Attachment B

EATLF Alternate

Revision 1 – 4/15/22

US Ecology
Wayne Disposal, Inc.
Belleville, Michigan

Engineered Artificial Turf Landfill Cover Equivalency Demonstration

Rev.0 - November 2021

Rev.1 – April 2022

Prepared for:

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1.0 PURPOSE

CTI and Associates, Inc. has prepared this report to demonstrate the equivalency of Engineered Artificial Turf Landfill Cover (EATLC) system to Part 111 cover system. Final cover requirements specified by Code of Federal Regulations (CFR) §264.310 require the final cover to in part:

- Provide long-term minimization of migration of liquids through the closed landfill
- Promote drainage of the cover
- Have a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present.

In addition to prescriptive requirements for the final cover over a hazardous waste landfill, Michigan Administrative Code R 299.9619(6)(a) also states the owner or operator can: Substitute an equivalent design which shall include a flexible membrane liner component with a minimum thickness of 1 mm (40 mil), depending on the type of material selected, and demonstrates to the director that it provides equivalent environmental protection.

The following sections will demonstrate that EATLC provides similar or better performance to the current final cover system. This demonstration compares the following key characteristics:

- Minimizing Maintenance
- Minimizing Infiltration
- Minimizing Erosion Potential
- Promotion of Surface Water Runoff
- Resisting Damage from Settlement
- Promoting Slope Stability

2.0 CONFIGURATION OF THE FINAL COVER SYSTEM

2.1 RULE REQUIRED COVER SYSTEM

The current rule required cover system for a hazardous waste landfill consists of the following components (from bottom to top):

- Compacted Clay – 90cm/36-in (min)
- Flexible Membrane Liner - 40-mil
- Additional Material - 60cm/24-in maximum depth of frost protection

2.2 ENGINEERED ARTIFICIAL TURF LANDFILL COVER SYSTEM

The Engineered Artificial Turf Landfill Cover system will consist of the following components (from bottom to top):

- Leveling Layer - 1-ft (min)
- Geosynthetic Clay Liner (Two layers)
- HDPE Geomembrane - 40-mil textured
- Engineered Artificial Turf
- Sand Infill - 0.5-inch

Figure 2 below depicts the details of the final cover system based on the proposed EATLC design. Additional details of the EATLC system as part of the final cover system are included in **Attachment A**. Photos of the top and underside of the EATLC are presented in **Figure 3 and 4**, respectively.

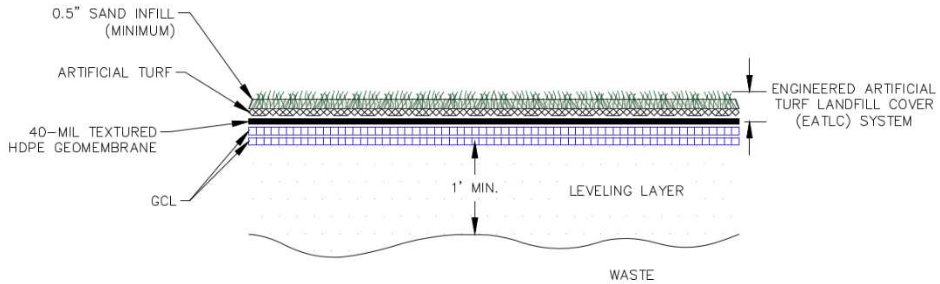


Figure 1 – Engineered Artificial Turf Landfill Cover System

Figure 2 - View of engineered artificial turf with sand infill and textured geomembrane

Figure 3 - Underside view of engineered artificial turf and textured geomembrane

3.0 EQUIVALENCY DEMONSTRATION

3.1 SUMMARY

This demonstration generally applies to alternative covers consisting of engineered artificial turf. However, all the specific data cited is reflective of ClosureTurf, a commercially available product manufactured by WatershedGeo designed specifically for landfill cover systems. It is to date perhaps the best known and best studied system. Other similar systems exist and as they are developed and come to market are likely to behave similarly and have similar properties. WDI will evaluate other similar systems at the time of the final cover installation based on specifications and the data provided by manufacturers. The selected products shall provide equivalent functions and performance as demonstrated in this report.

This demonstration shows that based on all the key and relevant criteria evaluated, engineered artificial turf landfill cover systems have been demonstrated to perform at least as well as traditional cover systems. **Table 1** below shows a summary of these specific criteria. The remainder of the document provides detail to support the conclusions in **Table 1**. Drawings and details depicting EATLC used in the final cover system at WDI are contained in **Attachment A**.

Table 1 – Comparison of Engineered Artificial Turf Landfill Cover to Part 111 Rules Hazardous Landfill Cover

Category		Criterion for Evaluation	Equivalency of **EATLC** to Part 111 Rules Hazardous Landfill Cover			
				EATLC		Conventional Cover
Incl. 40 mil min Geomembrane [per R 299.9619(6)(a)]			✓	40 mil		40 mil (typ)
Minimize	Maint-enance	Turf resilience	✓	Permanent, no mowing, no reseeding		Continual mowing and upkeep
		Slope stability	✓	Critical interface is FML/GCL/GCL/Soil		Critical interface is FML/GCL/Soil
		Static factor of safety (sat. cond)	✓	1.9-2.4 (typ) – slope 4:1		1.3 – 1.5 (typ) - max. slope 4:1
	Erosion	Annual estimated erosion amount	✓	<0.5 tons per acre per year		Up to 2 tons per acre per year

		Resistance to shear forces	✓	Limiting flow velocity is >11 ft/s		Limiting flow velocity 5 ft/s (without turf reinforcement mats)
	Infiltra-tion	Storm water leakage into landfill	✓	0.000 in/day (per HELP Model)		0.000 in/day (per HELP model)
		Reduce ponding potential	✓	Min. slopes ≥ 4% (easy to observe ponding)		Min. slopes ≥ 4%
Promote Runoff		Subsurface drainage capacity	✓	No need (all drainage managed on surface)		Limited by geocomposite capacity
		Runoff curve number	✓	92-95 (typ)		<90 (typ)
		Cover retains water	✓	Infiltration layer eliminated		Infiltration layer holds water
Resist Damage from Settlement		Rutting and deformation of cover	✓	Low potential, subgrade stays dry		Higher potential, subgrade retains water
		Time to complete repairs	✓	Hours		Days to repair/ weeks for new media

3.2 Maintenance

The vegetative/infiltration layer in traditional cover systems typically requires a number of significant maintenance activities through closure and post-closure of the landfill. These can include:

- Mowing/excess vegetation removal
- Establishment/reestablishment of vegetation
- Erosion protection/repair
- Desiccation repair
- Addressing burrowing animals/burrow repair
- Settlement/Ponding
- Silt/sedimentation removal from drainage channels

By contrast, one of the biggest advantages of engineered artificial turf landfill cover systems is it greatly reduces the maintenance efforts making for a more protective barrier because it is more likely to remain intact throughout the closure/post-closure period.

EATLC has the following maintenance related properties:

- It does not require mowing
- Panels can be replaced more easily and within a matter of hours
- Resistance to erosion
- Resistance to damage from animals
- Settlement is more easily spotted and repaired
- Negligible sedimentation runoff

The technical aspects of these items are detailed more fully below.

3.2.1 Design Life

The engineered turf blades of engineered turf are specifically designed to resist the damaging effects of prolonged ultraviolet exposure. The design lifetime of the complete cover system is represented by the half-life of when half of the tensile strength of the synthetic turf fibers is reached from UV degradation. For ClosureTurf, Watershed Geo has conducted UV performance testing over the past several years at a testing facility in New River, Arizona and at some of the original closure turf installation locations (Pensacola, Florida and Jena, Louisiana). Independent performance assessments indicate that the half-life

(50% retained tensile strength) of the UV exposed HDPE grass blades is in excess of 100 years. See Figure 7 of the report included as part of **Attachment B**. The extrapolated service life is expected to be on the order of 200 years or greater, based upon the minimum required tensile strength.

The other components of the EATLC system also have design lives well over 100 years. Both the geomembrane and the geotextile backing component of engineered turf are shielded from UV exposure by the turf fibers and the infill sand and resist degradation. This results in extending the design life in comparison to exposed materials, so those protected components are expected to have a design life of several hundred years.

3.2.2 Veneer Stability

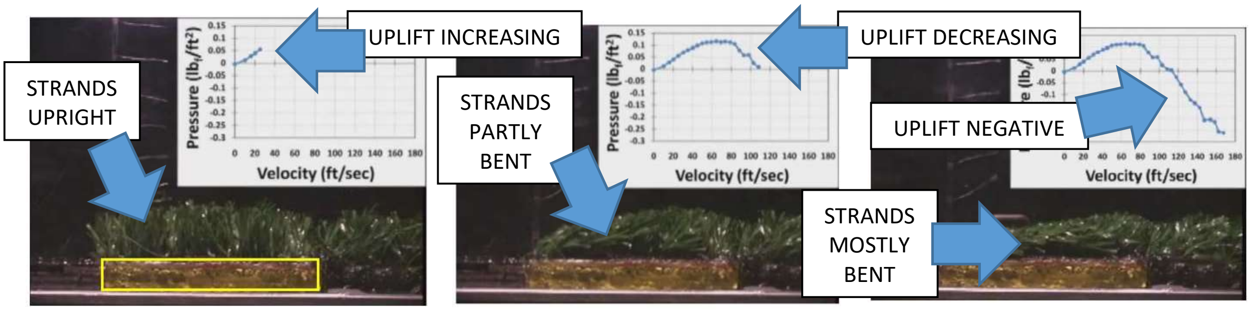
Sliding of the soil cover on top of the geomembrane in a traditional cover system is a potential design concern. This is especially true after major storm events if the drainage system between the soil and geomembrane is not properly designed. For EATLC, the thick soil component is removed, eliminating the potential for seepage forces to build up providing for greater stability. For the proposed design at WDI, the critical interfaces are the same for both systems, that is FML/GCL, GCL/GCL, and GCL/Soil. By eliminating the soil veneer, greater stability and steeper slopes with the same factor of safety are achievable.

