 per acre.

If the dual composite is required to add clay to the bottom of one of the composite liners, the dual composite option would likely be more expensive than the GCL substation single composite liner depending on thickness of the requested clay layer.

5.2.2 Construction Quality Assurance

Components of a dual composite liner are consistent with a GCL replacement liner. The dual composite liner removes all clay from the design and replaces it with GCL with an additional leak detection layer. All of these additional materials used in the design require additional source material testing and quality control testing onsite.

During construction, the lower GCL is placed over subbase material instead of a clay layer. More stringent testing and inspections will need to be included during construction to ensure the subbase material is adequate for placement of the GCL.

The dual composite liner discussed includes gravel as a leak detection layer, which would likely require a cushion geotextile to separate the gravel from other geosynthetics or the use of a very small sized gravel or coarse sand that won't damage the geosynthetics.

Because Wisconsin requires leak detection surveys of geomembranes, the design should include methods for conducting the leak detection on the dual composite geomembrane. Without a soil component under any of the geomembrane, the GCL will need to have wires installed across the panels, or the geomembrane will need to be a leak location liner with a conductive film on the bottom. The leak location survey will likely need to be conducted in two mobilizations for each geomembrane, creating a logistical risk to the construction.

5.2.3 Slope Stability

Evaluation of the relative slope stability of a dual composite liner was performed by using the same typical landfill scenario introduced in Section 5.1.3. The assumed material parameters remained the same as well and are summarized in Table 6.

Table 6: Slope Stability Material Parameters

Material Name	Unit Weight (lbs/ft^3)	Saturated Unit Weight (lbs/ft^3)	Strength Type	Cohesion (psf)	Phi (deg)
Temporary Sand Cover	110	115	Mohr-Coulomb	0	28
Waste	90	-	Mohr-Coulomb	300	33
Textured GM/Clay Interface	125	-	Mohr-Coulomb	0	18
Compacted Clay	130	140	Mohr-Coulomb	1000	0
GCL Internal Interface	125	-	Mohr-Coulomb	0	16
Granular Drainage Layer	120	125	Mohr-Coulomb	0	38
Native Medium Dense Sand	125	130	Mohr-Coulomb	0	30
Native Sandstone	160	165	Mohr-Coulomb	360,000	0

The model was used to evaluate the slope stability of a four-foot compacted clay liner with a textured geomembrane to provide results that can be expected from such a liner system. The model was also used to evaluate the slope stability of a dual composite base liner. The slope stability analysis was performed to compare the relative stability between a dual composite base liner and a four-foot compacted clay liner with textured geomembrane. Methodology used to run the stability analysis remained the same for both liner systems, as did all aspects of the model except the liner systems themselves. Further details on the model and results from both scenarios are presented below.

The static stability of the dual composite base liner was evaluated using the computer program SLIDE2 Version 9.014 (Rocscience, 2021). Generalized limit equilibrium method of stability analysis developed by Morgenstern and Price (Abramson, et al, 2002) was utilized for the analysis. Block and circular search patterns were utilized to find failure surfaces that resulted in the minimum calculated FS. Block search patterns were also utilized to search for slip surfaces within suspected weak interfaces, which occurs within the GCL for the dual composite base liner case. The lowest FS were obtained for circular failure. Both failure directions (left to right and right to left) were utilized to find failure surfaces that resulted in the minimum FS. The lowest FS were obtained with the right to left failure direction (3:1 exterior landfill slope); therefore, discussion and results are only presented for the right to left failure direction. A seismic coefficient was not used for this analysis account for seismic loading. Groundwater was assumed to be below the liner elevation and native dense sand was assumed.

Results from the stability analysis are found in Table 7, below. Failure in both liner systems was modeled to occur at the weakest interface. The liner with four feet of compacted clay with textured HDPE has a weak interface at the HDPE/clay interface. The friction angle at that interface was taken from the GRI database and was assumed to be 18 degrees. The weak interface for the dual composite base liner was the internal strength of the bentonite pad within the GCL and was assumed to have a 16-degree friction angle as reported by GRI. The difference in calculated FS is largely due to the difference in friction angle. Site-specific slope stability modeling should be completed for use in practice, but due to the similarities in liner interface strength parameters, the slope stability results can be expected to be similar as well.

Table 7: Slope Stability Results

Analysis	Method	Calculated FoS Value	Figure
Four feet Compacted Clay with Textured HDPE	Non-Circular	4.25	B1
Dual Composite Base Liner	Non-Circular	3.94	B5

5.2.4 Groundwater Impact and Permeability

A HELP model of the dual composite alternate liner was conducted for comparison with the initial Wisconsin NR 504 liner. All assumptions from the HELP model discussed in Section 4.1 are consistent with the following changes:

- Two HDPE geomembranes were used, each 60-mil thick with the same CQA and placement quality as the initial two HELP models
- No clay layer was included, all clay has been replaced with an underlying GCL below the geomembrane
- The GCL has an assumed hydraulic conductivity of 3×10^{-9} cm/sec
- A gravel layer with pipe spacings of 130 feet was included between the upper and lower composite liners
- The gravel layer is one foot thick with a hydraulic conductivity of 3×10^{-1} cm/sec

- The bottom of liner was considered to be 10 feet above groundwater with the liner being three feet thinner (four feet of clay with geosynthetics in Wisconsin NR 504 liner vs one foot of drainage aggregate and geosynthetics in dual composite liner)

Table 8: Dual Composite Liner HELP Model

Description	Annual Average	40 Year Peak (24-hour period)
Percolation to groundwater (cubic feet)	0.0842	0.5614
Head on top of Geomembrane (inches)	0.0887	0.9299

The HELP model results indicate 0.0842 ft^3 (0.62 gallons) of leachate into the groundwater 10 feet below the bottom of liner per acre each year. The standard Wisconsin NR 504 composite liner had 14.6 gallons per acre per year, and the GCL composite liner has 1.5 gallons of leachate into groundwater per acre per year. The dual composite liner reduces percolation from the CCL composite liner by a factor of 23, while reducing the percolation from the GCL composite by a factor of 2.5.

5.2.5 Integrity and Resistance to Degradation

As discussed in the GCL substitution section, the GCL design should confirm that the GCL used is compatible with the in-situ soil and leachate of the new landfill cell. When designing the dual composite, it is important to consider the composition of the groundwater in relation to the lower GCL. While the upper GCL is likely to encounter leachate as part of its hydration and ion exchange, the lower GCL is more likely to encounter groundwater, especially if the GCL is constructed in a zone of saturation. Similar to the leachate testing discussed previously, the lower composite can be tested for hydraulic conductivity using groundwater sourced from the landfill location to confirm if the GCL bentonite is compatible with the ion exchange of the groundwater.

The lower GCL is also more protected from temperature gradients; and therefore, less likely to desiccate from moisture leaving the bentonite. The lower GCL will have two leachate drainage layers as well as two HDPE liners which act as insulators against warmer moist temperatures from the waste decomposition. Because of this, the lower GCL is less likely to desiccate than the upper GCL.

5.2.6 Impact on Other Liner Components

As discussed in the GCL substitution section, the dual composite liner will have impacts for drilling the vertical gas wells after waste has already been placed. Substituting GCL for all clay in a dual composite liner will reduce the thickness of the liner. The combined thickness of the drainage layer and leak location layer will be approximately two feet thick. The reduced thickness makes it possible for a driller's bucket auger to puncture both the primary and secondary liners in one lift. While possible, it is unlikely the driller would be able to puncture both due to likely cave-ins or collapse of wet decomposed material at the bottom of the landfill. The dual composite liners also provide the protection that, if the driller goes through the initial geomembrane, they should notice the geomembrane in their spoils and cease drilling before puncturing the second geomembrane.

As noted in the previous section, a landfill can utilize techniques to avoid liner punctures during drilling works. To help ensure confidence in the survey levels, the designer can take a smaller grid to avoid fluctuations in the elevations of the liner surface. They can also use caisson wells in construction of the vertical gas wells to avoid drilling over the liner system. If the thickness of the liner is a concern, the design may incorporate a thicker drainage material above the liner that includes a filter material that can act as driller's notification of the liner location.

In addition to the implications of the landfill gas system, the leak detection layer requires the site to operate separate leachate storage systems. Water captured in the leak detection layer may not actually be leachate. It is possible the water collected in the leak detection system is groundwater intrusion depending on if the liner system was constructed in a zone of saturation. If the water within this layer is groundwater, it should be sampled, monitored with flow, and recorded to determine if there is any percolation from the upper composite liner.

5.2.7 Summary of Design Impacts

If an alternate design for replacement of compacted clay utilizes a dual composite liner, the design will need to account for the following items:

- Inclusion of leak detection pipework pumping, storage, and treatment separate from leachate pumping, storage, and treatment
- Conducting leak location surveys without a clay component of the landfill liner
- Logistics of conducting leak location survey on both geomembranes in the dual composite liner
- Assurances of gas well drilling over a thinner liner to avoid future drilling through the liner
- Leachate compatibility with the upper GCL bentonite to avoid ion exchange desiccation
- CQA review of GCL placed over subbase material instead of clay or include a smaller soil layer to buffer the lower GCL
- Inclusion of cushion geotextile or sizing the soil material of the leak detection layer so that it does not negatively impact the geosynthetics
- More stringent analysis for slope stability to account for the geosynthetic-to-geosynthetic interface shear and internal bentonite friction angle
- Thickness of the liner to avoid diffusion transport to groundwater
- Saturation of the soil prematurely hydrating the lower GCL

6.0 SEVEN MILE CREEK, EAU CLAIRE, WISCONSIN LINER DISCUSSION

As part of the review of alternate liner options and alternative liner approvals, this report includes a discussion of a proposed alternate liner system at the Seven Mile Creek Landfill in Eau Claire, Wisconsin (Seven Mile Creek Landfill).

6.1 Background of Site

Seven Mile Creek Landfill is located at the NW 1/4, NE 1/4 of Section 17, T27, R08W, 8001 Olson Drive, Eau Claire, Wisconsin 54703. The existing licensed landfill receives municipal, commercial, and industrial non-hazardous solid waste. The facility has a composting operation that occurs outside the landfill limits. The landfill was started by the City of Eau Claire in the 1970s.

Generally, the geology in the vicinity of the landfill consists of alluvial sand and gravel deposits overlying the Cambrian age sandstone bedrock. The alluvial material is 15 to 60 feet thick with occasional silt layers. Below the alluvium, the sandstone bedrock is part of the Eau Claire and Mont Simon Formations. The glacial soils and sandstone are underlain by Precambrian crystalline rock. Surficial soils are sands and loamy sands with high permeabilities.

The water table is in alluvial soils, and sandstone is approximately 35 feet below the ground surface (bgs) along the eastern side of the landfill and about 45 feet bgs on the western side. The direction of groundwater flow beneath the landfill is towards the south-southwest. The horizontal gradient varies from 0.006 ft/ft near Seven Mile Creek on the site's western side to 0.025 ft/ft on the eastern side. Hydraulic conductivity in the unconsolidated sands averages 3.3 x 10^{-3} cm/sec.

6.2 Alternate Design Proposed by Site

The review of the alternate design proposed by the Seven Mile Creek is based on the Tetra Tech report, "NR 500 Alternate Landfill Liner Design Evaluation" submitted in October 2019. The document's argument is broken up into the following:

- USEPA Region 5 liner designs
- Regulatory authority for WDNR to approve alternate liner designs
- Performance evaluation of proposed alternate liner
- Environmental, social, economic risk assessment
- Design, construction, and long-term care

The requirements of each of the USEPA Region 5 states has been discussed above. The approval process for each of these states has also been discussed as well as other states outside of USEPA Region 5. The regulatory authority of the WDNR to approve the alternate design is not discussed within this desktop study and has not been included in the scope of this review.

Each of the other sections of the proposed alternate design report are discussed below.

6.2.1 Performance Evaluation of Proposed Alternate Liner

The Seven Mile Creek Report provides a narrative that discusses a paper written by Dr. Craig Benson and Dr. James Tinjum. The paper is titled, "Evaluation of Effectiveness of NR 504 and Alternative Composition Liners." The paper appears to be written specifically for the Seven Mile Creek Landfill based on a cover letter written by the authors, but no discussion of site-specific conditions is mentioned in the paper.

The paper does not present any information that is deemed inaccurate or misleading, but the contaminant transport model is presented in general terms and does not specifically mention expected soils below the liner, the high groundwater table, or high bedrock expected at the Seven Mile Creek facility or the hydraulic gradient of the site.

The paper does not use a HELP model analysis for comparison of the alternate liner types. The percolation rates use the composite liner equation discussed earlier in this report. As discussed before, this equation is used to estimate maximum flow through the liner system based on assumptions and maximum leachate head conditions. The calculated leachate head is not provided and only briefly discussed as being minimal. As noted previously, industry standard and USEPA use the HELP model, as the output files provide clear and reviewable input parameters as well as clear and comparable output values for percolation through each layer of the liner.

Based on the discussion in the report, the Wisconsin NR 504 liner provides almost no additional protections over a subtitle D liner using one-half the amount of clay. The liner providing the highest protection from leachate percolation was the dual composite liner not the GCL with two feet of clay.

When reviewing the diffusion contaminant transport, the figures provided imply only the first two liner alternatives were reviewed, which are standard subtitle D liner and the GCL with two feet of clay liner. The dual composite liner results are not presented. All liner options presented showed little to no contaminant accumulation for 100 years. After 100 years, the concentrations increased, but the paper notes that the analysis ignored the biodegradation of volatile organic compounds (VOCs), which would make concentrations negligible after 100 years. Based on their results, all the liner options presented would provide adequate diffusion protection for the life of the landfill through post closure period.