Veneer stability analyses were performed to compare each cover system by determining the required interface friction angle for the critical interface(s) and demonstrate the stability of the final cover soils over the cap/cover system geosynthetics. The longest and steepest slope was chosen to be analyzed for minimum interface shear strength requirements, and the following two conditions were checked: Static Unsaturated and Static Saturated. The results of this analysis are given in **Attachment C**. The analyses indicate that the factors of safety are well above the minimum required values for both conditions.

3.2.3 Wind Uplift

A related concern for EATLC is wind uplift. The geotextile/turf layer is designed to be installed on top of the geomembrane and remain in place without anchoring it to the geomembrane below. It relies on interface friction and overlying sand ballast to remain immobile.

The Georgia Tech Research Institute conducted 2D, full scale wind tunnel tests to evaluate ClosureTurf under several wind speeds to evaluate aerodynamic properties and potential for uplift. The experiment measured the aerodynamic forces acting on the permeable upper turf layer and evaluated the wind speed in relation to the sand ballast. The purpose of the ballast is twofold: 1) Prevent liftoff and 2) Prevent tangential motion along the interface between the turf material and the geomembrane underlayment resulting from aerodynamic lift and drag acting on the turf layer. The testing performed determined the sand ballast requirements needed to counteract the uplift pressure. Illustration of the test and the results are depicted in **Figure 5** below. Interestingly, maximum uplift occurs at around 50 mph before the uplift begins to drop and become negative. This is due to the grass blades bending over, breaking the suction force resulting in a downward force due to drag. The maximum uplift corresponds to approximately 0.12 psf. This is much less than the downward force created by 0.5 in of sand which is approximately 4.5 psf.



V_{inf} = 25 ft/sec = 17 mph V_{inf} = 110 ft/sec = 75 mph V_{inf} = 170 ft/sec = 115 mph

Figure 4 – Wind tunnel testing results

The wind tunnel testing compared uplift pressure at both the interior and along the edge of the samples. Maximum uplift pressure was observed along the edge. At 66 mph, which represents the historical peak wind gust for Detroit based on the available wind data from the National Climatic Data Center, the minimum sand ballast required was 0.2 in. Additional details are contained in **Attachment D.**

Likewise, another wind tunnel study completed to evaluate geosynthetic covers which included Closure Turf. This study evaluated the maximum mean wind uplift pressure utilizing wind speeds from ASCE 7-16 and compared them to the weight of the Closure Turf engineered turf cover with a sand infill thickness of 0.5 inches. The study and subsequent calculation are located in Attachment D/Attachment D - Amendment#1.

3.2.4 Rutting

For conventional soil covers, the soil infiltration layer holds water during the wetter portions of the year. When this occurs in areas that require routine access or areas along access road alignments can experience rutting from vehicles and possibly even foot traffic.

Engineered artificial turf was evaluated by another 3rd party consultant (SGI) for subgrade integrity where ground pressure from heavy equipment was evaluated in relation to maintaining the integrity of the engineered artificial turf landfill cover components. Results showed that when the subgrade is protected by EATLC, including the sand infill, the subgrade can handle equipment with tire pressures up to 60 psi on 3H:1V slopes and up to 90 psi on relatively flat slopes with no appreciable damage to the engineered turf of the subgrade. This evaluation is contained in **Attachment E**.

3.2.5 Ponding/Settlement Repairs

For a conventional cover system, settlement may lead to ponding on the surface and local saturation of infiltration layer. Because of the resulting soft subgrade, repairs may be delayed due to difficulties getting the necessary heavy equipment to the area and/or risking additional damage to the cover system from rutting and erosion from the equipment. As shown in **Figure 6**, excessive settlement can also affect the performance of the underlying geosynthetics which may or may not be apparent at the surface. Vegetated cover soils can obscure the ability to inspect for geosynthetic defects or anomalies resulting from excessive settlement. The presence of the vegetated soil layer also hinders the ability to implement repairs, in the event that the corrective measures are necessary since it must be fully over excavated to make repairs which can require significant effort and delay repairs even more. Finally, once the repairs are made, it may take several weeks to reestablish vegetation before the repair is fully implemented. Total time for repairs is likely measured in weeks perhaps to more than a month.

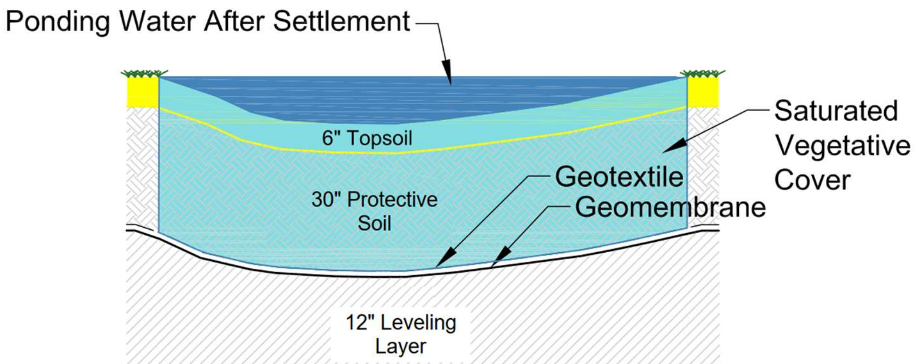


Figure 5 – Repairs to conventional cover

In contrast, repair of settlement in areas where engineered artificial turf landfill cover is utilized can be addressed much more quickly as depicted in **Figure 7**. Because there is no soil component, the potential for soft subgrade is minimized and the geosynthetic components can be readily accessed and inspected. Any ponded water can be pumped and removed, the geosynthetics removed to reveal the settlement area, the depressed area filled with soil to bring it back up to grade, and the area quickly seamed and repaired. There is no need to reseed the area. Total time for repair can likely be measured in hours.

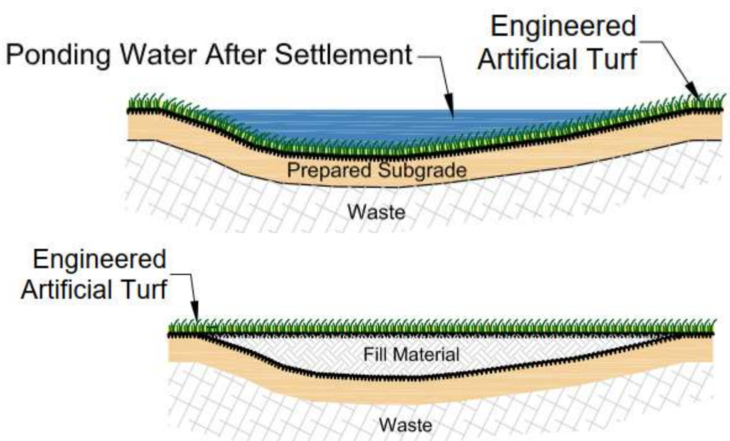


Figure 6 – Repairs to Engineered Artificial Turf Landfill Cover

3.3 EROSION

For a conventional cover system, the ability to resist erosion is primarily related to the establishment (and retention) of adequate vegetation. It can be difficult to establish and maintain adequate vegetation across the full extent of a landfill. Extended periods of drought can quickly transition to high intensity downpours.

The vegetative/infiltration soil layer is the primary component of the conventional cover system which is subject to erosion. On-site soils that are likely to be used for this layer consist primarily of a combination of silt, clay, and sand particles in various proportions. Erosional stability of these individual particles is influenced by soil adhesion, vegetative cover, and internal friction. Erosion of the vegetative soil layer cannot be entirely arrested since some of the stability parameters vary over time and various climatic conditions. Silt loams, loams, fine sands and sandy loams are the most detachable soil particles (Morgan, 2005) which make up a large percentage of vegetative soil.

Based on the current design, the estimated annual rate of soil erosion (discharge) from the conventional vegetative cover system is predicted to range up to 1.3 tons per acre, per year (USE 2021). Also, significant, additional erosion could occur during a single, extreme storm event potentially resulting in damage to the engineered soil components requiring costly repairs. Additionally, perimeter channels within a conventional cover can become laden with sediments which can be detrimental to vegetation in that zone and can lead to water quality concerns, erosion rills, and an increasingly complex maintenance program to maintain adequate vegetation.

Engineered artificial turf landfill cover is designed to essentially eliminate this potential by eliminating the vegetative/infiltration soil layer. The EATLC system does have a 0.5-in thick specified infill sand layer that is spread within the engineered artificial turf layer which is used for ballast and for UV protection of the underlying geotextile backing of the engineered artificial turf components. However, in comparison to traditional cover, the sand infill is much less erodible. It consists of a coarse-grained sand meeting specific standards tested for resistance to erosion. Stability of the sand aggregates is influenced by internal friction and turf strand reinforcement which are static properties and allow for the potential for soil erosion to be minimized by design.

Watershed Geo has completed extensive hydraulic testing to evaluate the sand infill's performance under various surface water conditions. The summary of this testing program is included in **Attachment F** and the sand infill specifications developed from this testing is included in **Attachment G**. Sand infill that conforms to these specifications is expected to experience minimal sand movement under the design surface water conditions.

3.4 Infiltration Equivalency

By design, the vegetated soil layer is intended to act as a large sponge which soaks up precipitation during storm events and provides a moisture reservoir for the vegetation. However, one of the undesirable consequences of the sponge action is that each time the soil layer becomes saturated (during prolonged storm events), the soil layer will slowly release or seep a steady flow of water across the underlying cover membrane for several days after the storm event. Subsequently, the opportunity for water leakage through any cover membrane defects is extended. Therefore, the presence of the vegetated soil layer inadvertently prolongs an undesirable window of opportunity where leakage might occur.

Alternative engineered artificial turf landfill cover systems perform similar to or better than the prescribed traditional cover systems in terms of infiltration (Carlson, et al., 2019). The primary reasons for this are 1) The geomembrane material is itself designed to be essentially impermeable and 2) Because they don't have a soil component that could potentially hold water, synthetic turf cover systems like ClosureTurf have a much smaller hydraulic head over the geomembrane layer driving infiltration in comparison to traditional cover systems. The full technical paper cited is provided in **Attachment H**.

The final cover systems described in Section 2.0 were each modeled in the USEPA's Hydrologic Evaluation of Landfill Performance (HELP) Model. The results showed that EATLC compared to the current permitted traditional cover system produced similar rates and sheds much more water than a traditional cover system. The analysis shows that both cover systems allow for negligible flow through the geosynthetic composite cover. The EATLC system meets the criteria from a hydrologic standpoint of being at least as protective as the permitted cover system. Complete results for the entire simulation period are included in **Attachment I**.

3.5 Surface Water Considerations

The use of an engineered artificial turf landfill cover system allows the landfill to manage a larger volume of surface water with similar or smaller annual infiltration compared to a traditional cover system. For a traditional cover system, benches and berms are designed to intercept long flow paths of runoff and prevent rill erosion. With engineered artificial turf, the cover system isn't subjected to this same rill erosion even for long flow lengths. This allows for the removal of mid-slope features and the EATLC is then able to utilize surface flow as the primary means of conveyance. Without these intercept features and with the higher run-off coefficients, the cover system will discharge faster and minimize the time that surface water is flowing on the geomembrane liner. The complete technical paper that compares the hydrologic performance of engineered artificial turf to a traditional cover system is included in **Attachment J**.

A surface water analysis was performed for the use of EATLC. The currently permitted design was updated to account for the properties of EATLC. For example, the design run-off curve number for EATLC is 95, compared to 84 for the traditional cover system. Compared to the traditional final cover system the downslope channels and almost all of the diversion berms in the landfill expansion area were removed. The only berms that remain are along select locations of the perimeter of the landfill to route runoff to ditches and storm sewer inlets. Plans showing the location of the remaining berms are included in **Attachment A**. The runoff velocity and flow depths in some downstream ditches also increased. To handle this, the ditches receiving sheet flow from EATLC areas will be lined with engineered artificial turf. The height of the containment berms on the outside edge of the perimeter channels are being increased or channel lining modified, as necessary, to accommodate the higher runoff volumes. Also, some culverts increased in size to transmit the increased flows. The complete surface water analysis is included in **Attachment K**. The EATLC stormwater management system is shown on Figures 1 and 2 in Attachment K-1.5.

The run-off water quality characteristics, including turbidity (total suspended solids), for a traditional cover system tend to degrade during high intensity precipitation events, because of increased flow rates and increased erosional shear forces on the vegetative soils. The turbidity water quality related to an EATLC system remains clear throughout a wide spectrum of high intensity storm events since the manufactured sand infill lacks fine silt or clay particles and has been engineered to specifically resist the range of expected erosional forces.

Concerns regarding other potential water quality considerations (nitrates, BOD, fertilizers, etc.) are also eliminated with an EATLC system.

3.6 Additional Considerations

In addition to the technical considerations, there are other considerations for the use of engineered artificial turf landfill cover.

3.6.1 Aesthetics

Figure 7 – Engineered artificial turf options

The engineered artificial turf component is available in a variety of colors to better blend in with adjacent topography and vegetation. It can be installed with a random pattern to look more natural as shown in **Figure 8.**

3.6.2 Carbon Footprint

Based on a 2012 study, the CO_2 footprint of engineered artificial turf systems are only 20% of the traditional multilayered cover systems (Koerner, 2012). This is largely due to greatly reducing truck and equipment traffic and the ability to install engineered artificial turf approximately 50% faster than conventional cover. This process is depicted in **Figure 9**. This also increases safety for both onsite personnel and offsite motorists sharing the road with haul trucks.

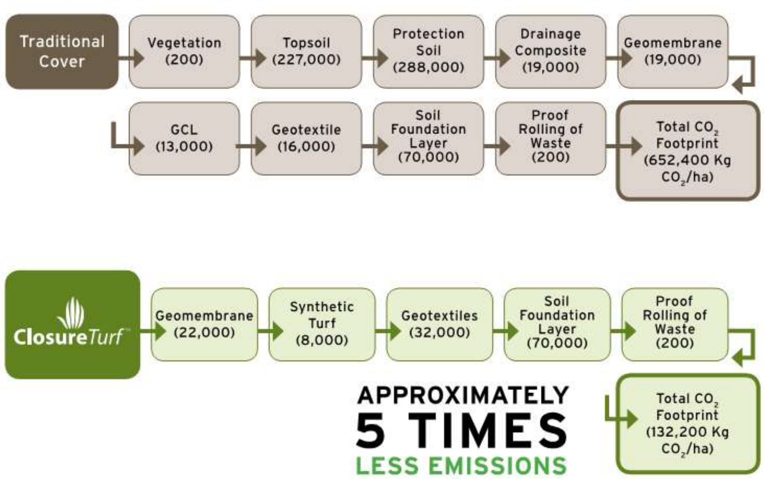


Figure 8 – CO_2 footprint traditional vs. ClosureTurf

3.6.3 Renewable Energy

Engineered artificial turf landfill cover systems can also be leveraged to be better locations for renewable energy projects. As depicted in Figure 9 which shows obvious challenges with mowing around solar panels, lowered maintenance costs are perhaps the most noticeable advantage where mowing can be eliminated, erosion potential is very low, and repairs are more easily performed where needed. In some cases, maintenance requirements like mowing can make projects cost prohibitive.

Figure 9 – Example of renewable energy project where maintenance could be reduced using EATLC

4.0 REFERENCES

Carlson, C. P., Zhu, M. & Ebrahimi, A., 2019. *Hydrologic Performance of Synthetic Turf Cover Systems and Their Equivalency to Prescriptive Cover Systems.* Houston, Industrial Fabrics Association International, p. 8.

Koerner, R. M., 2012. Traditional vs. Exposed Geomembrane Landfill Covers. *Geosynthetics*, 1 October, pp. 34-41.

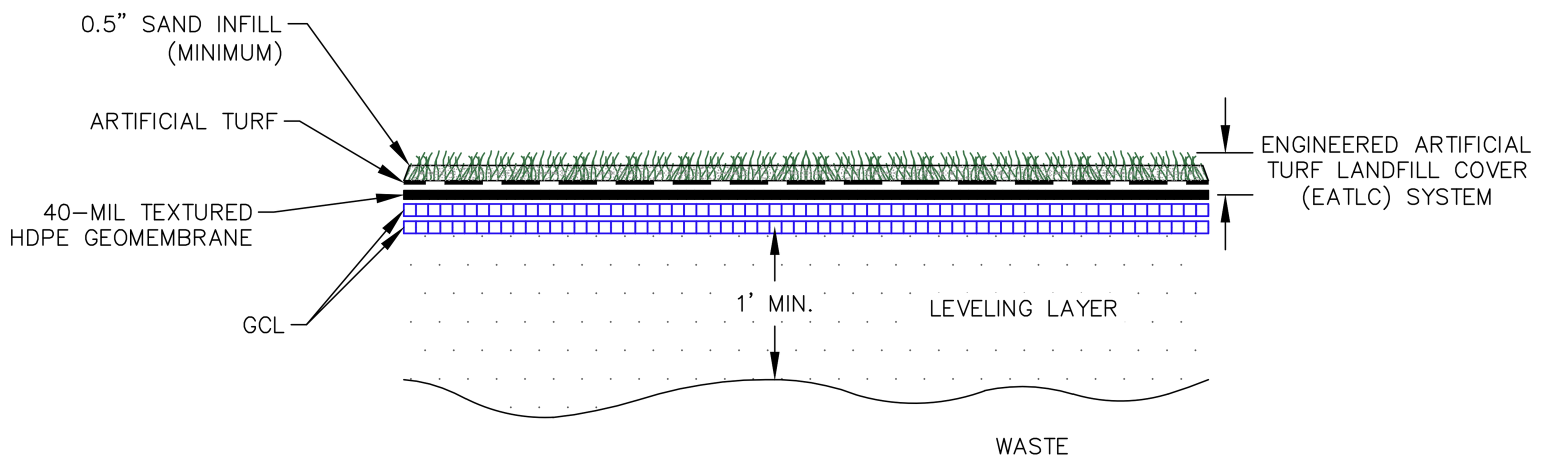
Morgan, R. P. C., 2005. *Soil Erosion and Conservation.* 3rd ed ed. Malden, MA: Blackwell Pub.