The narrative within the report concludes with four points discussing the improvement in construction of composite liners since the writing of the existing landfill regulations. The first three improvements discuss the advances in the manufacturing, installation, and quality control of geosynthetics in the past several decades, which are accurate and applicable.

The last improvement discussed is the use of leak detection surveys using the dipole method. The narrative does not offer any other information on the dipole method other than it helps locate liner penetrations. It is unclear if the report is arguing for the use of the dipole method to help establish equivalency for the Seven Mile Creek design. Wisconsin requires dipole testing of all composite liners for MSW landfills. If the report intends to use the dipole method to help create assurances of the Seven Mile Creek design's integrity, aspects of the design should discuss the measures taken to ensure an accurate survey; i.e., using a wire across all GCL panels or wetting GCL to provide a conductive subbase material below the geomembrane.

6.2.2 Environmental, Social, Economic Risk Assessment

The design compared the Wisconsin NR 504 liner with four alternate liner options:

- Standard Subtitle D Liner – Two feet of clay with 60 mil HDPE geomembrane
- Proposed Liner – Two feet of clay with GCL and 60 mil HDPE geomembrane
- Geosynthetic Only Liner - GCL with secondary 60 mil HDPE geomembrane and geosynthetic drainage layer and primary 60 mil HDPE geomembrane
- Hybrid Liner – Two feet compacted clay with 60 mil HDPE using four feet of clay at the sumps and base grades larger than two percent

The alternate liner reports argues that the additional two feet of compacted clay does not add protection over the standard Subtitle D design. In addition, the excavation and hauling of low permeability clay from borrow sources several hours away carries its own environmental impact. Without naming a borrow source, the report notes that clays can often be found in wetland areas that are vulnerable to excavation works. It is unclear if Seven Mile Creek is proposing to use a borrow source from a wetlands area; and therefore, unclear if this is a factor for consideration.

Other environmental or local impacts discussed include air emissions from truck hauling, road condition from increase in haul trucks, and noise and traffic at the borrow source. The report does not state a specific implied borrow source, and it is unclear if the contractor removing the clay would be the same contractor constructing the landfill cell or an independent contractor operating the borrow source or quarry operator. The concerns listed for truck hauling, noise, and road impacts at the borrow source are valid. If the borrow source is a dedicated clay borrow area, these issues are a consideration whether it is the landfill or some other facility using the clay source. The dedicated borrow source operator, and not the landfill, are responsible for mitigating the impacts. Additionally, construction Stormwater Pollution Prevention Plans (SWPPP) are required for any borrow area over one acre and should address several of the concerns raised.

The last argument made in favor of reduced clay thickness is the logistical argument that additional clay will require a longer construction schedule that will be more susceptible to rain, frost, or reduced daylight hours. The discussion does not include any logistical argument of placing a GCL or geosynthetics, how long each acre of construction would require, and how it would compare to the additional two feet of compacted clay. It does not include a discussion of GCL construction to properly confine the panels with drainage aggregate within 30 days of placement to ensure the GCL does not prematurely swell or protect the GCL from rainfall. While arguing the logistical issues of the extended construction schedule, the report also argued that all landfills in the State of Wisconsin have constructed their landfill cells with the same liner system and were able to achieve these logistical goals. No examples of sites experiencing issues with the logistical challenge of the thicker liner component were provided.

A narrative discussion and comparison of the four liner types is not provided. The comparison of the four liner types is only made as part of Table 2 of the Seven Mile Creek Report. The table provides a matrix comparing impacts of each of the alternate liner designating each with a score. The scores are not a ranking of one to four, but instead are arbitrarily designated with a score determined by the author of the report. The liner which achieves the best score is alternate 3, which is the dual composite liner separated by a geosynthetic drainage layer. The table then states that this liner does not meet Subtitle D requirements and is impractical. However, as noted above, multiple landfills in the States of Florida and Michigan use this design. While the design does not use two feet of compacted clay, it is possible to meet subtitle D compliance with the appropriate site-specific groundwater modeling discussed in Section 4.0 of this study. Using the scores provided, the Seven Mile Creek Report has come to the wrong conclusion based on their own analysis.

6.2.3 Design, Construction, and Long-Term Care

The report provided the following for design construction and long-term care:

In comparing the long-term performance of the required NR500 composite liner design to the alternate composite liner design there is no evidence to suggests that the alternate composite liner design would fail to perform adequately during the operating life and long-term care period for the landfill. A combination of geosynthetic materials and soil liners is expected to provide the best protection when exposed to a variety of chemical compounds found in leachate. over this extended period of 100’s of years.

No further discussion was provided. The report did not provide a discussion of possible CQA requirements for construction of a GCL. The report did not provide additional assurance in construction of the GCL to ensure the GCL was compatible with the native soils or expected leachate. The report did not provide discussion of the impact of a reduced thickness on aspect of gas drilling or slope stability. While this is a feasibility report, the liner type proposed has not been used at this facility before. The facility could have offered to provide a general discussion of these considerations during the feasibility stage and later provide site-specific details during the Plan of Operation development.

6.3 Discussion of Equivalency Review

As discussed in this study, substitution of GCL for compacted clay in landfill liners is a common acceptable method in multiple states, including states within the USEPA Region 5 sharing the most similar geology and climate to Wisconsin. Outside of Region 5, GCLs are included in the state code of multiple states that require dual composite liners. These states may still require compacted clay as part of one of the dual composite liners. GCLs are especially used in states with sandy soils or high groundwater as a means of supplementing clay lean sites or providing increased leachate infiltration protection without requiring significant earthwork to raise the bottom of liner above the groundwater table.

GCLs have been in common use for several decades, not just within the United State but globally. In that time, designers have refined ways to best incorporate GCLs into designs to utilize their low hydraulic conductivity, self-healing, and easily installed panels. However, the successful history and use of GCLs at other sites in other states and regions alone is not evidence of equivalency and does not provide evidence that a GCL is suitable for use in all designs at all sites. Facilities that wish to substitute GCLs for clay should be able to show site- and design-specific applications with equivalent or increased performance for:

- Compatibility with expected soils and leachate within the landfill site
- Appropriate CQA methods and plans in place to ensure the contractor installs the panels correctly to ensure the GCL does not undergo sodium ion exchange or loss of moisture which will desiccate the quality of the GCL
- Appropriate records are kept of the liner surface to ensure future operators of the cell understand the gas well drilling constraints of a thinner liner
- Additional measures taken, as needed, to check for pinholes or liner defects after construction of the liner system if requested by the regulatory authority
- Design shows improved percolation rate and equivalent mass transport through diffusion rates for contaminants; modeling should use site-specific conditions, expected design, and rainfall; i.e., HELP model
- Appropriate measures in place to have confining pressure on the GCL within 30 days of placement

As discussed above, the Seven Mile Creek Landfill submitted analysis for general comparison of alternate liner designs against a standard Wisconsin NR 504 landfill liner. Seven Mile Creek did not submit a HELP model to show leachate infiltration analysis for site-specific conditions expected at the landfill cell. The feasibility report noted that other states allow GCLs in the landfill design but did not provide other documentation other states require as part of their regulations. The design did not include a CQA plan to ensure the contractor would install the GCL appropriately with third party oversight to provide confidence in the installation. The request did not provide groundwater modeling to show contaminant transport and concentrations at a point of compliance outside the limits of waste as per RCRA Subtitle D. Using the scores and grades provided by the consultant, the preferred option was not the suggested option.

Based on discussion above of GCL submission for compacted clay, Golder believes that the proposed alternate liner design would provide additional protection from leachate, and if appropriate construction methods were used, the alternate design would likely be equivalent or superior to the standard Wisconsin NR 504 design. Since Wisconsin does not have a more specific alternate liner approval process detailed in state code, such as Pennsylvania, the proposed design should have, at a minimum, conducted point of compliance modeling and site-specific infiltration analysis calculations. This information was not provided as part of the alternate design request; and thus, Golder believes the request was not complete to prove equivalency nor was the liner suggested by the facility the most efficient or cost-effective alternative.

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APPENDIX A

50 State Liner Regulations Summary

	Liner Components						Regulatory Requirements			
	Clay or Soil Component	Secondary Liner (Lower)	GCL	Leak Detection Layer	Primary Liner (Upper)	Leachate Collection Layer	Other Notes	Regulations for Liners	Notes on Alternate Design Approvals	Regulations for Alternate Liner Approval
AL	Construct 2 feet of compacted clay with a maximum Hydraulic conductivity of $1x10^{-7}$ cm/sec directly below the flexible membrane liner.		Alternate designs have been approved for GCL in place of 1 ft of compacted clay. The remaining clay can be $1x10^{-5}$ cm/sec		Geomembrane 60 mil minimum thickness if HDPE, 40 mil minimum thickness if other than HDPE		Alternate designs will be considered under the condition a groundwater receptor no more than 150 meters from site, on property owned by site, does not exceed groundwater contaminant concentrations	Ala. Admin. Code r. 335-13-4-.18	Alternate designs shall ensure that concentration values are not exceeded in the uppermost aquifer at a compliance location specified in the rules. The agency shall consider the following when accessing alternate designs for approval: hydrogeologic conditions of the site, climate of the site, and volume and characteristics of the leachate.	Ala. Admin. Code r. 335-13-4-.18-3(h)
AK	Construct 2 feet of compacted clay with a maximum Hydraulic conductivity of $1x10^{-7}$ cm/sec directly below the flexible membrane liner.				Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE			18 AAC 60.330		
AZ	Construct 2 feet of compacted clay with a maximum Hydraulic conductivity of $1x10^{-7}$ cm/sec directly below the flexible membrane liner.				Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE			R18-13-1613		
AR	Construct 2 feet of compacted clay with a maximum Hydraulic conductivity of $1x10^{-7}$ cm/sec directly below the flexible membrane liner.				Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE			Reg.22.424(a)(2)		
CA	Construct 2 feet of compacted clay with a maximum Hydraulic conductivity of $1x10^{-7}$ cm/sec directly below the flexible membrane liner.				HDPE Geomembrane 60 mil minimum thickness		State requirements allow for use of alternate liner, such as replacement of compacted clay for GCL if the site can prove equivalency and unnecessary financial impact of maintaining design. (i.e. cost to import clay is overly restrictive than to install GCL)	Title 27 CCR	California state regulations establish minimum design standards. The state is divided up into 9 subregions managed by Water Boards that establish more strict requirements dependent on site specific data, historical or climatological information.	
CO	1) Natural lithology with minimum 20 feet of thickness of maximum $1x10^{-6}$ cm/sec. Top 12 inches recompacted to maximum achieve $1x10^{-7}$ cm/sec hydraulic conductivity.				None		Colorado has 3 options for liner designs	6 CCR 1007-2-3.2.5	Alternative liner designs are allowed for approval but dependent on site specific information and waste type. Must comply with modeling for contaminant concentrations	6 CCR 1007 -2-3.2.5(4)
	2) 3 feet of compacted clay with maximum $1x10^{-7}$ cm/sec hydraulic conductivity				None				Alternate designs include: GCLS, natural lithology, soil admixtures, geomembranes, polymer	
	3) Construct 2 feet of compacted clay with a maximum Hydraulic conductivity of $1x10^{-7}$ cm/sec directly below the flexible membrane liner.				Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE					
CT	Compacted native soil beneath Secondary FML,	Lower FML shall be a thickness greater than 60 mil		12 inches of granular earthen material above 12 inches of granular free draining material (or equivalent geosynthetic) connected to leak detection system between FML's	Upper FML shall be a thickness greater than 60 mil	12 inches granular earthen filler material, underlain by geotextile underlain by 12 inches granular free draining material or equivalent geosynthetic.	Alternate designs have allowed 5 feet of natural soils if the in situ material has permeability of $1x10^{-7}$ cm/sec in place of imported subbase material	Sec. 22a-209-14(g)	An application to construct and operate a new municipal solid waste disposal area may propose alternate technologies to meet the goals of subsections (g) (1) through (g) (4), (h), (i), (j), and, (k) of Section 22a-209-14 of the Regulations of Connecticut State Agencies, which goals are to protect the waters of the State from pollution and to prevent the dispersion of waste. The applicant shall demonstrate that such alternate technologies will achieve these goals to the same degree as the requirements of the said subsections, that such alternate technologies have been utilized in similar circumstances, and that such alternate technologies are supported by scientific and engineering evidence that they will provide an equivalent degree of protection against water pollution and dispersion of waste as implementation of the requirements specified in the said subsection	Sec. 22a-209-7