USE, 2021. 2021 WDI Permit Modification, Calculation A-6.9

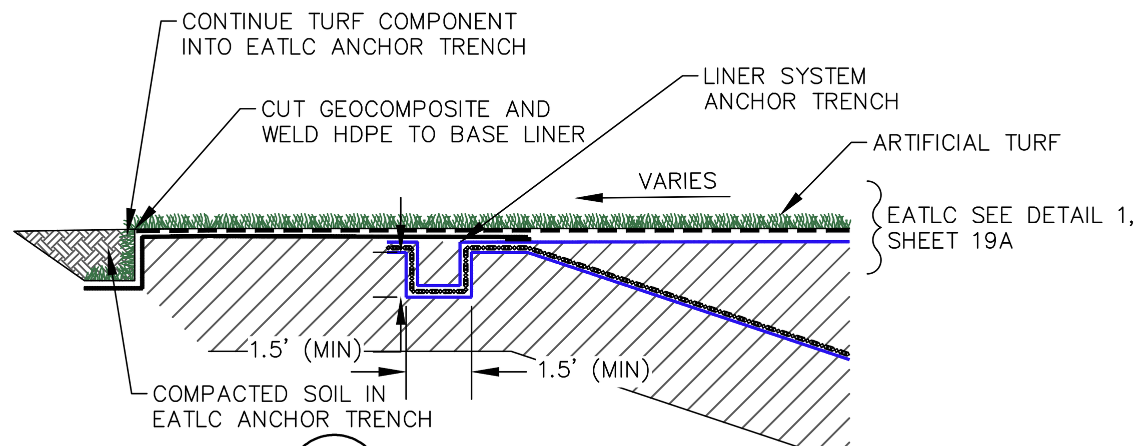
Attachment A

Drawings

Sheet 19A_Rev2 – 4/15/22



1 / 19 A **FINAL COVER SYSTEM**
NOT TO SCALE



2 / 19 A **ANCHOR TRENCH**
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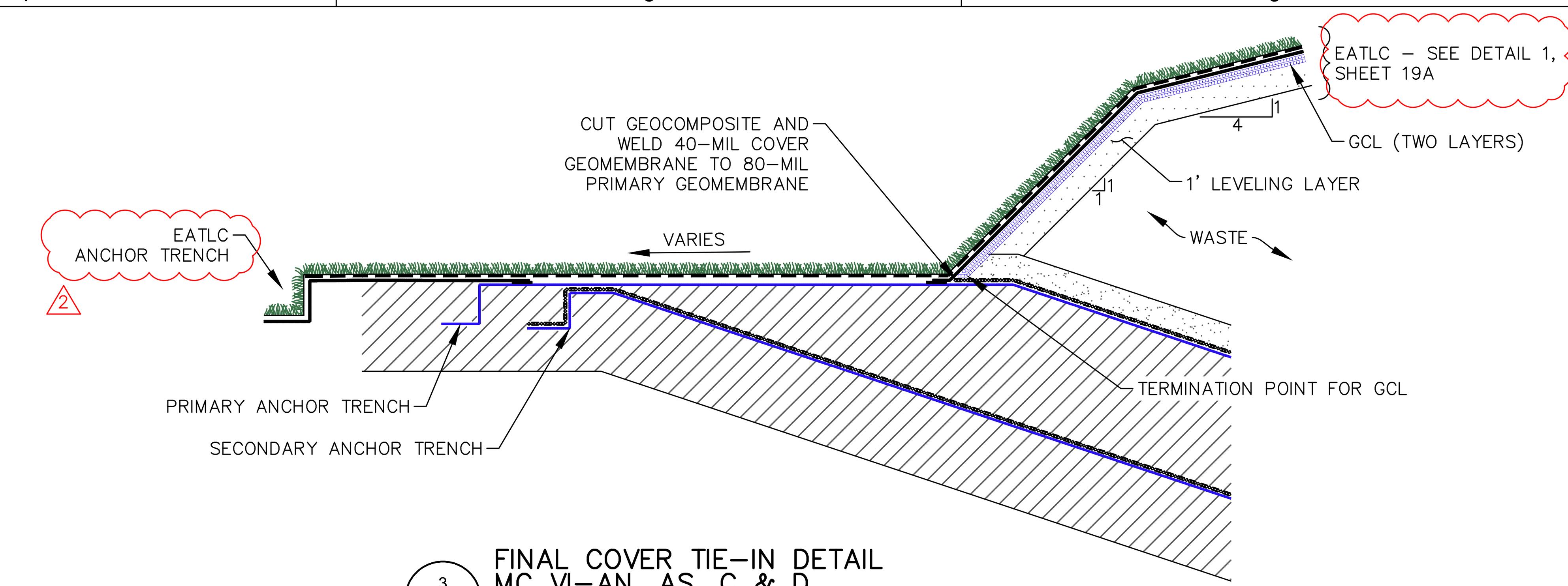
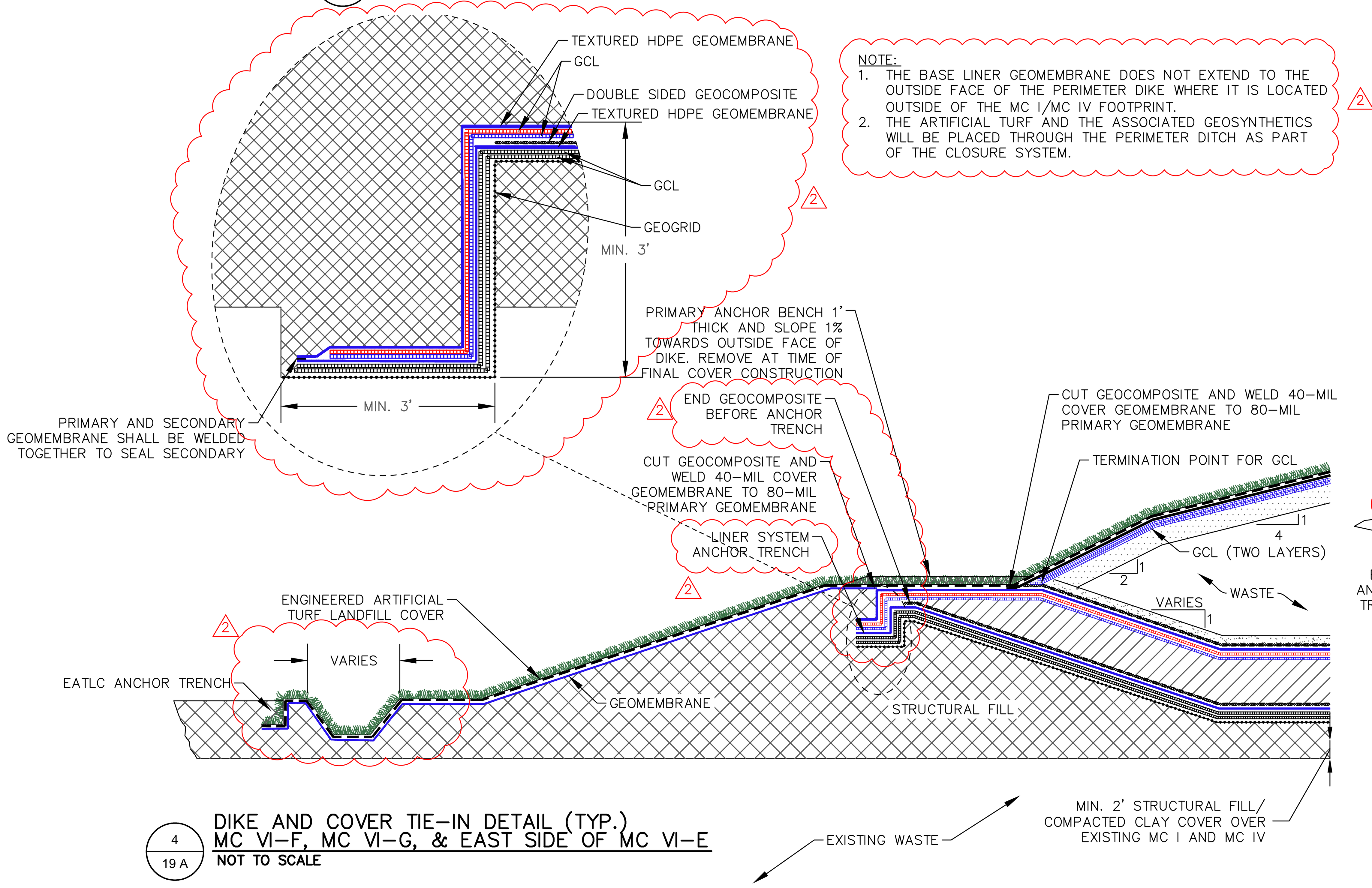