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DE	1) If bottom of liner is 5 feet above seasonal high water table, 2 feet compacted clay with maximum $1x10^{-7}$ cm/sec hydraulic conductivity	1) None		1) None	FML shall be a thickness greater than 45 mil		Delaware allows for three options for composite liners.	7 Del.1301, 5.3.2	Dual composite liners are required if the groundwater table is within 5' of the bottom of designed liner system.	
	2) Natural 5' thick compacted clay with maximum $1x10^{-7}$ cm/sec hydraulic conductivity	2) None		1) None					Natural clay liners will only be allowed if the groundwater is not used for water supply	
	3) Double Liner shall have at least 2 feet of compacted clay below the primary liner (with GCL replacement) and 5 feet of clay below secondary (lower) liner.	3) Can be either synethetic (with a minimum thickness of 30 mil FML) or natural (5 feet thick clay)	GCL can be used below upper FML in place of 2 feet of clay.	Leak detection layer between dual liners 12" of soil with permeability >1 x 10^-2 cm/sec	Upper FML shall be a thickness greater than 30 mil					
FL	1) Thickness of underlying clay material is dependent on the clay's permeability and the maximum designed hydraulic head of the leachate above the liner systems. Clay thickness vary between 12 inches and 36 inches.				FML shall be a thickness greater than 60 mil HDPE		Florida allows for two options for liner systems	Section 62-701.400.3(B)		
	2) Double liner system requires 6 inches subbase with maximum $1x10^{-5}$ cm/sec.	Lower FML shall be a thickness greater than 60 mil HDPE	GCL can be used to replace 6" of subbase if it has 1x10^-7 cm/sec	Leak detection layer shall have minimum hydraulic conductivity of 10 cm/sec	Upper FML shall be a thickness greater than 60 mil HDPE		Agency may require additional requirements for liners based on site specific conditions			
GA	Construct 2 feet of compacted clay with a maximum Hydraulic conductivity of $1x10^{-7}$ cm/sec directly below the flexible membrane liner.				Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE bottom of liner must be at least 5 feet above the top of seasonal high groundwater		Less stringent requirements may be allowed depending on site location. If site is located in area of higher pollution susceptibility or in significant groundwater recharge area, then standard composite liner is required. If not the liner system may be designed as long as it can limit pollution concentration values defined in regulations.	Rule 391-3-4-.07(d)		
HI	Construct 2 feet of compacted clay with a maximum Hydraulic conductivity of $1x10^{-7}$ cm/sec directly below the flexible membrane liner.				Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE			§11-58.1-14		
ID	Construct 2 feet of compacted clay with a maximum Hydraulic conductivity of $1x10^{-7}$ cm/sec directly below the flexible membrane liner.				Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE			Sect 39-7409	A site-specific design based upon environmental performance, shall ensure it meets federal requirements of 40 CFR258.40.	Section 39-7409(b)
IL	1) 5 feet of clay for earth liner with maximum hydraulic conductivity of $1x10^{-7}$ cm/sec.				1) None		Illinois allows for 2 options or liners	Section 811.306		
	2) 3-foot of clay with maximum hydraulic conductivity of $1x10^{-7}$ cm/sec				Geomembrane 60 mil minimum thickness		The design is assessed using a contaminant transport model using in situ conditions. The model must show the design prevents any chemical contaminant will not exceed background value at a point located 100 feet from the water boundary within 100 years of closure. If the model does not show that, the deisgn must be altered to a more stringent requirement.		Illinois code states "operator may utilize liner configurations other than those specified in this section, special construction techniques and admixtures provided that: 1) alternative technology or material provides equivalent or superior performance to the requirments of this section. 2)technology or material has been successfully utilized in at least one application similar to the proposed application 3)methods for manufacturering quality control and construction quality control can be implemented	Section 811.306(g)

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IN	3 feet deep compacted clay soil with $1x10^{\wedge -7}$ cm/sec maximum hydraulic conductivity. Bottom of clay must be 10 feet above uppermost aquifer.		Required in sump areas	Required in sump areas	Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE		At sump areas of the landfill the following components are required: 2 feet compacted clay, leak detection zone, 3 feet of compacted clay, geomembrane, GCL, geomembrane, drainage layer, protective cover.	Section 329 Indiana Administrative Code 10-17-2		
	Soil separation layer is required for aquifer separation in some landfills depending on location. Separation layer must be 2 feet thick with $1x10^{-5}$ cm/sec maximum hydraulic conductivity.			Underliner drainage layer required is liner is within aquifer of significance or 10 feet of aquifer level.			If Liner is above aquifer of significance or within 10 feet of aquifer level, additional soil layer is required for separation with liner system			
IA	Construct 2 feet of compacted clay with a maximum hydraulic conductivity of $1x10^{-7}$ cm/sec directly below the flexible membrane liner.				Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE		Alternative designs have been approved for the use of 4 feet of clay only with no geosynthetic component.	113.75(5)"a"(1)	The alternate liner design must provide evidence of contaminant levels below Table 1 within the regulation. The monitoring point shall be downgradient of waste and within 50' of waste boundary	113.75(5)"a"(2)
KS	Construct 2 feet of compacted clay with a maximum hydraulic conductivity of $1x10^{-7}$ cm/sec directly below the flexible membrane liner.		GCL have been approved for substitution of 1' of compacted clay		Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE		Kansas has general requirements for landfills and separate requirements for landfills below a certain size.	Chapter 65 - Article 34; 28-29-104	Regulations state that approval of alternate designs shall be considered when "the technology or material has been successfully utilized in at least one application similar to the proposed application and methods for ensuring quality control during the manufacture and construction of the liner can be implemented."	
	For landfills that meet regulations for small landfill's the site will use only 2 feet of clay or in situ materials for the liner.						Size requirements: Receives less than 20 tons per day based on annual average. No evidence of groundwater contamination. Receives less than 25 inches of precipitation per year, community using the landfill has no practical alternative within 75 miles.		Alternative designs will be allowed dependent on groundwater contaminant concentrations. Values detailed in the regulations shall not exceed in the uppermost aquifer at a compliance location within 150 meters from the edge of waste and at least 15.24 meters from edge of property.	
KY	Bottom subbase material may be naturally occuring if it meets $1x10^{-7}$ cm/sec permeability and is at least 20 feet thick. Otherwise 1 foot of clay at $1x10^{-7}$ cm/sec is used with a FML for the secondary liner.	Hydraulic conductivity of $1x10^{-12}$ cm/sec with thickness either 40 mil or 60 mil depending on materials maximum water vapor transmission rate	GCL's have been used to substitute for 1 foot of clay material but may require more stringent bentonite standards within the product	12 inches drainage layer with minimum $1x10^{-3}$ cm/sec permeability	Hydraulic conductivity of $1x10^{-12}$ cm/sec with thickness either 40 mil or 60 mil depending on materials maximum water vapor transmission rate		Kentucky allows for 20 feet of natural material to be used as the seocndary (bottom) liner or a dual composite liner system if the in situ material is too permeable.	Section 401 KAR 48:080		
	Primary liner requires 3' of compacted clay with maximum $1x10^{-7}$ cm/sec permeability.									
LA	Construct 3 feet of compacted clay with a maximum hydraulic conductivity of 1x10-7 cm/sec directly below the flexible membrane liner.		Many landfills will substitute 1 foot of compacted clay for GCL or 2 feet if GCL has membrane component		Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE		Landfills may be required to provide additional design protections depending on proximity to drinking water sources	Title 33, Part VII, Subpart 1 Section 711(B)(5)c.ii	An alternate liner system that provides equivalent or greater protection as demonstrated by generally accepted modeling techniques and based on factors specific to the site and to the solid waste received is acceptable. The burden of proof of adequacy of the alternate liner design shall be on the permit holder or applicant.	Title 33, Part VII, Subpart 1 Section 711(B)(5)c.iii
ME	Construct 2 feet of compacted clay with a maximum hydraulic conductivity of 1x10-7 cm/sec directly below the flexible membrane liner.		GCL may be used as substitute for 12 inches of barrier soil layer		Geomembrane 60 mil minimum thickness			06-096 Chapter 401:2D(1)	Maine has an alternative liner approvals system which requires proof of equivalency and presents clear objectives of the equivalency. Regulations also include a table of alternative design option above minimal standards. The improvments allow the designer to make modelling adjustments to contaminant travel performance modeling.	Chapter 401, 06-096

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MD	1ft of clay or other native soil with $1x10^{-7}$ cm/sec, above 2 feet of clay with permeability less than $1x10^{-5}$ cm/sec				Geomembrane shall be thicker than 30 mil if reinforced. If the FML is not reinforced it shall be minimum 50 mils in thickness.		Common liners approved include 2 feet of prepared subbase with a GCL, and 60mil HDPE liner with cushion fabric and drainage material on top	MD Code Regs. 26.04.07.16	Geosynthetic component with a minimum 50 mil single reinforced or 30 mil reinforced with $1x10^{-10}$ cm/sec permeability is acceptable to substitute for clay component	
MA	1' of clay within the primary liner, 2' of compacted clay within the secondary (lower)liner, 1x10-7 cm/sec	>60 mils	GCL can substitute for 1' of compacted clay in both the primary or secondary liners	Leak detection layer required between primary and secondary liners	>60 mils	24" of granular material above the primary liner system.		310 CMR 19.110(3)		
MI	2' clay or alternative soil layer with equivalent permeability requirements. If site can prove natural soil hydraulic conductivity, then liner can be single composite. Otherwise Must be dual composite.	Can either be 60 mil HDPE or equivalent of 10' of clay at 1x10-7cm/sec	Equivalent of 2' of clay in place of clay is acceptable with evidence of equivalency	leak detection if using a secondary liner in place of 10' of natural material	Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE		New landfill cells require leakage control systems that include natural soil barier, double liner system that has a secondary liner that can include compacted clay, natural soil barrier or alternate system approved by the director	Part 115 R 299.4102(b)i	Allow for a demonstration of equivalency or improvement to the prescribed composite liner and leachate collection system requirements for proposed alternatives. The proposed alternatives must have supporting calculations, testing and demonstrations to allow for the Department to approve the alternate.	R299.4102(c)(ii)(C)
MN	4 foot natural soil barrier for clay or 2 foot with composite liner		GCL can replaced 1 foot of compacted clay on sideslopes		Geomembrane shall be thicker than 30 mil if reinforced. If the FML is not reinforced it shall be minimum 60 mils in thickness.			Part 7035.2815 (7)E	Alternate designs only if approved by commissioner of MPCA	Part 7035.2815(7)K
MS	Construct 2 feet of compacted clay with a maximum Hydraulic conductivity of $1x10^{-7}$ cm/sec directly below the flexible membrane liner.				Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE			Administrative Procedures Act Rules Title 11, Part 4, Rule 1.1 (C)(21)	Alternate designs will be considered on a site specific basis if the site can provide a design that limits concentration values below the Subtitle D values at a location 150 meters from the waste boundary on land owned by the site.	
MO	Construct 2 feet of compacted clay with a maximum Hydraulic conductivity of $1x10^{-7}$ cm/sec directly below the flexible membrane liner.				Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE			10 CSR 80-3		
MT	Construct 2 feet of compacted clay with a maximum Hydraulic conductivity of $1x10^{-7}$ cm/sec directly below the flexible membrane liner.				Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE			Rule 17.50.1202-1204	Small landfill exceptions are allowed only under very specific circumstances of remote locations and no contamination evidence	
NE	Construct 2 feet of compacted clay with a maximum Hydraulic conductivity of $1x10^{-7}$ cm/sec directly below the flexible membrane liner.				Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE			Title 132, Chapter 3.003.04	Alternate designs shall ensure that concentration values are not exceeded in the uppermost aquifer at a compliance location specified in the rules. The agency shall consider the following when accessing alternate designs for approval: hydrogeologic conditions of the site, climate of the site, size of the facility and volume and characteristics of the leachate.	Title 132, Chapter 3.003.04A2
NV	Construct 2 feet of compacted clay with a maximum Hydraulic conductivity of $1x10^{-7}$ cm/sec directly below the flexible membrane liner.				Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE			NAC 444.681		
NH	3 feet of compacted clay or recompacted native soils with maximum hydraulic conductivity $1x10^{-7}$ cm/sec	Lower FML shall be a thickness greater than 60 mil	GCL is allowed in place of compacted clay as long as it meets or exceeds permeability of clay component	12" of granular material separating liner systems, geosynthetics may be used on slopes in place of soils	Upper FML shall be a thickness greater than 60 mil		MSW landfills shall be double lined facilities	Env-Sw 805.04		

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	Naturally low permeable soils with maximum hydraulic conductivity of $1x10^{-6}$ cm/sec require 3 feet of clay with maximum hydraulic conductivity of $1x10^{-7}$ cm/sec.					Minimum one foot of sand with hydraulic condutivity $1x10^{-2}$ cm/sec or greater.	State allows lower design requirements for locations with naturally low permeability		Designs must use a 3D mass transport model for contaminant migration	
NJ	2 feet thick clay with $1x10^{-7}$ cm/sec maximum hydraulic conductivity				Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE		Almost all landfills in state require the dual composite liner due to proximity to drinking water sources	NJAC 7:26-2A.6		
	2 feet thick clay with $1x10^{-7}$ cm/sec maximum hydraulic conductivity for both upper and lower composite liners	Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE		Required between upper and lower composite liners if double composite required	Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE		Landfills located in areas with bedrock at or near the surface and serves as source for community water shall have a double composite liner system.			
NM	2 feet of compacted clay with maximum $1x10^{-7}$ cm/sec hydraulic conductivity		GCL can be substituted in place of clay		Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE			Title 20 Chapter 9, 4.13	Alternate liner designs must prove equivalent or better. The agency will review the climatic factors and volume and physical and chemical characteristics of the leachate when reviewing the alternate design.	Title 20 Chapter 9, 4.13(B)
NY	2 feet of compacted clay with maximum $1x10^{-7}$ cm/sec hydraulic conductivity below the secondary liner.	Geomembrane 60 mil minimum thickness	GCL is required below primary liner and must demonstrate permeability lower than $1x10^{-7}$ cm/sec.	leachate removal system between composite liners must be capable of 1,000 gallons per acre per day.	Geomembrane 60 mil minimum thickness	24 inches of leachate collection material		6 CRR-NY 363-6	State does allow some alternative designs, but optoins are limited and not often approved.	Section 363-6.21
	Standard Liner Design: 2 feet compacted clay with maximum hydraulic conductivity of $1x10^{-7}$ cm/sec.				Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE		NC has a standard liner option with two alternate liner designs and an approvals process for any other alternative designs	15A NCAC 13B.1624		
NC	Alternate Design: 18 inches of compacted clay with maximum hydraulic conductivity of $1x10^{-5}$ cm/sec		GCL used to replace 18 inches of clay from standard design		Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE		Alternate design details very specific requirements for GCL		An alternative base liner system may be approved by the Division if the owner demonstrates through a two-phase modeling approach that the alternative liner design meets the following: rate of leakage through the liner is less than standard designs, design will ensure contaminant concentrations listed in code are not exceeded.	
	Alternate Design: 12 inches of compacted clay with maximum hydraulic conductivity of $1x10^{-5}$ cm/sec	Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE			Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE	If use dual liner, leachate collection layer shall maintain head less than 1 inch				
ND	2 feet compacted clay with maximum 1x10^-7 cm/sec hydraulic conductivity for composite liner or 4 feet of compacted clay liner without FML				HDPE Geomembrane 60 mil minimum thickness			Chapter 33.1-20-06.1-02		
OH	3 feet of clay with maximum $2x10^{-7}$ cm/sec or 2 feet when used in conjuncture with GCL		GCL may replace 1 feet of clay for compacted clay liner portion of composite system		HDPE Geomembrane 60 mil minimum thickness		Regulations require liner cushion layer above liner and below leachate collection layer. Leachate collection layer shall be 1 foot of granular material.	OAC 3745-27-08(C) - (D)	Regulations note that alternate designs for leachate collection or capping systems may be considered if the site can prove equivalency, however, no means of alternate designs are provided for liner systems other than GCL use in replacement of 1 foot of clay.	

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OK	Construct 2 feet of compacted clay with a maximum Hydraulic conductivity of $1x10^{-7}$ cm/sec directly below the flexible membrane liner.				>30 mil FML, if HDPE >60mil, must have a factor of safety of 2 or greater for the manufacturer's tensile strength and puncture resistance when compared to the facilities design of the waste body. Must also have test as per the EPA test method 9090, compatibility tests for waste and membrane liners.		Landfills that receive less than 20 tons daily may requires less stringent liner requirements. Subject to agency approval and climate conditions, waste management plan, and waste reduction and recycling plan.	252:515-11-2(b)	Alternate designs shall ensure that concentration values are not exceeded in the uppermost aquifer at a compliance location specified in the rules. The agency shall consider the following when accessing alternate designs for approval: hydrogeologic conditions of the site, climate of the site, size of the facility and volum and characteristics of the leachat and slope stability.	252:515-11-2(c)
OR	Construct 2 feet of compacted clay with a maximum Hydraulic conductivity of $1x10^{-7}$ cm/sec directly below the flexible membrane liner.				Geomembrane 60 mil minimum thickness			340-093-0170(3)(a)	Regulation notes "meets design criteria in 40 CFR 258, Subpart D, or an alternate design approved by the Department…." Due to each half of the state having opposite climates, statewide rules requie more site specific requirements for alternate designs	
PA	6 inch subbase layer below secondary liner. Of the dual liners, the system that isn't composite requires maximum permeability of $1x10^{-7}$ cm/sec. If the clay is apart of the composite liner maximum permeability is $1x10^{-5}$ cm/sec.		GCL may function as part of the composite liner	12 inches thick of granual material with minimum $1x10^{-2}$ cm/sec	HDPE Geomembrane 60 mil minimum thickness		Requires dual liners, but only one has to be composite.	Title 25 Chapter 273.253-256	Equivalent designs are submitted with the design for approval and notification to the regulator is made for equivalency review within submission form. Regulations create clear approvals process for alternate review and approvals requirements	Code Chapter 271.231
RI	18 inches clay below primary (upper)liner and 24" clay below secondary (lower) liner.	FML must have maximum hydraulic conductivty of $1x10^{-12}$ cm/sec		A secondary leachate collection system shall include geocomposite or 12 inches granular material between the liners.	FML must have maximum hydraulic conductivty of $1x10^{-12}$ cm/sec	24 inches of granular material above the primary liner system.	Slopes less than 25% require double composite liner. Steeper slopes require just 1 layer FML and 2 feet clay compacted layer	250-RICR-140-05-2.2.3	Does not allow any alternate designs that do not include the secondary (lower) liner. Regulations do allow design to provide equivalent design to primary (upper) liner system.	250-RICR-140-05-2.2.14
SC	Construct 2 feet of compacted clay with a maximum Hydraulic conductivity of $1x10^{-7}$ cm/sec directly below the flexible membrane liner.				Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE			S.C. Code Section 44-96-10 Part IV Subpart D 258.40	Alternate landfill designs shall be reviewed on a case by case basis by the state to prove the design demonstrates environmental and public health protection standards.	S.C. Code Section 44-96-10 Part IV Subpart D 258.40(q)
SD	Construct 2 feet of compacted clay with a maximum Hydraulic conductivity of $1x10^{-7}$ cm/sec directly below the flexible membrane liner.				Geomembrane 60 mil minimum thickness		Due to the state having most groundwater 100 feet or more below ground level, alternate designs are usually 2 feet of compacted clay.	Administrative Rules 74:27:12:17	Variances to the design criteria will be reviewed on a case by case basis. Regulations do no specify any specific requirements other than meets minimal federal requirements.	Administrative Rules 74:27:12:24
TN	Construct 2 feet of compacted clay with a maximum Hydraulic conductivity of $1x10^{-7}$ cm/sec directly below the flexible membrane liner.		GCL can be used to replace compacted clay. The amount of clay that is replaced is dependent on HELP model results for the GCL.		Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE		Underlying soil component shall have specific properties established in the rules. Rules established minimal hydraulic conductivities below the liner above the seasonal high aquifer water table in uppermost aquifer. Admixtures and special construction techniques can be used to improve soil.	Chapter 0400-11-01-.04(4)a	Alternate liners are allowed and require approval by the comissioner. The alternate design must provide equivalence or superior performance to minimal standards established by the rules.	Chapter 0400-11-01-.04(4)a4
TX	Construct 2 feet of compacted clay with a maximum Hydraulic conductivity of $1x10^{-7}$ cm/sec directly below the flexible membrane liner.		GCL can be used to replace compacted clay. The amount of clay that is replaced is dependent on HELP model results for the GCL.		Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE		Regulations only requires the design provide containment to ensure concentration values listed in the Rule do not exceed the uppermost aquifer at a relevant point of compliance. This allows for variations to the liner design.	Title 30, Part 1: Chapter 330-Subchapter H: Section 330.331	Alternate designs authorized by the executive director if it demonstrations using the HELP model that contaminant concentrations listed in the rules are not excceded. Alternate designs have included 4' of soil, only 60mil of HDPE with model suport, and GCL substitution for compacted clay.	

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UT	Construct 2 feet of compacted clay with a maximum Hydraulic conductivity of 1x10^{-7} cm/sec directly below the flexible membrane liner.				Geomembrane 60 mil minimum thickness			R315-303-3(3)(a)	The Director may approve an alternative liner design on a site specific basis, if it can be documented that, under the conditions of location, hydrogeology, the equivalent design will minimize the migration of solid waste constituents or leachate into the ground or surface water at least as effectively as the liner design required by rules	R315-303-3(3)(b)
VT	2 feet of compacted clay with maximum 1x10^{-7} cm/sec hydraulic conductivity for both upper and lower FML	HDPE Geomembrane 60 mil minimum thickness		Leak detection layer between dual liners 12 inches of soil with permeability less than 1 x 10^{-2} cm/sec	HDPE Geomembrane 60 mil minimum thickness			Rule: 20P-005, § 6-1004	Rules note "...or alternative composite (synethetic and natural material) liner system which achieves the equivalent hydraulic barrier properties."	
VA	Construct 2 feet of compacted clay with a maximum Hydraulic conductivity of 1x10^{-7} cm/sec directly below the flexible membrane liner.		GCL is written into regulations that it can be substituted for 1 foot of clay and has a hydraulic conductivity lower than 1x10^{-9} cm/sec		Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE		Site may submit a petition to allow for an alternate design. Director may approve the design if it demonstrates the alternate design will ensure concentrations of values in rules will not be exceeded in uppermost aquifer.	9VAC20-81-130(J)		9VAC20-81-130(J)b
WA	Construct 2 feet of compacted clay with a maximum Hydraulic conductivity of 1x10^{-7} cm/sec directly below the flexible membrane liner.	Not Required if presumptive design is used	Requires alternative liner demonstration if proposed to replace compated clay	Not required if presumptive design is used	Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE	Designed and constructed to maintain less than 1 foot of leachate over the liner and less than 2 feet of leachate over the sump		WAC 173-351-300(2) for MSW landfills	Alternative designs approved by the jurisdictional health department (which typically request Washington Department of Ecology to review). Alternative designs must ensure that the concentration values listed in Table 1 of the codes and the criteria in the water quality standards for groundwaters of the state of Washington, Chapter 173-200 WAC, will not be exceeded in the hydrostatigraphic unit(s) identified in the hydrogeologic characterization/report at the relevant point of compliance as specified during the permitting process in WAC 173-351-700 or through the permit modification process in WAC 173-351-720(6). Alternative designs must also sufficiently control methane to meet the criteria in WAC 173-351 200(4).	WAS 173-351-300 (2)(b)
WV	Construct 2 feet of compacted clay with a maximum Hydraulic conductivity of 1x10^{-7} cm/sec directly below the flexible membrane liner.				HDPE Geomembrane 60 mil minimum thickness	Leachate detection zone beneath liner at least 12 inches thick and more permeable than1x10^{-3} cm/sec		33CSR1 4.5.d.5		
WI	4 feet thick compacted clay with maximum 1x10^{-7} cm/sec hydraulic conductivity				HDPE Geomembrane 60 mil minimum thickness			Chapter NR 504.06(2)		
WY	Construct 2 feet of compacted clay with a maximum Hydraulic conductivity of 1x10^{-7} cm/sec directly below the flexible membrane liner.		Regulations allow for substitution of 2 feet of compacted clay with GCL if provided equivalency		Geomembrane 60 mil minimum thickness if HDPE, 30 mil minimum thickness if other than HDPE			W.S. § 35-11-527		W.S. § 35-11-601

APPENDIX B

HELP Model Results

HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE
HELP MODEL VERSION 4.0 BETA (2018)
DEVELOPED BY USEPA NATIONAL RISK MANAGEMENT RESEARCH LABORATORY

Title:	Wisconsin Liner HELP Model	**Simulated On:**	4/16/2021 14:13

Layer 1
Type 1 - Vertical Percolation Layer (Cover Soil)
LS - Loamy Sand
Material Texture Number 4

Thickness	=	12	inches
Porosity	=	0.437	vol/vol
Field Capacity	=	0.105	vol/vol
Wilting Point	=	0.047	vol/vol
Initial Soil Water Content	=	0.1223	vol/vol
Effective Sat. Hyd. Conductivity	=	1.70E-03	cm/sec

Layer 2
Type 1 - Vertical Percolation Layer (Waste)
Municipal Solid Waste (MSW) (900 pcy)
Material Texture Number 18

Thickness	=	600	inches
Porosity	=	0.671	vol/vol
Field Capacity	=	0.292	vol/vol
Wilting Point	=	0.077	vol/vol
Initial Soil Water Content	=	0.2941	vol/vol
Effective Sat. Hyd. Conductivity	=	1.00E-03	cm/sec

Layer 3
Type 2 - Lateral Drainage Layer
G - Gravel
Material Texture Number 21

Thickness	=	12	inches
Porosity	=	0.397	vol/vol
Field Capacity	=	0.032	vol/vol
Wilting Point	=	0.013	vol/vol
Initial Soil Water Content	=	0.0436	vol/vol
Effective Sat. Hyd. Conductivity	=	3.00E-01	cm/sec
Slope	=	2	%
Drainage Length	=	130	ft

Layer 4

Type 4 - Flexible Membrane Liner
HDPE Membrane
Material Texture Number 35

Thickness	=	0.06	inches
Effective Sat. Hyd. Conductivity	=	2.00E-13	cm/sec
FML Pinhole Density	=	2	Holes/Acre
FML Installation Defects	=	2	Holes/Acre
FML Placement Quality	=	2	Excellent

Layer 5

Type 3 - Barrier Soil Liner
C (Moderate)
Material Texture Number 29

Thickness	=	48	inches
Porosity	=	0.451	vol/vol
Field Capacity	=	0.419	vol/vol
Wilting Point	=	0.332	vol/vol
Initial Soil Water Content	=	0.451	vol/vol
Effective Sat. Hyd. Conductivity	=	6.80E-07	cm/sec

Layer 6

Type 1 - Vertical Percolation Layer
LS - Loamy Sand
Material Texture Number 4

Thickness	=	120	inches
Porosity	=	0.437	vol/vol
Field Capacity	=	0.105	vol/vol
Wilting Point	=	0.047	vol/vol
Initial Soil Water Content	=	0.105	vol/vol
Effective Sat. Hyd. Conductivity	=	1.70E-03	cm/sec

Note: Initial moisture content of the layers and snow water were computed as nearly steady-state values by HELP.

General Design and Evaporative Zone Data

SCS Runoff Curve Number	=	57.2	
Fraction of Area Allowing Runoff	=	80	%
Area projected on a horizontal plane	=	10	acres
Evaporative Zone Depth	=	8	inches
Initial Water in Evaporative Zone	=	0.876	inches
Upper Limit of Evaporative Storage	=	3.496	inches
Lower Limit of Evaporative Storage	=	0.376	inches
Initial Snow Water	=	0.08554	inches

Initial Water in Layer Materials	=	212.7	inches
Total Initial Water	=	212.785	inches
Total Subsurface Inflow	=	0	inches/year

Note: SCS Runoff Curve Number was calculated by HELP.