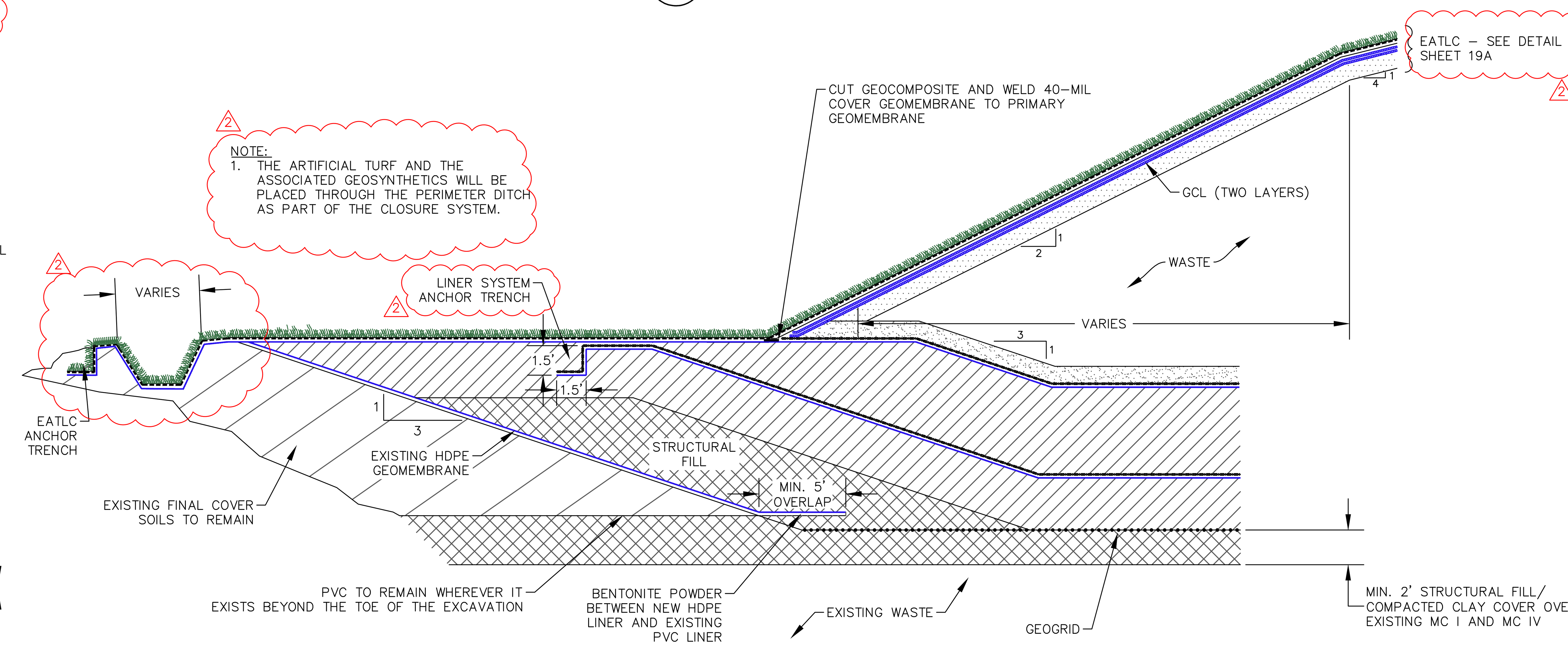
3 / 19 A **FINAL COVER TIE-IN DETAIL MC VI-AN, AS, C & D**
NOT TO SCALE

NOTE:
1. THE BASE LINER GEOMEMBRANE DOES NOT EXTEND TO THE OUTSIDE FACE OF THE PERIMETER DIKE WHERE IT IS LOCATED OUTSIDE OF THE MC I/MC IV FOOTPRINT.
2. THE ARTIFICIAL TURF AND THE ASSOCIATED GEOSYNTHETICS WILL BE PLACED THROUGH THE PERIMETER DITCH AS PART OF THE CLOSURE SYSTEM.

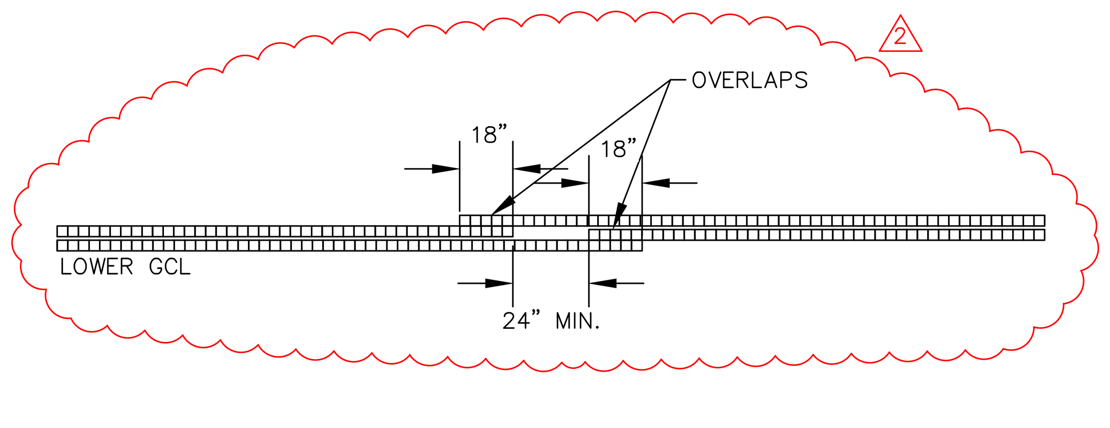


4 / 19 A **DIKE AND COVER TIE-IN DETAIL (TYP.) MC VI-F, MC VI-G, & EAST SIDE OF MC VI-E**
NOT TO SCALE

NOTE:
1. THE ARTIFICIAL TURF AND THE ASSOCIATED GEOSYNTHETICS WILL BE PLACED THROUGH THE PERIMETER DITCH AS PART OF THE CLOSURE SYSTEM.



5 / 19 A **DIKE AND COVER TIE-IN DETAIL NORTH SIDE OF MC VI-E**
NOT TO SCALE



6 / 19 A **GEOSYNTHETIC CLAY LINER OVERLAP DETAIL**
NOT TO SCALE

NOTE:
1. ALL GEOSYNTHETIC CLAY LINER (GCL) SHALL BE COVERED WITH GEOMEMBRANE WITHIN 24 HOURS AFTER PLACEMENT OF GCL AND OVERLAPPED A MINIMUM OF 18-INCHES DURING INSTALLATION.
2. ALL OVERLAPPED SEAMS ARE TO BE HEAT-TACKED USING A QUICK PASS OF A FLAME TORCH FOLLOWED BY QUICK APPLICATION OF APPROPRIATE PRESSURE AS PROVIDED BY A ROLLER, FOOT PRESSURE, OR OTHER MEANS.
3. THE CONTRACTOR SHALL INSTALL THE TWO LAYERS OF THE GCL STAGGERED BY A MINIMUM OF 24-INCHES BETWEEN UPPER AND LOWER GCL SEAMS.
4. REINFORCED GCL MUST BE USED ON ALL SLOPES AS PART OF THE CLOSURE SYSTEM.
5. CONSTRUCTION OF THE FINAL COVER SYSTEM SHALL BE SUPPORTED BY A VENEER STABILITY ANALYSIS. EACH GEOSYNTHETIC/GEOSYNTHETIC AND GEOSYNTHETIC/SOIL INTERFACE INCLUDED IN EATLC SYSTEM SHALL BE CONSIDERED FOR PREQUALIFICATION TESTING PRIOR TO INSTALLATION OF THE COVER SYSTEM. THE CRITICAL INTERFACE SHALL BE DETERMINED BY A COMPARISON OF INTERFACE STRENGTH TEST RESULTS OF REPRESENTATIVE SAMPLES OF MATERIALS USED FOR CONSTRUCTION FOR EACH INTERFACE. THE CRITICAL INTERFACE IS THE LOWEST SHEAR STRENGTH TEST RESULT THAT CORRESPONDS TO THE NORMAL STRESS EXHIBITED BY THE EATLC COVER SYSTEM WHICH IS EXPECTED TO BE BETWEEN 5 AND 6 PSF.

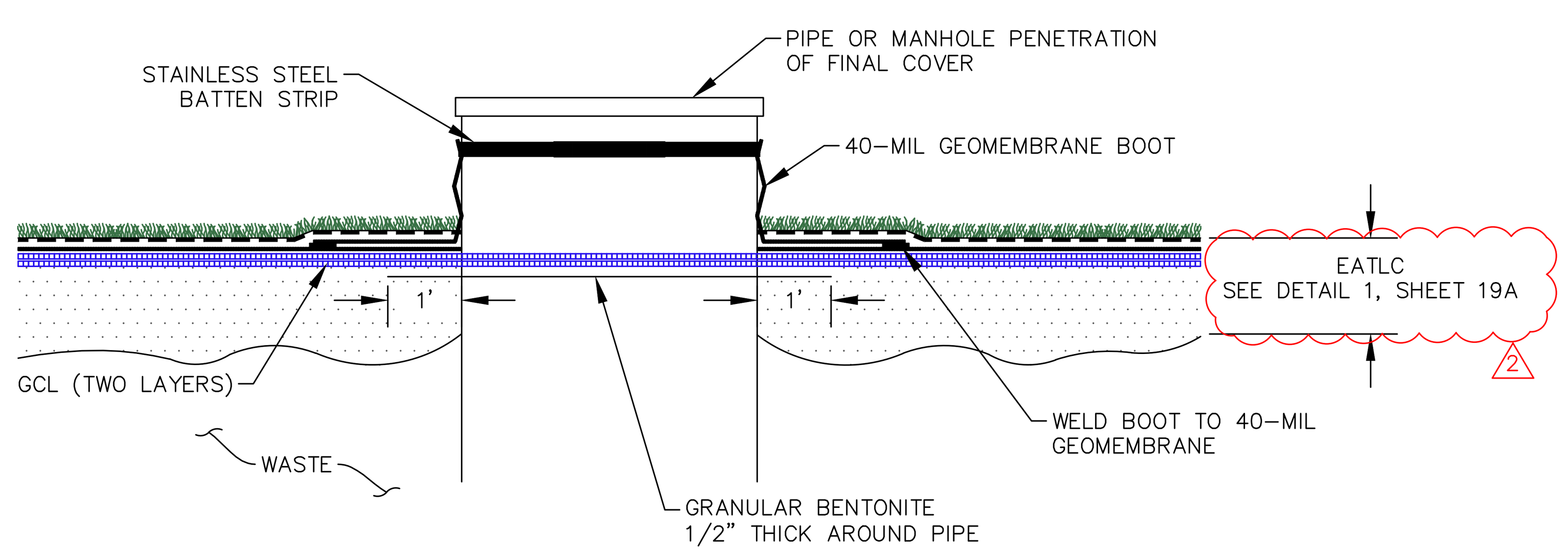
AT MINIMUM, THE FOLLOWING INTERFACES SHALL HAVE INTERFACE TEST RESULTS FOR COMPARISON.
- BASE GEOTEXTILE OF THE EATLC AND GEOMEMBRANE
- GEOMEMBRANE AND TOP LAYER OF GCL.
- TOP LAYER OF GCL AND BOTTOM LAYER OF GCL.
- BOTTOM LAYER OF GCL AND LEVELING SOIL LAYER.
- INTERNAL SHEAR STRENGTH OF THE GCL UNDER HYDRATED CONDITIONS.