Evapotranspiration and Weather Data

Station Latitude	=	44.75	Degrees
Maximum Leaf Area Index	=	4	
Start of Growing Season (Julian Date)	=	126	days
End of Growing Season (Julian Date)	=	280	days
Average Wind Speed	=	16.14	mph
Average 1st Quarter Relative Humidity	=	73	%
Average 2nd Quarter Relative Humidity	=	62	%
Average 3rd Quarter Relative Humidity	=	69	%
Average 4th Quarter Relative Humidity	=	74	%

Note: Evapotranspiration data was obtained for , Wisconsin

Normal Mean Monthly Precipitation (inches)

Jan/Jul	Feb/Aug	Mar/Sep	Apr/Oct	May/Nov	Jun/Dec
0.913372	1.118375	1.978924	3.988621	4.178431	5.504162
3.903103	4.820072	3.971273	2.209989	1.933466	1.044033

Note: Precipitation was simulated based on HELP V4 weather simulation for:
Lat/Long: 44.75/-91.51

Normal Mean Monthly Temperature (Degrees Fahrenheit)

Jan/Jul	Feb/Aug	Mar/Sep	Apr/Oct	May/Nov	Jun/Dec
22.7	25.9	35.3	48.3	64.4	74.4
80.6	77.3	68.7	50.8	34.8	22.6

Note: Temperature was simulated based on HELP V4 weather simulation for:
Lat/Long: 44.75/-91.51
Solar radiation was simulated based on HELP V4 weather simulation for:
Lat/Long: 44.75/-91.51

Average Annual Totals Summary

Title: Wisconsin Liner HELP Model
Simulated on: 4/16/2021 14:15

	Average Annual Totals for Years 1 - 40*			
	(inches)	[std dev]	(cubic feet)	(percent)
Precipitation	35.56	[4.54]	1,290,966.7	100.00
Runoff	2.894	[1.986]	105,049.3	8.14
Evapotranspiration	24.205	[2.903]	878,635.5	68.06
Subprofile1				
Lateral drainage collected from Layer 3	8.4728	[2.4129]	307,561.5	23.82
Percolation/leakage through Layer 5	0.000050	[0.000014]	1.8326	0.00
Average Head on Top of Layer 4	0.0887	[0.0253]	---	---
Subprofile2				
Percolation/leakage through Layer 6	0.000054	[0.000016]	1.9569	0.00
Water storage				
Change in water storage	-0.0078	[1.1698]	-281.6	-0.02

* Note: Average inches are converted to volume based on the user-specified area.

Peak Values Summary

Title: Wisconsin Liner HELP Model
Simulated on: 4/16/2021 14:15

	Peak Values for Years 1 - 40*	
	(inches)	(cubic feet)
Precipitation	3.28	119,054.2
Runoff	1.725	62,613.7
Subprofile1		
Drainage collected from Layer 3	0.1327	4,815.3
Percolation/leakage through Layer 5	0.000001	0.0279
Average head on Layer 4	0.5072	---
Maximum head on Layer 4	0.9299	---
Location of maximum head in Layer 3	10.77	(feet from drain)
Subprofile2		
Percolation/leakage through Layer 6	0.000016	0.5663
Other Parameters		
Snow water	2.7494	99,802.5
Maximum vegetation soil water	0.4370	(vol/vol)
Minimum vegetation soil water	0.0470	(vol/vol)

Final Water Storage in Landfill Profile at End of Simulation Period

Title: Wisconsin Liner HELP Model
Simulated on: 4/16/2021 14:15
Simulation period: 40 years

	Final Water Storage	
Layer	(inches)	(vol/vol)
1	2.6415	0.2201
2	175.2000	0.2920
3	0.3856	0.0321
4	0.0000	0.0000
5	21.6480	0.4510
6	12.5999	0.1050
Snow water	0.0000	---

HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE
HELP MODEL VERSION 4.0 BETA (2018)
DEVELOPED BY USEPA NATIONAL RISK MANAGEMENT RESEARCH LABORATORY

Title: Wisconsin Liner HELP Model **Simulated On:** 4/16/2021 15:46

Layer 1

Type 1 - Vertical Percolation Layer (Cover Soil)
LS - Loamy Sand
Material Texture Number 4

Thickness	=	12	inches
Porosity	=	0.437	vol/vol
Field Capacity	=	0.105	vol/vol
Wilting Point	=	0.047	vol/vol
Initial Soil Water Content	=	0.1223	vol/vol
Effective Sat. Hyd. Conductivity	=	1.70E-03	cm/sec

Layer 2

Type 1 - Vertical Percolation Layer (Waste)
Municipal Solid Waste (MSW) (900 pcy)
Material Texture Number 18

Thickness	=	600	inches
Porosity	=	0.671	vol/vol
Field Capacity	=	0.292	vol/vol
Wilting Point	=	0.077	vol/vol
Initial Soil Water Content	=	0.2941	vol/vol
Effective Sat. Hyd. Conductivity	=	1.00E-03	cm/sec

Layer 3

Type 2 - Lateral Drainage Layer
G - Gravel
Material Texture Number 21

Thickness	=	12	inches
Porosity	=	0.397	vol/vol
Field Capacity	=	0.032	vol/vol
Wilting Point	=	0.013	vol/vol
Initial Soil Water Content	=	0.0436	vol/vol
Effective Sat. Hyd. Conductivity	=	3.00E-01	cm/sec
Slope	=	2	%
Drainage Length	=	130	ft

Layer 4

Type 4 - Flexible Membrane Liner
HDPE Membrane
Material Texture Number 35

Thickness	=	0.06	inches
Effective Sat. Hyd. Conductivity	=	2.00E-13	cm/sec
FML Pinhole Density	=	2	Holes/Acre
FML Installation Defects	=	2	Holes/Acre
FML Placement Quality	=	2	Excellent

Layer 5

Type 3 - Barrier Soil Liner
Bentonite (High)
Material Texture Number 17

Thickness	=	0.23622	inches
Porosity	=	0.75	vol/vol
Field Capacity	=	0.747	vol/vol
Wilting Point	=	0.4	vol/vol
Initial Soil Water Content	=	0.75	vol/vol
Effective Sat. Hyd. Conductivity	=	3.00E-09	cm/sec

Layer 6

Type 1 - Vertical Percolation Layer
C - Clay (Low Density)
Material Texture Number 15

Thickness	=	24	inches
Porosity	=	0.475	vol/vol
Field Capacity	=	0.378	vol/vol
Wilting Point	=	0.265	vol/vol
Initial Soil Water Content	=	0.378	vol/vol
Effective Sat. Hyd. Conductivity	=	1.70E-05	cm/sec

Layer 7

Type 1 - Vertical Percolation Layer
LS - Loamy Sand
Material Texture Number 4

Thickness	=	120	inches
Porosity	=	0.437	vol/vol
Field Capacity	=	0.105	vol/vol
Wilting Point	=	0.047	vol/vol
Initial Soil Water Content	=	0.105	vol/vol
Effective Sat. Hyd. Conductivity	=	1.70E-03	cm/sec

Note: Initial moisture content of the layers and snow water were computed as nearly steady-state values by HELP.

General Design and Evaporative Zone Data

SCS Runoff Curve Number	=	57.2	
Fraction of Area Allowing Runoff	=	80	%
Area projected on a horizontal plane	=	10	acres
Evaporative Zone Depth	=	8	inches
Initial Water in Evaporative Zone	=	0.876	inches
Upper Limit of Evaporative Storage	=	3.496	inches
Lower Limit of Evaporative Storage	=	0.376	inches
Initial Snow Water	=	0.08554	inches
Initial Water in Layer Materials	=	200.301	inches
Total Initial Water	=	200.386	inches
Total Subsurface Inflow	=	0	inches/year

Note: SCS Runoff Curve Number was calculated by HELP.

Evapotranspiration and Weather Data

Station Latitude	=	44.75	Degrees
Maximum Leaf Area Index	=	4	
Start of Growing Season (Julian Date)	=	126	days
End of Growing Season (Julian Date)	=	280	days
Average Wind Speed	=	16.14	mph
Average 1st Quarter Relative Humidity	=	73	%
Average 2nd Quarter Relative Humidity	=	62	%
Average 3rd Quarter Relative Humidity	=	69	%
Average 4th Quarter Relative Humidity	=	74	%

Note: Evapotranspiration data was obtained for , Wisconsin

Normal Mean Monthly Precipitation (inches)

Jan/Jul	Feb/Aug	Mar/Sep	Apr/Oct	May/Nov	Jun/Dec
0.913372	1.118375	1.978924	3.988621	4.178431	5.504162
3.903103	4.820072	3.971273	2.209989	1.933466	1.044033

Note: Precipitation was simulated based on HELP V4 weather simulation for:
Lat/Long: 44.75/-91.51

Normal Mean Monthly Temperature (Degrees Fahrenheit)

Jan/Jul	Feb/Aug	Mar/Sep	Apr/Oct	May/Nov	Jun/Dec
22.7	25.9	35.3	48.3	64.4	74.4

80.6	77.3	68.7	50.8	34.8	22.6

Note: Temperature was simulated based on HELP V4 weather simulation for:
Lat/Long: 44.75/-91.51
Solar radiation was simulated based on HELP V4 weather simulation for:
Lat/Long: 44.75/-91.51

Average Annual Totals Summary

Title: Wisconsin Liner HELP Model
Simulated on: 4/16/2021 15:49

	Average Annual Totals for Years 1 - 40*			
	(inches)	[std dev]	(cubic feet)	(percent)
Precipitation	35.56	[4.54]	1,290,966.7	100.00
Runoff	2.894	[1.986]	105,049.3	8.14
Evapotranspiration	24.205	[2.903]	878,635.5	68.06
Subprofile1				
Lateral drainage collected from Layer 3	8.4728	[2.4129]	307,563.1	23.82
Percolation/leakage through Layer 5	0.000006	[0.000001]	0.1997	0.00
Average Head on Top of Layer 4	0.0887	[0.0253]	---	---
Subprofile2				
Percolation/leakage through Layer 7	0.000005	[0.000007]	0.1965	0.00
Water storage				
Change in water storage	-0.0078	[1.1698]	-281.4	-0.02

* Note: Average inches are converted to volume based on the user-specified area.

Peak Values Summary

Title: Wisconsin Liner HELP Model
Simulated on: 4/16/2021 15:49

	Peak Values for Years 1 - 40*	
	(inches)	(cubic feet)
Precipitation	3.28	119,054.2
Runoff	1.725	62,613.7
Subprofile1		
Drainage collected from Layer 3	0.1327	4,815.3
Percolation/leakage through Layer 5	0.000000	0.0024
Average head on Layer 4	0.5072	---
Maximum head on Layer 4	0.9299	---
Location of maximum head in Layer 3	10.77	(feet from drain)
Subprofile2		
Percolation/leakage through Layer 7	0.000015	0.5615
Other Parameters		
Snow water	2.7494	99,802.5
Maximum vegetation soil water	0.4370	(vol/vol)
Minimum vegetation soil water	0.0470	(vol/vol)

Final Water Storage in Landfill Profile at End of Simulation Period

Title: Wisconsin Liner HELP Model
Simulated on: 4/16/2021 15:49
Simulation period: 40 years

	Final Water Storage	
Layer	(inches)	(vol/vol)
1	2.6415	0.2201
2	175.2000	0.2920
3	0.3856	0.0321
4	0.0000	0.0000
5	0.1772	0.7500
6	9.0720	0.3780
7	12.6000	0.1050
Snow water	0.0000	---

HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE
HELP MODEL VERSION 4.0 BETA (2018)
DEVELOPED BY USEPA NATIONAL RISK MANAGEMENT RESEARCH LABORATORY

Title: Wisconsin Liner HELP Model **Simulated On:** 4/16/2021 16:17

Layer 1

Type 1 - Vertical Percolation Layer (Cover Soil)
LS - Loamy Sand
Material Texture Number 4

Thickness	=	12	inches
Porosity	=	0.437	vol/vol
Field Capacity	=	0.105	vol/vol
Wilting Point	=	0.047	vol/vol
Initial Soil Water Content	=	0.1223	vol/vol
Effective Sat. Hyd. Conductivity	=	1.70E-03	cm/sec

Layer 2

Type 1 - Vertical Percolation Layer (Waste)
Municipal Solid Waste (MSW) (900 pcy)
Material Texture Number 18

Thickness	=	600	inches
Porosity	=	0.671	vol/vol
Field Capacity	=	0.292	vol/vol
Wilting Point	=	0.077	vol/vol
Initial Soil Water Content	=	0.2941	vol/vol
Effective Sat. Hyd. Conductivity	=	1.00E-03	cm/sec

Layer 3

Type 2 - Lateral Drainage Layer
G - Gravel
Material Texture Number 21

Thickness	=	12	inches
Porosity	=	0.397	vol/vol
Field Capacity	=	0.032	vol/vol
Wilting Point	=	0.013	vol/vol
Initial Soil Water Content	=	0.0436	vol/vol
Effective Sat. Hyd. Conductivity	=	3.00E-01	cm/sec
Slope	=	2	%
Drainage Length	=	130	ft

Layer 4

Type 4 - Flexible Membrane Liner
HDPE Membrane
Material Texture Number 35

Thickness	=	0.06	inches
Effective Sat. Hyd. Conductivity	=	2.00E-13	cm/sec
FML Pinhole Density	=	2	Holes/Acre
FML Installation Defects	=	2	Holes/Acre
FML Placement Quality	=	2	Excellent