7. INTERFACE FRICTION TESTS PERFORMED TO QUALIFY ACCEPTABLE MATERIALS FOR PLACEMENT OF EATLC COVER MATERIALS SHALL CONSIDER LARGE-DISPLACEMENT STRENGTH TEST RESULTS ON THE FINAL COVER SIDE-SLOPES STEEPER THAN 10% AND PEAK STRENGTH TEST RESULTS FOR ALL OTHER SLOPES ANALYSIS. THE MINIMUM DESIGN FACTOR OF SAFETY FOR STATIC STABILITY SHALL BE 1.3 FOR FINAL COVER SIDE-SLOPES STEEPER THAN 10% THAT CONSIDER LARGE-DISPLACEMENT INTERFACE TESTING RESULTS. THE MINIMUM DESIGN FACTOR OF SAFETY FOR STATIC STABILITY SHALL BE 1.5 FOR ALL OTHER FINAL COVER SLOPES THAT CONSIDER PEAK STRENGTH.
8. NO EQUIPMENT TRAFFIC SHALL BE ALLOWED TO TRAVERSE AREAS OF EATLC WITHOUT PRIOR APPROVAL BY THE ENGINEER.

VENEER STABILITY INTERFACE STRENGTH REQUIREMENTS

	FINAL COVER SLOPES > 10%	FINAL COVER SLOPES ≤ 10%
REQUIRED INTERFACE STRENGTH TEST DATA	LARGE-DISPLACEMENT STRENGTH	PEAK STRENGTH
MIN. EQUIV. ACCEPTABLE INTERFACE STRENGTH*	18 DEGREES	20.5 DEGREES
MIN. ACCEPTABLE FS FOR VENEER STABILITY	1.3	1.5

*COMBINATIONS OF TESTED INTERFACE FRICTION ANGLE AND SHEAR STRENGTH INTERCEPT MEASURED AT THE NORMAL STRESS (5-6 PSF)EXHIBITED BY THE EATLC COVER SYSTEM THAT SATISFIES THE FACTOR OF SAFETY CRITERIA ARE ACCEPTABLE



7 / 19 A **FINAL COVER PENETRATION DETAIL (TYP.)**
NOT TO SCALE

REV	DATE	REVISION DESCRIPTION	DRN	APP
2	04/12/22	NOTE ADDITIONS, GEOSYNTHETIC MODIFICATIONS	WRG	XZ
1	10/08/21	SUBCELLS 04-07 REVISIONS; FINAL GRADE MODIFICATIONS; MISCELLANEOUS CHANGES	WRG	XZ

DATE: 04/15/22
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WAYNE DISPOSAL, INC. SITE NO. 2 - MASTER CELL VI-F&G
VAN BUREN TOWNSHIP, WAYNE COUNTY, MICHIGAN

ENGINEERED TURF FINAL COVER DETAILS

PROJECT NUMBER 1218070017
SCALE AS SHOWN
DRAWING NO **19 A**

Attachment C

Veneer Stability Analysis

Revision 1 – 4/15/22

Project Name:	WDI Final Cover Alternative Evaluation	Client:	U.S. Ecology
Project Number:	1208070066	Project Manager:	Xianda Zhao, Ph.D., P.E.
Project Location:	Belleville, Michigan	QA Manager:	Te-Yang Soong, Ph.D., P.E.

Calculation Sheet Information

Calculation Medium: ☒ Electronic
☐ Hard-copy Number of pages (excluding cover sheet):

Title of Calculation:	Veneer Stability Analysis
Calculation Originator:	Andrew McAvinew, P.E.
Calculation Contributors:	
Calculation Checker:	James Moseley, P.E.

Calculation Objective

1. Determine the minimum drained and undrained strength parameters (friction angle and cohesion/adhesion), necessary to obtain the appropriate factors of safety for cover system stability, specifically for the proposed engineered turf system.

Assumptions/Open Items

1. No geosynthetic reinforcements
2. No tension allowed in geosynthetics (T=0)
3. No interface adhesion
4. Geotextile/turf thickness is 0.5 mm
5. GCL is two (2) 0.25 mm layers
6. ClosureTurf and sand infill are fully interlocked and do not represent a critical interface
7. Critical interface(s) are between the GM/GCL/GCL/Subgrade soil

Design Criteria/Design Basis (with Reference to Source of Data)

1. The required minimum factors of safety for static unsaturated and static saturated are 1.5 and 1.1, respectively.

Results/Conclusions

1. The minimum strength parameters were developed using the minimum factors of safety. These minimum specifications calculated are within the range of reasonable characteristics for the materials involved.

Tabular Summary of Analyses

Component	Controlling Analysis	Minimum Strength Parameters*				
		ϕ (deg)	c (psf)	δ_A (deg)	δ_B (deg)	a (psf)
Sand Infill	Static Unsaturated, Minimum FS = 1.5	25	0	-	-	-
All geosynthetic and soil interfaces above FML	Static Unsaturated, Minimum FS = 1.5	-	-	20.5	-	0
All geosynthetic and soil interfaces below FML	Static Unsaturated, Minimum FS = 1.5	-	-	-	20.5	0

*Minimum specifications assume no cohesion/adhesion. Laboratory testing of the components over the range of normal stresses to be encountered in the field may result in a Mohr-Coloumb failure envelope suggesting a nonzero value for cohesion/adhesion. In such cases, the friction angle may be lower than that specified and still be acceptable as long as the actual shear strength for the materials is greater than the envelop devloped with the minimum specification noted above.

References/Source Documents

1. WDI MC6 – Rev 1 drawing set.

Revision Records

Checker comments provided on: ☐ Hard-copy ☒ Electronic File

No.	Revision Identifier (Number or Letter)	Version Type		Originator Initials	Date	Checker Initials	Date
		Draft	Final				
1	Rev. 0	☐	☒	APM	07/07/21	JLM	10/05/21
2		☐	☐				
3		☐	☐				

Approval	
☐ The Detail Check has been completed. Any significant issues not resolved between the Checker and Originator have been resolved by the Approver.	
Originator Signature	Date
Checker Signature	Date
Approved Signature	Date

cti 34705 W 12 Mile Rd, Ste 230 Farmington Hills, MI 48331 Tel. (248) 486-5100	US Ecology, Wayne Disposal Veneer Stability Calculation 2021 Permit Modification	JOB 1208070066 SHEET NO 1 OF 3 CALCULATED BY APM DATE 07/07/21 CHECKED BY JLM DATE 10/05/21 SCALE NA

Objective:

Determine the minimum drained and undrained strength parameters (friction angle and cohesion/adhesion), necessary to obtain the appropriate factors of safety for cover system stability, specifically for the proposed engineered turf system.

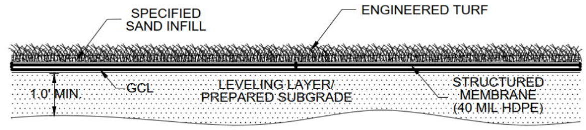


Figure 1. Cross Section (Typical ClosureTurf Cover)

Method:

Use methods outlined in journal paper *Influence Of Water Flow On The Stability Of Geosynthetic-Soil Layered Systems On Slopes* by Giroud et. al. for calculations of static stability. Seismic conditions are not evaluated because the facility is not located in a historically seismic active area.

Figure 1 depicts Wayne Disposal proposed cover system design using engineered turf
Figure 2 shows variables assumed in Giroud's method

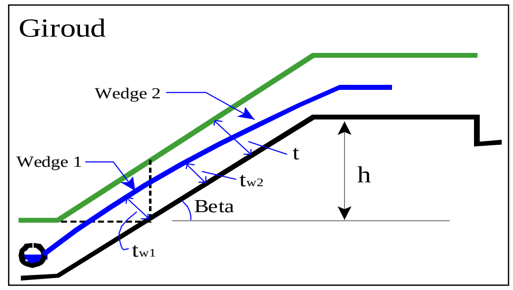


Figure 2. Variable Definitions

Calculations: Condition 1 - Static Unsaturated

Assume: the following conditions:

- No geosynthetic reinforcements
- No tension allowed in geosynthetics (T=0)
- No interface adhesion
- Geotextile/turf thickness is 0.5 mm
- GCL is two (2) 0.25 mm layers
- ClosureTurf and sand infill are fully interlocked and do not represent a critical interface.

Given: Soil conditions, liner system design, and slope geometry

Slope Geometry

Slope Angle (b)		4 :1 =	14.04	degrees
Slope Height (h)	205	ft		

Engineered Turf Material Properties

	Turf/GTX	Sand Infill	Wt. Avg.	
Thickness (t)	0.002	0.042	0.043	ft (GTX is 0.5 mm (assumed)/sand infill is 0.5 in typ.)
Dry Unit Weight (γ_d)	135.5	105.0	106.2	pcf (turf based on vendor info, sand is conservatively assumed)
` field cond. (w_F)	N/A	15.0	15.0	% (field moisture of sand conservatively assumed)
Unit Weight - field cond. (γ_T)	135.5	120.8	121.3	pcf
Specific Gravity (G_S)	N/A	2.65	2.65	(sand conservatively assumed)
Saturated Moisture (w_{SAT})	N/A	21.7	21.7	%
Saturated Unit Weight (γ_{SAT})	135.5	127.8	128.1	pcf
Buoyant Unit Weight (γ_B)	73.1	65.4	65.7	pcf
Total Normal Stress (σ)	0.22	5.03	5.25	pcf (total normal stress of ClosureTurf)
Shear Strength - both (ϕ) , (c)	25	deg,	0	psf (internal friction angle for sand, conservatively assumed)

Determine: The factor of safety (FS_A) against sliding of the engineered components along interfaces between materials above FML

where:
$$FS_A = \frac{\gamma_t (t - t_w) + \gamma_b t_w}{\gamma_t (t - t_w) + \gamma_{sat} t_w} \frac{\tan\delta_A}{\tan\beta} + \frac{a_A/\sin\beta}{\gamma_t (t - t_w) + \gamma_{sat} t_w} + \frac{\gamma_t (t - t_w^*) + \gamma_b t_w^*}{\gamma_t (t - t_w) + \gamma_{sat} t_w} \frac{t}{h} \frac{\sin\phi}{2\sin\beta \cos\beta \cos(\beta+\phi)}$$
$$+ \frac{c\, t/h}{\gamma_t (t - t_w) + \gamma_{sat} t_w} \frac{\cos\phi}{\sin\beta \cos(\beta+\phi)} + \frac{T/h}{\gamma_t (t - t_w) + \gamma_{sat} t_w}$$

δ_A = interface friction angle between engineered components above FML
a_A = adhesion between engineered components above FML
T = geosynthetic tension above the slip surface
t_w = thickness of flow in Wedge 2 (see Figure 2)
t^*_w = thickness of flow in Wedge 1 (see Figure 2)
(All other variables previously defined)

Determine: The factor of safety (FS_B) against sliding of the engineered components along interfaces between materials below FML

where:
$$FS_B = \frac{\tan\delta_B}{\tan\beta} + \frac{a_B/\sin\beta}{\gamma_t (t - t_w) + \gamma_{sat} t_w} + \frac{\gamma_t (t - t_w^*) + \gamma_b t_w^*}{\gamma_t (t - t_w) + \gamma_{sat} t_w} \frac{t}{h} \frac{\sin\phi}{2\sin\beta \cos\beta \cos(\beta+\phi)}$$
$$+ \frac{ct/h}{\gamma_t (t - t_w) + \gamma_{sat} t_w} \frac{\cos\phi}{\sin\beta \cos(\beta+\phi)} + \frac{T/h}{\gamma_t (t - t_w) + \gamma_{sat} t_w}$$

δ_B = interface friction angle between engineered components above FML
a_B = adhesion between engineered components above FML
(All other variables previously defined)

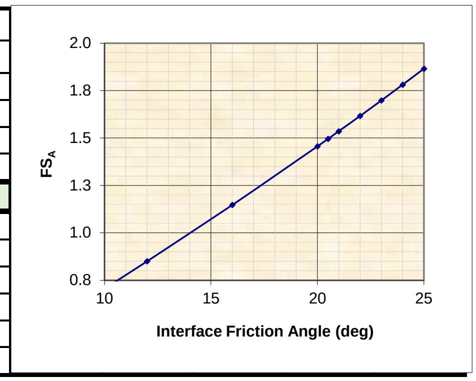
Calculations: Cover Condition 1 - Static Unsaturated (continued)

The first term quantifies the contribution of the interface friction angle to stability. The second term quantifies the contribution of the interface adhesion to stability. The third and fourth terms quantify the contribution of the toe buttressing effect, which results from the shear strength of the soil located at the toe of the slope above the slip surface. Both terms depend on the soil internal friction angle, whereas only the fourth term depends on the soil cohesion. The fifth term quantifies the contribution to the factor of safety of any tension in the geosynthetics located above the slip surface (which may include one or more geosynthetics specifically used as reinforcement).

Required angle of friction (δ) to obtain a FS_A and FS_B equal to 1.5 under unsaturated conditions is tabulated as follows:

Factor of Safety Above FML (FS_A)

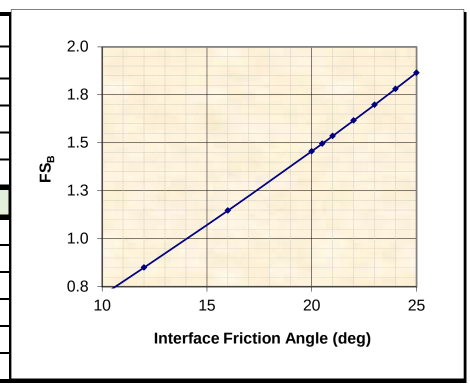
Interface Strength Param.		Water on slope		
δ_A (deg)	a_A (psf)	t_w (ft)	t^*_w (ft)	FS_A
10	0	0	0	0.71
12	0	0	0	0.85
16	0	0	0	1.15
20	0	0	0	1.46
20.5	0	0	0	1.50
21	0	0	0	1.54
22	0	0	0	1.62
23	0	0	0	1.70
24	0	0	0	1.78
25	0	0	0	1.87
26	0	0	0	1.95



► δ_A @ FS=1.5 20.5 deg ==> use 20.5 deg for spec. (check against other conditions)

Factor of Safety Below FML (FS_B)

Interface Strength Param.		Water on slope		
δ_B (deg)	a_B (psf)	t_w (ft)	t^*_w (ft)	FS_B
10	0	0	0	0.71
12	0	0	0	0.85
16	0	0	0	1.15
20	0	0	0	1.46
20.5	0	0	0	1.50
21	0	0	0	1.54
22	0	0	0	1.62
23	0	0	0	1.70
24	0	0	0	1.78
25	0	0	0	1.87
26	0	0	0	1.95



► δ_B @ FS=1.5 20.5 deg ==> use 20.5 deg for spec. (check against other conditions)

Calculations: Cover Condition 2 - Static Saturated

Determine: *The static factor of safety for $FS_{A\,\&\,B}$ assuming varying depth of surface water on top of the engineered turf modeling surface water depths from sheet and/or shalllow concentrated flow on top of the cover system. ClosureTurf does not have a subsurface drainage layer; therefore, evaluation of seepage induced pressure in the cover system is not applicable. The manufacturer of ClosureTurf has demonstrated that erosion of the sand infill is very unlikely under the anticipated flow conditions (See Attachment A) and flow will generally occur on top of the sand infill where relative permeability is much higher. Because of the shallow depth of sand infill, flow characteristics, and resistance to erosion, seepage forces within the sand can be neglected. Under these conditions, the first two terms in the stability equation reduce to:*

$$FS_{A\&B} = \frac{a}{(\gamma_t - \gamma_w)z}\frac{2}{\sin(2\beta)} + [cot\beta]tan\delta + \ldots.$$

The factor of safety should meet or exceed 1.1 under saturated conditions. Because seepage forces are neglected, there is no need to distiguish between the interfaces above or below the impermeable membrane. Assume minimum shear strength parameters δ and a are equal to values from analysis for Cover Condition 1. It should be noted that this analysis also assumes no apparent adhesion is present in the interface. This assumption is extremely conservative because each of the critical interfaces (GM/GCL/GCL/soil) all involve cohesive materials which likley will be present under wet conditoins. Any appreciable measureable apparent adhesion will make the materials inherently stable

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Assume: The following conditions:

- No geosynthetic reinforcements
- No tension allowed in geosynthetics (T=0)
- No interface adhesion
- Geotextile/turf thickness is 0.5 mm
- GCL is two (2) 0.25 mm layers
- ClosureTurf and sand infill are fully interlocked and do not represent a critical interface.
- Critical interface(s) are between the GM/GCL/GCL/subgrade soil
- Seepage forces are negligible and are not considered