Layer 5

Type 3 - Barrier Soil Liner
Bentonite (High)
Material Texture Number 17

Thickness	=	0.23622	inches
Porosity	=	0.75	vol/vol
Field Capacity	=	0.747	vol/vol
Wilting Point	=	0.4	vol/vol
Initial Soil Water Content	=	0.75	vol/vol
Effective Sat. Hyd. Conductivity	=	3.00E-09	cm/sec

Layer 6

Type 2 - Lateral Drainage Layer
G - Gravel
Material Texture Number 21

Thickness	=	12	inches
Porosity	=	0.397	vol/vol
Field Capacity	=	0.032	vol/vol
Wilting Point	=	0.013	vol/vol
Initial Soil Water Content	=	0.032	vol/vol
Effective Sat. Hyd. Conductivity	=	3.00E-01	cm/sec
Slope	=	2	%
Drainage Length	=	130	ft

Layer 7

Type 4 - Flexible Membrane Liner
HDPE Membrane
Material Texture Number 35

Thickness	=	0.06	inches
Effective Sat. Hyd. Conductivity	=	2.00E-13	cm/sec
FML Pinhole Density	=	2	Holes/Acre
FML Installation Defects	=	2	Holes/Acre
FML Placement Quality	=	2	Excellent

Layer 8

Type 3 - Barrier Soil Liner
Bentonite (High)
Material Texture Number 17

Thickness	=	0.23622	inches
Porosity	=	0.75	vol/vol
Field Capacity	=	0.747	vol/vol
Wilting Point	=	0.4	vol/vol
Initial Soil Water Content	=	0.75	vol/vol
Effective Sat. Hyd. Conductivity	=	3.00E-09	cm/sec

Layer 9

Type 1 - Vertical Percolation Layer
LS - Loamy Sand
Material Texture Number 4

Thickness	=	120	inches
Porosity	=	0.437	vol/vol
Field Capacity	=	0.105	vol/vol
Wilting Point	=	0.047	vol/vol
Initial Soil Water Content	=	0.105	vol/vol
Effective Sat. Hyd. Conductivity	=	1.70E-03	cm/sec

Note: Initial moisture content of the layers and snow water were computed as nearly steady-state values by HELP.

General Design and Evaporative Zone Data

SCS Runoff Curve Number	=	57.2	
Fraction of Area Allowing Runoff	=	80	%
Area projected on a horizontal plane	=	10	acres
Evaporative Zone Depth	=	8	inches
Initial Water in Evaporative Zone	=	0.876	inches
Upper Limit of Evaporative Storage	=	3.496	inches
Lower Limit of Evaporative Storage	=	0.376	inches
Initial Snow Water	=	0.08554	inches
Initial Water in Layer Materials	=	191.79	inches
Total Initial Water	=	191.876	inches
Total Subsurface Inflow	=	0	inches/year

Note: SCS Runoff Curve Number was calculated by HELP.

Evapotranspiration and Weather Data

Station Latitude	=	44.75	Degrees
Maximum Leaf Area Index	=	4	

Start of Growing Season (Julian Date)	=	126	days
End of Growing Season (Julian Date)	=	280	days
Average Wind Speed	=	16.14	mph
Average 1st Quarter Relative Humidity	=	73	%
Average 2nd Quarter Relative Humidity	=	62	%
Average 3rd Quarter Relative Humidity	=	69	%
Average 4th Quarter Relative Humidity	=	74	%

Note: Evapotranspiration data was obtained for , Wisconsin

Normal Mean Monthly Precipitation (inches)

Jan/Jul	Feb/Aug	Mar/Sep	Apr/Oct	May/Nov	Jun/Dec
0.913372	1.118375	1.978924	3.988621	4.178431	5.504162
3.903103	4.820072	3.971273	2.209989	1.933466	1.044033

Note: Precipitation was simulated based on HELP V4 weather simulation for:
Lat/Long: 44.75/-91.51

Normal Mean Monthly Temperature (Degrees Fahrenheit)

Jan/Jul	Feb/Aug	Mar/Sep	Apr/Oct	May/Nov	Jun/Dec
22.7	25.9	35.3	48.3	64.4	74.4
80.6	77.3	68.7	50.8	34.8	22.6

Note: Temperature was simulated based on HELP V4 weather simulation for:
Lat/Long: 44.75/-91.51
Solar radiation was simulated based on HELP V4 weather simulation for:
Lat/Long: 44.75/-91.51

Average Annual Totals Summary

Title: Wisconsin Liner HELP Model
Simulated on: 4/16/2021 16:21

	Average Annual Totals for Years 1 - 40*			
	(inches)	[std dev]	(cubic feet)	(percent)
Precipitation	35.56	[4.54]	1,290,966.7	100.00
Runoff	2.894	[1.986]	105,049.3	8.14
Evapotranspiration	24.205	[2.903]	878,635.5	68.06
Subprofile1				
Lateral drainage collected from Layer 3	8.4728	[2.4129]	307,563.1	23.82
Percolation/leakage through Layer 5	0.000006	[0.000001]	0.1997	0.00
Average Head on Top of Layer 4	0.0887	[0.0253]	---	---
Subprofile2				
Lateral drainage collected from Layer 6	0.0000	[0]	0.1096	0.00
Percolation/leakage through Layer 8	0.000002	[0]	0.0902	0.00
Average Head on Top of Layer 7	0.0000	[0]	---	---
Subprofile3				
Percolation/leakage through Layer 9	0.000002	[0.000006]	0.0842	0.00
Water storage				
Change in water storage	-0.0078	[1.1698]	-281.4	-0.02

* Note: Average inches are converted to volume based on the user-specified area.

Peak Values Summary

Title: Wisconsin Liner HELP Model
Simulated on: 4/16/2021 16:21

	Peak Values for Years 1 - 40*	
	(inches)	(cubic feet)
Precipitation	3.28	119,054.2
Runoff	1.725	62,613.7
Subprofile1		
Drainage collected from Layer 3	0.1327	4,815.3
Percolation/leakage through Layer 5	0.000000	0.0024
Average head on Layer 4	0.5072	---
Maximum head on Layer 4	0.9299	---
Location of maximum head in Layer 3	10.77 (feet from drain)	
Subprofile2		
Drainage collected from Layer 6	0.0000	0.0020
Percolation/leakage through Layer 8	0.000000	0.0002
Average head on Layer 7	0.0000	---
Maximum head on Layer 7	0.0000	---
Location of maximum head in Layer 6	0.00 (feet from drain)	
Subprofile3		
Percolation/leakage through Layer 9	0.000015	0.5614
Other Parameters		
Snow water	2.7494	99,802.5
Maximum vegetation soil water	0.4370 (vol/vol)	
Minimum vegetation soil water	0.0470 (vol/vol)	

Final Water Storage in Landfill Profile at End of Simulation Period

Title: Wisconsin Liner HELP Model
Simulated on: 4/16/2021 16:21
Simulation period: 40 years

	Final Water Storage	
Layer	(inches)	(vol/vol)
1	2.6415	0.2201
2	175.2000	0.2920
3	0.3856	0.0321
4	0.0000	0.0000
5	0.1772	0.7500
6	0.3840	0.0320
7	0.0000	0.0000
8	0.1772	0.7500
9	12.6000	0.1050
Snow water	0.0000	---

APPENDIX C

Construction Cost Estimates

Table 1: Construction Cost - 1 Acre Wisconsin Landfill Liner Locally Sourced Clay

Line Item	Description	Units	Quantity	Unit Price	Total
1	Excavate and Replace Nonconforming Material from Subgrade	CY	2420	$10.50	$25,410.00
2	Final Grading of Subbase	SF	43,560	$0.09	$3,920.40
3	Supply and Install of 4 feet of Compacted Clay Liner	CY	6,453.33	$6.90	$44,528.00
4	Supply and Install 60 – mil HDPE FML	SF	43,560	$0.56	$24,393.60
5	Supply and Install 1-foot-thick leachate collection layer	SF	43,560	$1.03	$44,866.80
				Total	$143,118.80

- Liner is constructed as per Wisconsin Chapter 504.06 requirements for clay and FML
- Unit prices for geosynthetics do not account for recent spikes in costs due to global pandemic and Texas power outages which have caused a supply shortage nationally.
- All soil materials are locally sourced on site.
- Removal of top 6 inches of topsoil for liner subbase preparation.
- Does not include lysimeter or leachate pipework construction as part of the liner construction
- Cost do not include items like Mobilization/Demobilization or Erosion Control and are only indicative of earthworks required for liner construction.

Table 2: Construction Cost - 1 Acre Wisconsin Landfill Liner - Clay Import

Line Item	Description	Units	Quantity	Unit Price	Total
1	Excavate and Replace Nonconforming Material from Subgrade	CY	2420	$10.50	$25,410.00
2	Final Grading of Subbase	SF	43,560	$0.09	$3,920.40
3	Supply and Install of 4 feet of Compacted Clay Liner	CY	6,453.33	$40.00	$258,133.20
4	Supply and Install 60 – mil HDPE FML	SF	43,560	$0.56	$24,393.60
5	Supply and Install 1-foot-thick leachate collection layer	SF	43,560	$1.03	$44,866.80
				Total	$356,724.00

- Liner is constructed as per Wisconsin Chapter 504.06 requirements for clay and FML
- Unit prices for geosynthetics do not account for recent spikes in costs due to global pandemic and Texas power outages which have caused a supply shortage nationally.
- All coarse grain soil materials are locally sourced on site.
- Clay material is sourced and trucked from a location 1 hour from cell construction
- Removal of top 6 inches of topsoil for liner subbase preparation.
- Does not include lysimeter or leachate pipework construction as part of the liner construction
- Cost do not include items like Mobilization/Demobilization or Erosion Control and are only indicative of earthworks required for liner construction.

Table 3: Construction Cost - GCL Replacement for Clay

Line Item	Description	Units	Quantity	Unit Price	Total
1	Excavate and Replace Nonconforming Material from Subgrade	CY	2420	$10.50	$25,410.00
2	Final Grading of Subbase	SF	43,560	$0.09	$3,920.40
3	Supply and Install of 2 feet of Compacted Clay Liner	CY	3,226.67	$40.00	$129,066.80
4	Supply and Install GCL	SF	43,560	$0.57	$24,829.20
5	Supply and Install 60 – mil HDPE FML	SF	43,560	$0.56	$24,393.60
6	Supply and Install 1-foot-thick leachate collection layer	SF	43,560	$1.03	$44,866.80
				Total	$252,486.80

- Liner is constructed with 2 feet of compacted clay, a GCL and 60 mil HDPE geomembrane. The GCL has been substituted for 2 feet of compacted clay as part of the Wisconsin Chapter 504 landfill liner requirements.
- Unit prices for geosynthetics do not account for recent spikes in costs due to global pandemic and Texas power outages which have caused a supply shortage nationally.
- All coarse grain soil materials are locally sourced on site.
- Removal of top 6 inches of topsoil for liner subbase preparation.
- Does not include lysimeter or leachate pipework construction as part of liner construction
- Cost do not include items like Mobilization/Demobilization or Erosion Control and are only indicative of earthworks required for liner construction.
- GCL substitution is assumed for a site which needs to import clay. Unit rates are for importing and trucking clay >1hr

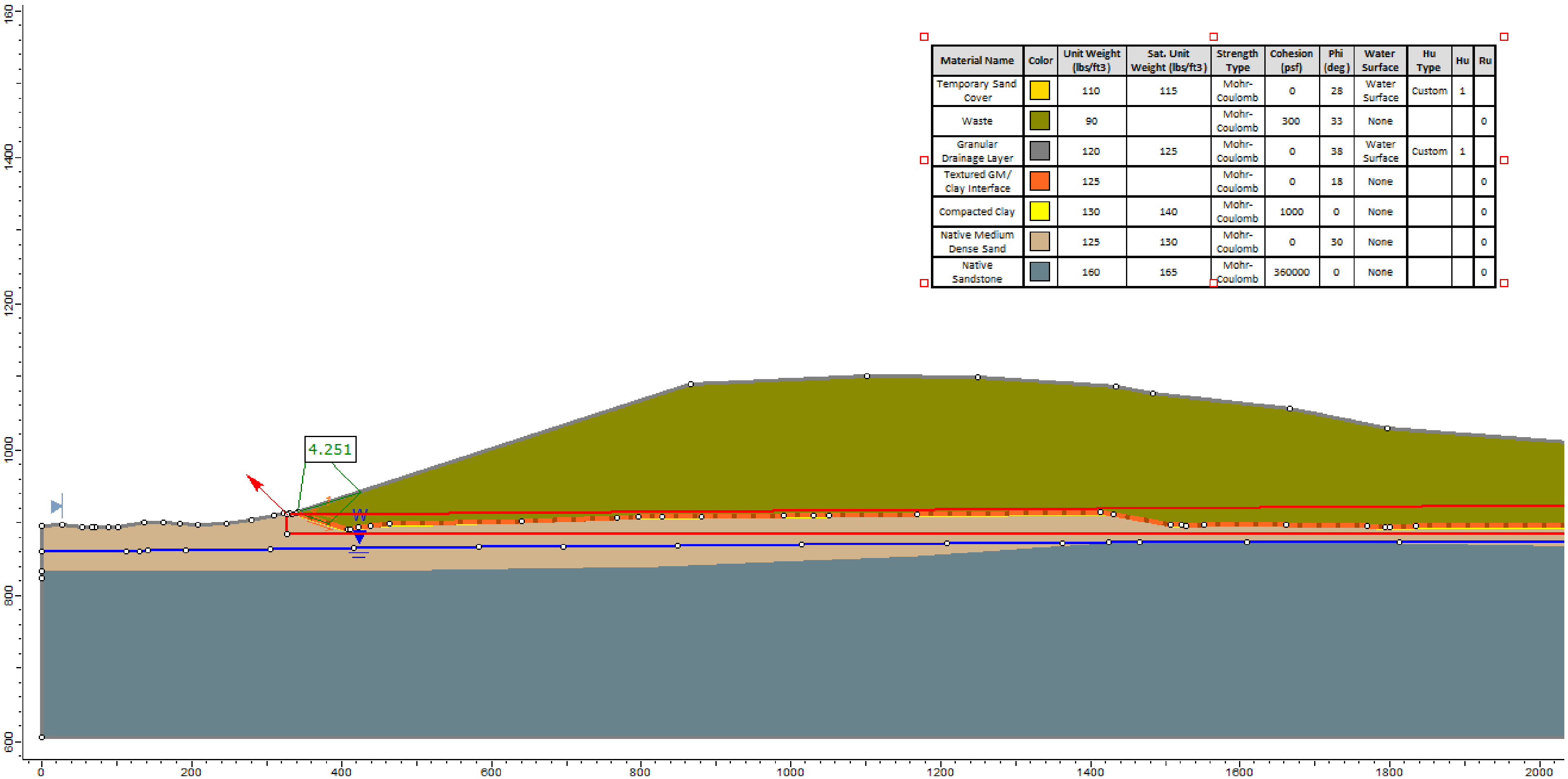
Table 4: Dual Composite Liner Cost Estimate

Line Item	Description	Units	Quantity	Unit Price	Total
1	Excavate and Replace Nonconforming Material from Subgrade	CY	2420	$10.50	$25,410.00
2	Final Grading of Subbase	SF	43,560	$0.09	$3,920.40
3	Supply and Install GCL	SF	87,120	$0.57	$49,658.40
4	Supply and Install Leak Detection Layer	SF	43,560	$1.03	$44,866.80
5	Supply and Install 60 – mil HDPE FML	SF	87,120	$0.56	$48,787.20
6	Supply and Install 1-foot-thick leachate collection layer	SF	43,560	$1.03	$44,866.80
				Total	$217,509.60

- Unit prices for geosynthetics do not account for recent spikes in costs due to global pandemic and Texas power outages which have caused a supply shortage nationally.
- All soil materials are locally sourced on site.
- Removal of top 6 inches of topsoil for liner subbase preparation.
- Does not include lysimeter or leachate pipework construction in any of the layers
- GCL substitution is assumed for a site which needs to import clay. Unit rates are for importing and trucking clay >1hr

APPENDIX D

Slope Stability Modeling Results



Material Name	Color	Unit Weight (lbs/ft3)	Sat. Unit Weight (lbs/ft3)	Strength Type	Cohesion (psf)	Phi (deg)	Water Surface	Hu Type	Hu	Ru
Temporary Sand Cover		110	115	Mohr-Coulomb	0	28	Water Surface	Custom	1	
Waste		90		Mohr-Coulomb	300	33	None			0
Granular Drainage Layer		120	125	Mohr-Coulomb	0	38	Water Surface	Custom	1	
Textured GM / Clay Interface		125		Mohr-Coulomb	0	18	None			0
Compacted Clay		130	140	Mohr-Coulomb	1000	0	None			0
Native Medium Dense Sand		125	130	Mohr-Coulomb	0	30	None			0
Native Sandstone		160	165	Mohr-Coulomb	360000	0	None			0

GOLDER

Golder Associates Inc.

SCALE	AS SHOWN
DATE	Apr 2021
MADE BY	DAF
CAD	-
CHECK	BLF
REVIEW	

FILE STABILITY

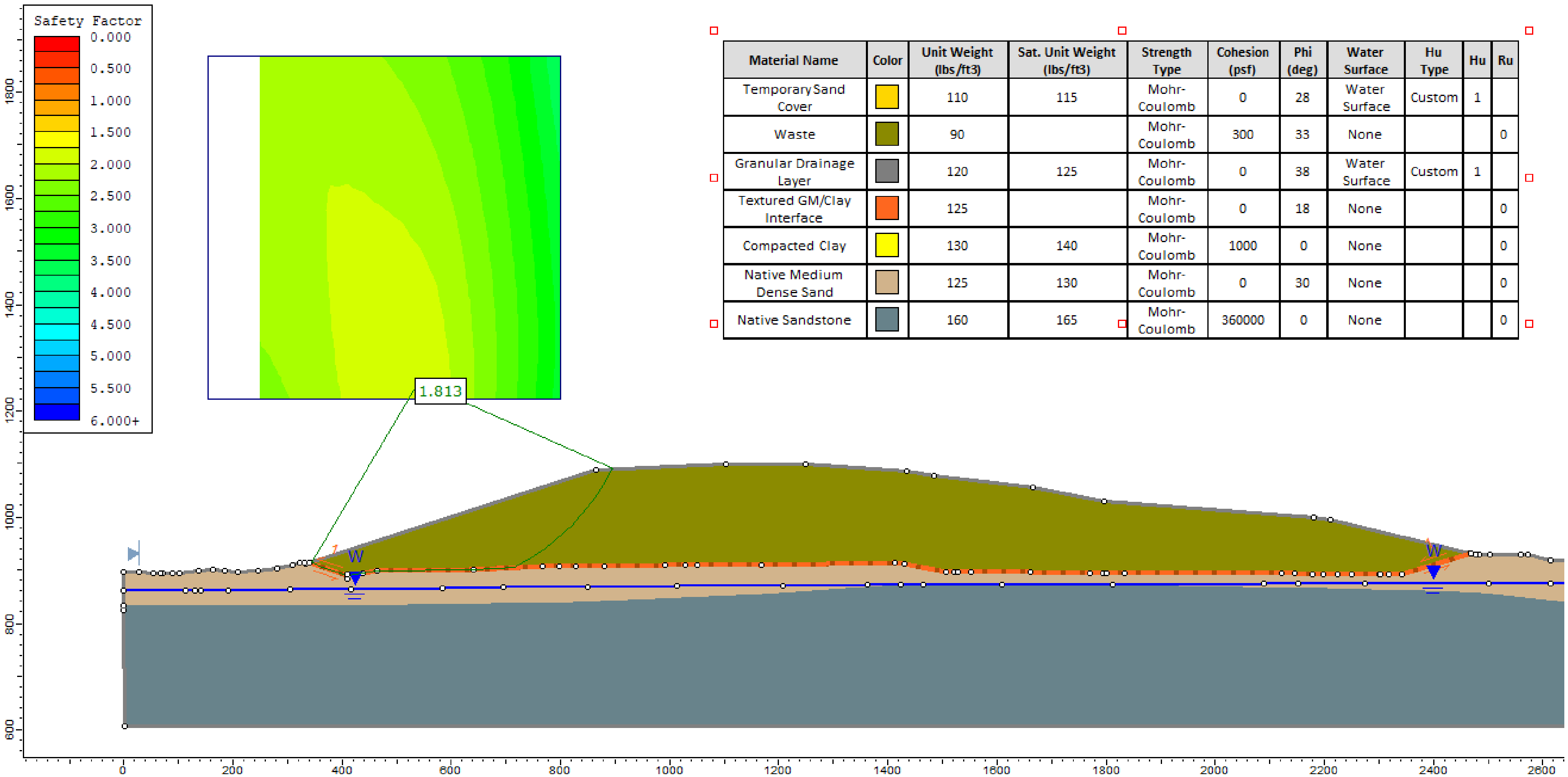
PROJECT No. 21457168 REV. 1

TITLE

4-foot Compacted Clay, Static, Block Failure Search

Wisconsin Department of Natural Resources

FIGURE **D1**



Material Name	Color	Unit Weight (lbs/ft3)	Sat. Unit Weight (lbs/ft3)	Strength Type	Cohesion (psf)	Phi (deg)	Water Surface	Hu Type	Hu	Ru
Temporary Sand Cover		110	115	Mohr-Coulomb	0	28	Water Surface	Custom	1	
Waste		90		Mohr-Coulomb	300	33	None			0
Granular Drainage Layer		120	125	Mohr-Coulomb	0	38	Water Surface	Custom	1	
Textured GM/Clay Interface		125		Mohr-Coulomb	0	18	None			0
Compacted Clay		130	140	Mohr-Coulomb	1000	0	None			0
Native Medium Dense Sand		125	130	Mohr-Coulomb	0	30	None			0
Native Sandstone		160	165	Mohr-Coulomb	360000	0	None			0

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DATE	Apr 2021	
MADE BY	DAF	**4-foot Compacted Clay, Static, Circular Failure Search**
CAD	-	
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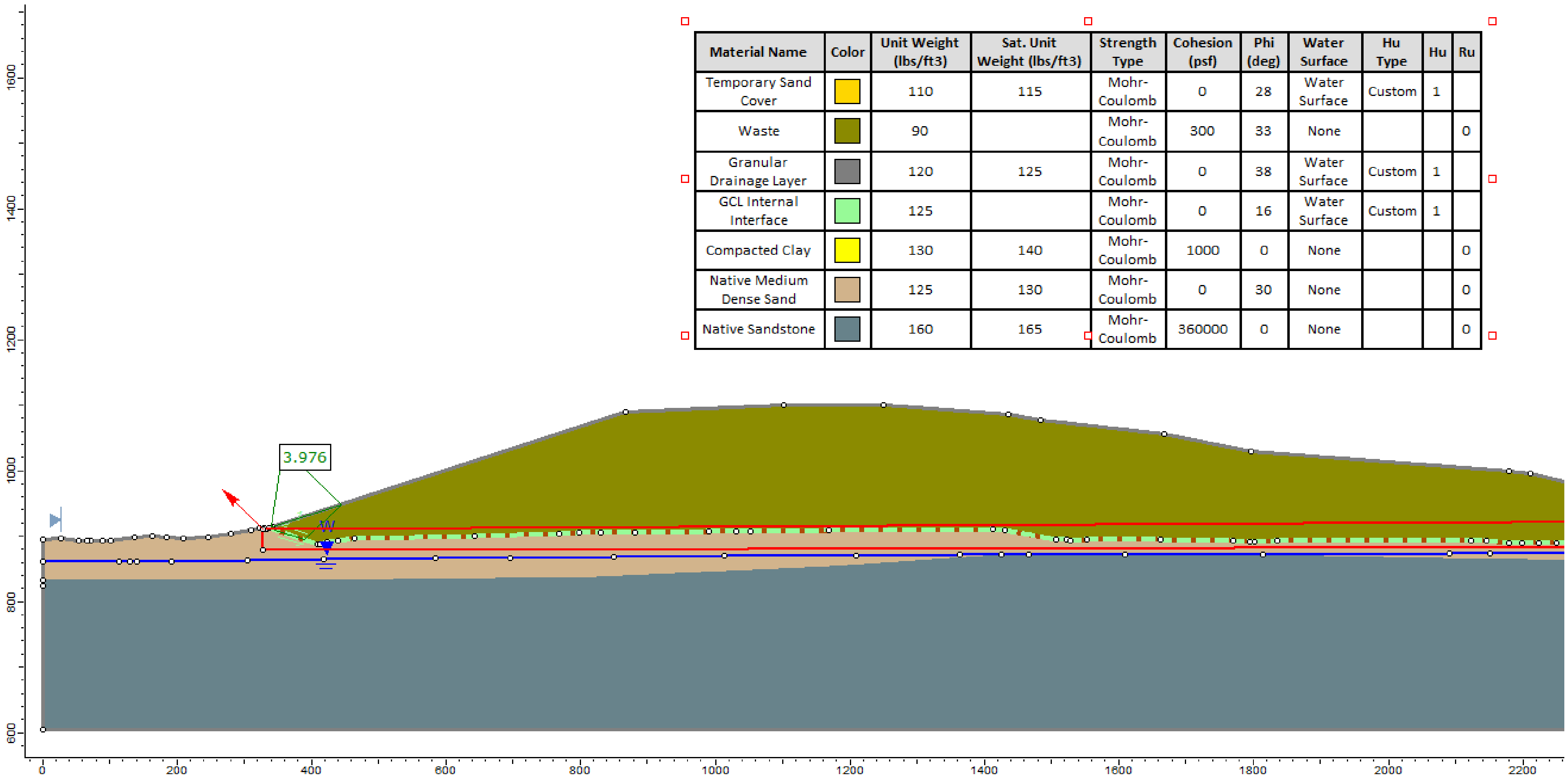
REVIEW		

FILE STABILITY

PROJECT No. 21457168 REV. 1

Wisconsin Department of Natural Resources

FIGURE **D2**



Material Name	Color	Unit Weight (lbs/ft3)	Sat. Unit Weight (lbs/ft3)	Strength Type	Cohesion (psf)	Phi (deg)	Water Surface	Hu Type	Hu	Ru
Temporary Sand Cover		110	115	Mohr-Coulomb	0	28	Water Surface	Custom	1	
Waste		90		Mohr-Coulomb	300	33	None			0
Granular Drainage Layer		120	125	Mohr-Coulomb	0	38	Water Surface	Custom	1	
GCL Internal Interface		125		Mohr-Coulomb	0	16	Water Surface	Custom	1	
Compacted Clay		130	140	Mohr-Coulomb	1000	0	None			0
Native Medium Dense Sand		125	130	Mohr-Coulomb	0	30	None			0
Native Sandstone		160	165	Mohr-Coulomb	360000	0	None			0

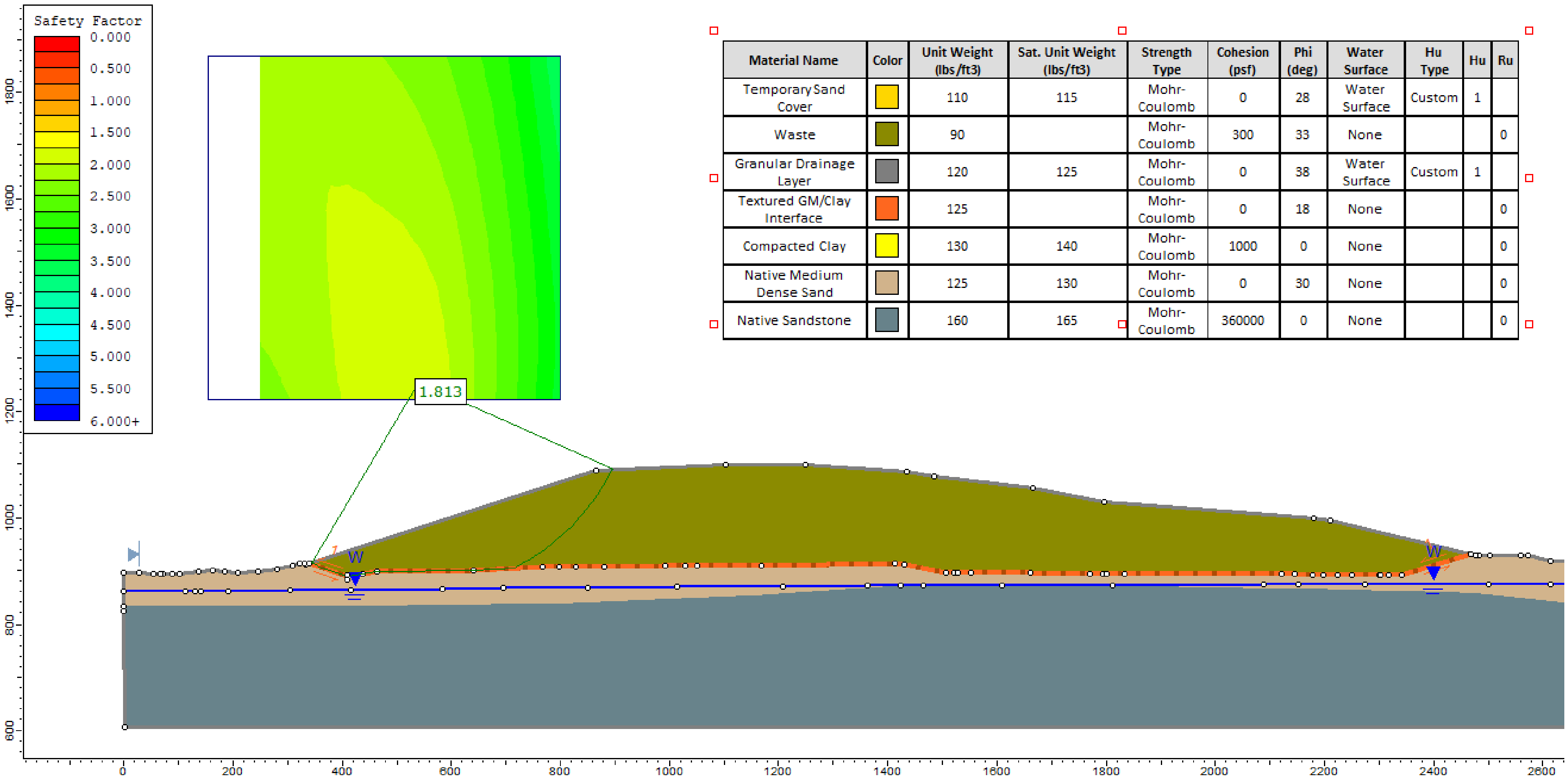
GOLDER

Golder Associates Inc.

SCALE	AS SHOWN	TITLE	
DATE	Apr 2021	**GCL with 2 feet of Clay Base, Static, Block Failure Search**	
MADE BY	DAF		
CAD	-		
FILE	STABILITY	CHECK	BLF
PROJECT No.	21457168	REV.	1
REVIEW			

Wisconsin Department of Natural Resources

FIGURE **D3**



Material Name	Color	Unit Weight (lbs/ft3)	Sat. Unit Weight (lbs/ft3)	Strength Type	Cohesion (psf)	Phi (deg)	Water Surface	Hu Type	Hu	Ru
Temporary Sand Cover		110	115	Mohr-Coulomb	0	28	Water Surface	Custom	1	
Waste		90		Mohr-Coulomb	300	33	None			0
Granular Drainage Layer		120	125	Mohr-Coulomb	0	38	Water Surface	Custom	1	
Textured GM/Clay Interface		125		Mohr-Coulomb	0	18	None			0
Compacted Clay		130	140	Mohr-Coulomb	1000	0	None			0
Native Medium Dense Sand		125	130	Mohr-Coulomb	0	30	None			0
Native Sandstone		160	165	Mohr-Coulomb	360000	0	None			0

GOLDER

Golder Associates Inc.

SCALE	AS SHOWN
DATE	Apr 2021
MADE BY	DAF
CAD	-
CHECK	BLF
REVIEW	

TITLE

GCL with 2 feet of Clay Base, Static, Circular Failure Search

FILE STABILITY

PROJECT No. 21457168 REV. 1

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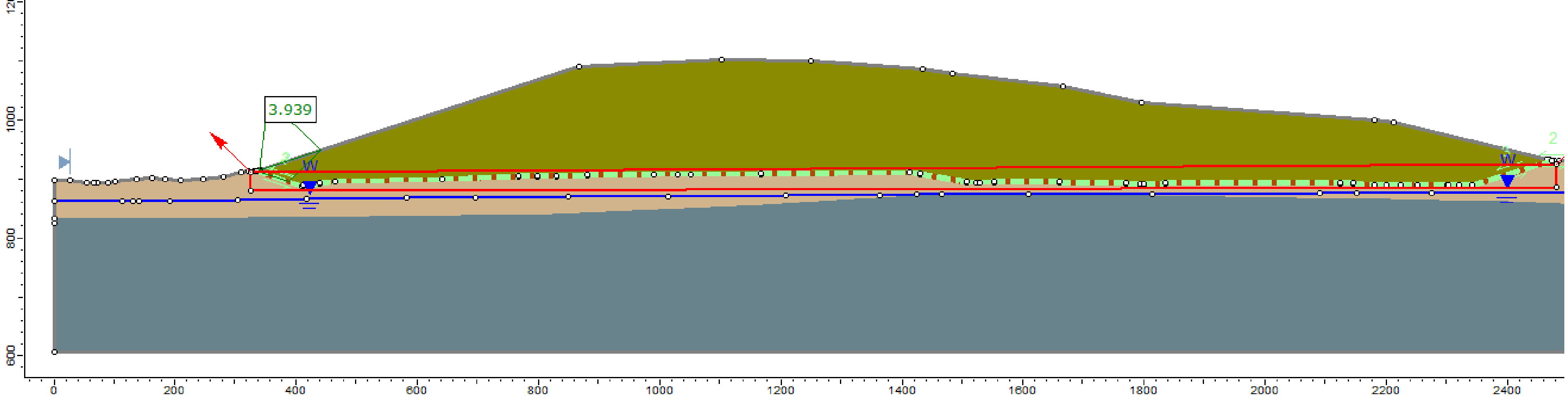
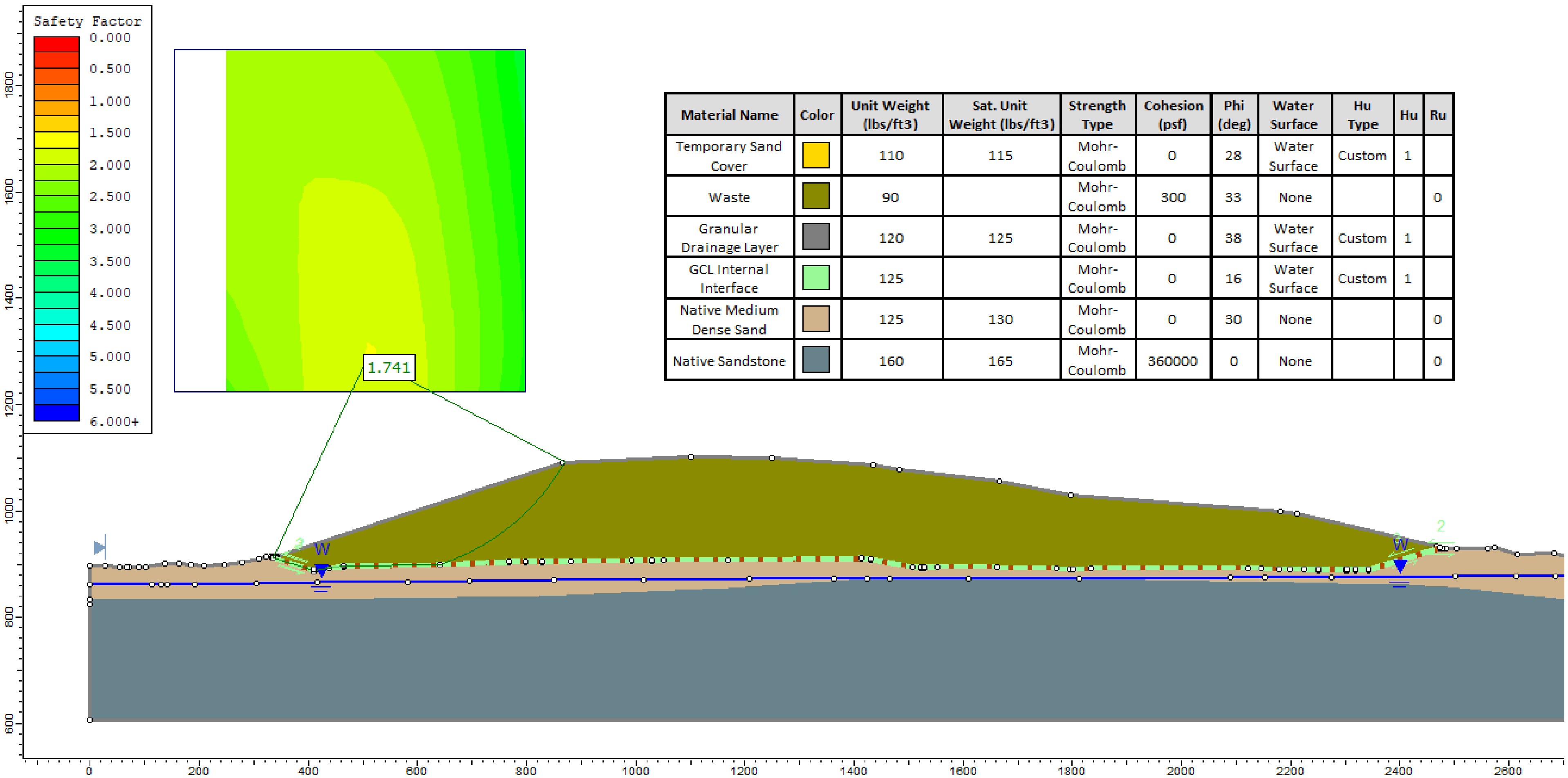
FIGURE **D4**

Material Name	Color	Unit Weight (lbs/ft3)	Sat. Unit Weight (lbs/ft3)	Strength Type	Cohesion (psf)	Phi (deg)	Water Surface	Hu Type	Hu	Ru
Temporary Sand Cover		110	115	Mohr-Coulomb	0	28	Water Surface	Custom	1	
Waste		90		Mohr-Coulomb	300	33	None			0
Granular Drainage Layer		120	125	Mohr-Coulomb	0	38	Water Surface	Custom	1	
GCL Internal Interface		125		Mohr-Coulomb	0	16	Water Surface	Custom	1	
Native Medium Dense Sand		125	130	Mohr-Coulomb	0	30	None			0
Native Sandstone		160	165	Mohr-Coulomb	360000	0	None			0



GOLDER Golder Associates Inc.	SCALE AS SHOWN DATE Apr 2021 MADE BY DAF CAD -	TITLE	**Dual Composite Base Liner, Static, Block Failure Search**
FILE STABILITY PROJECT No. 21457168 REV. 1	CHECK BLF REVIEW	**Wisconsin Department of Natural Resources**	FIGURE **D5**



Material Name	Color	Unit Weight (lbs/ft3)	Sat. Unit Weight (lbs/ft3)	Strength Type	Cohesion (psf)	Phi (deg)	Water Surface	Hu Type	Hu	Ru
Temporary Sand Cover		110	115	Mohr-Coulomb	0	28	Water Surface	Custom	1	
Waste		90		Mohr-Coulomb	300	33	None			0
Granular Drainage Layer		120	125	Mohr-Coulomb	0	38	Water Surface	Custom	1	
GCL Internal Interface		125		Mohr-Coulomb	0	16	Water Surface	Custom	1	
Native Medium Dense Sand		125	130	Mohr-Coulomb	0	30	None			0
Native Sandstone		160	165	Mohr-Coulomb	360000	0	None			0

GOLDER

Golder Associates Inc.

SCALE	AS SHOWN	TITLE	
DATE	Apr 2021	**Dual Composite Base Liner, Static, Circular Failure Search**	
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FIGURE **D6**

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