Given: Soil conditions, liner system design, and slope geometry

Slope Geometry

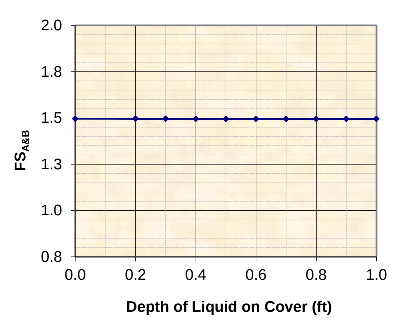
Slope Angle (b)	4 :1 =	14.04	degrees
Slope Height (h)	205 ft		

ClosureTurf Material Properties

	Turf/GTX	Sand Infill	Wtd. Avg.	
Thickness (t)	0.002	0.042	0.043	ft (GTX is 0.5 mm (assumed)/sand infill is 0.5 in typ.)
Dry Unit Weight (γ_d)	135.5	105.0	106.2	pcf (turf based on vendor info, sand is conservatively assumed)
Moisture - field cond. (w_F)	N/A	15.00	15.0	% (field moisture of sand conservatively assumed)
Unit Weight - field cond. (γ_T)	135.5	120.8	121.3	
Specific Gravity (G_S)	N/A	2.65	2.65	(sand conservatively assumed)
Saturated Moisture (w_{SAT})	N/A	21.7	21.7	%
Saturated Unit Weight (γ_{SAT})	135.5	127.8	128.1	pcf
Buoyant Unit Weight (γ_B)	73.1	65.4	65.7	pcf
Shear Strength - both (ϕ) , (c)	25 deg,		0	psf (internal friction angle for sand, conservatively assumed)

Factor of Safety Above FML ($FS_{A\&B}$)

Interface Strength Param.		Water on slope		
δ_A (deg)	a_A (psf)	t_w (ft)	t^*_w (ft)	FS_B
20.5	0	0.00	0.00	1.50
20.5	0	0.20	0.20	1.50
20.5	0	0.20	0.20	1.50
20.5	0	0.30	0.30	1.50
20.5	0	0.40	0.40	1.50
20.5	0	0.50	0.50	1.49
20.5	0	0.60	0.60	1.49
20.5	0	0.70	0.70	1.49
20.5	0	0.80	0.80	1.49
20.5	0	0.90	0.90	1.49
20.5	0	1.00	1.00	1.49



► $FS_{A\&B}$ reqd≥ 1.1 ==> minimum $FS_{A\&B}$ equals 1.49 with saturated sand infill ==> OK

Results: Tabular Summary of Analyses

Component	Controlling Analysis	Minimum Interface Shear Strength Parameters (Peak)*				
		ϕ (deg)	c (psf)	δ_A (deg)	δ_B (deg)	a (psf)
Sand Infill	Static Unsaturated, Minimum FS = 1.5	25	0	-	-	-
All geosynthetic and soil interfaces above FML	Static Unsaturated, Minimum FS = 1.5	-	-	20.5	-	0
All geosynthetic and soil interfaces below FML	Static Unsaturated, Minimum FS = 1.5	-	-	-	20.5	0

*Minimum specifications assume no cohesion/adhesion. Laboratory testing of the components over the range of normal stresses to be encountered in the field may result in a Mohr-Coloumb failure envelope suggesting a nonzero value for cohesion/adhesion. In such cases, the friction angle may be lower than that specified and still be acceptable as long as the actual shear strength for the materials is greater than the envelop developed with the minimum specification noted above.

Conclusions:

The proposed engineered turf cover system for WDI was evaluated for shallow translational/veneer failures along the geosynthetic components parallel to the slope. Worst case cross sections were utilized as noted in the analyses. Minimum factors of safety are based on typical industry standard values which were used to develop minimum strength parameters for each of the components. The minimum specifications noted above are within the range of reasonable characteristics for the materials involved. Therefore, the minimum specifications calculated are acceptable.

Attachment D

Wind Uplift Evaluation

Revision 1 – 4/15/22

July 8, 2010

Mr. Michael R. Ayres, P.E.
Closure Turf, LCC
3005 Breckinridge Blvd.
Duluth, GA 30096

Subject: **Aerodynamic Evaluations of Closure Turf Ground Cover Materials**

References: **1: Contract # AGR DTD 5/14/10**

Dear Mr. Ayres and Closure Turf LCC affiliates:

The Georgia Tech Research Institute is pleased to submit the attached Report, covering the period from May 14 to July 8, 2010, in fulfillment of Reference. This document details the tasks and analysis made on contracted work performed by the GTRI Aerospace, Transportation and Advanced Systems Laboratory and its team members on Phase I of the Project entitled "Aerodynamic Evaluations of Closure Turf Ground Cover Materials".

We look forward to continuation of this work for/with Closure Turf, LCC upon the adoption of Phase II activities related to aerodynamic investigation of Closure Turf Material or other desired evaluations.

Sincerely,

Graham M. Blaylock
Principal Investigator

Aerodynamic Evaluations of Closure Turf Ground Cover

Phase I REPORT

May 14 – July 8, 2010

Project Expires: August 14, 2010

Contract No. AGR DTD 5/14/10

Proposal No. ATASL-AATD-10-1119

GTRI Project No. D-6244

Prepared for:

Mr. Michael R. Ayres, P.E.
Closure Turf, LCC
3005 Breckinridge Blvd.
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Prepared by:

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Principal Investigator: Graham M. Blaylock, Research Engineer II
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Introduction

GTRI has been contracted by Closure Turf, LCC to **experimentally evaluate the aerodynamic properties and ballast requirements** of a novel synthetic ground-cover system under a range of wind speed conditions (V_{inf}). The Closure Turf Material was tested full-scale in **GTRI's subsonic Model Test Facility (MTF) wind tunnel** wherein the normal force loading (lb_f/ft^2) and the shear stress (lb_f/ft^2) were determined for a suitable section of the material. The turf material was tested in two configurations, one representing the perimeter of the turf installation (Fig 5) and the 2nd at a representative interior section (Fig 6). Both installations were evaluated on a **flat level surface**. The installation is shown in Figures 1a-d below.

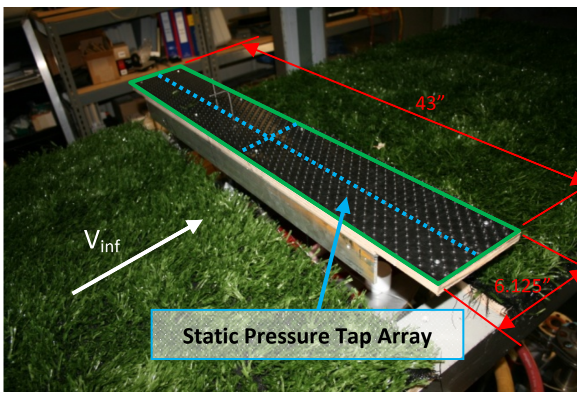

Figure 1a – Model Before Final Turf Layer

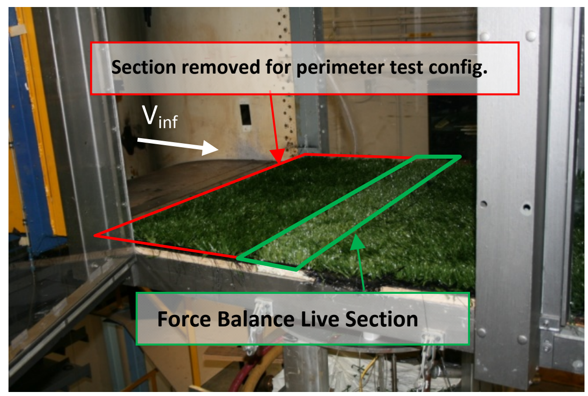

Figure 1b – Turf Installed & Model Lowered

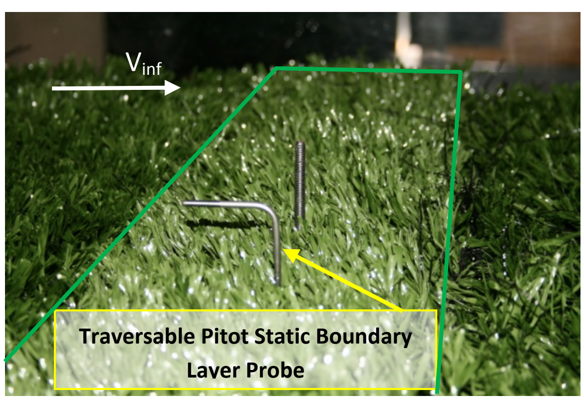

Figure 1c - Pitot Static Boundary Layer Probe

Figure 1d – Full Installation Looking Downstream

Program Description

Closure Turf system - The Closure Turf ground cover system consists of two independent layers. The first layer is a **geomembrane** to cap the upper soil layer. This is then covered with a **geotextile** turf layer (Fig 2a and 2b)

Geomembrane Layer -The impermeable geomembrane is made from Agru 50-mil LLDPE Super Gripnet® material and is used to cap the terrain being covered. It has an array of spikes to interface to the soil below and an array of studs to interface with the turf covering above. Throughout the testing and subsequent analysis of the Closure Turf system, **it was assumed that the geomembrane will be sufficiently installed to prevent movement of that layer.**

Geotextile Turf Layer – This component is designed to be installed on top of the geomembrane. The turf is intended to remain in place without an anchoring system linking it to the geomembrane below. It relies on the interface friction and sand ballast added on top of the turf to ensure that it remains immobile under all environmental conditions. It is constructed of two permeable sheets of woven HDPE mesh material which are linked together with synthetic blades of grass that are looped through the two HDPE substrates (Fig 2a).

Figure 2a – Closure Turf Synthetic Ground Cover System

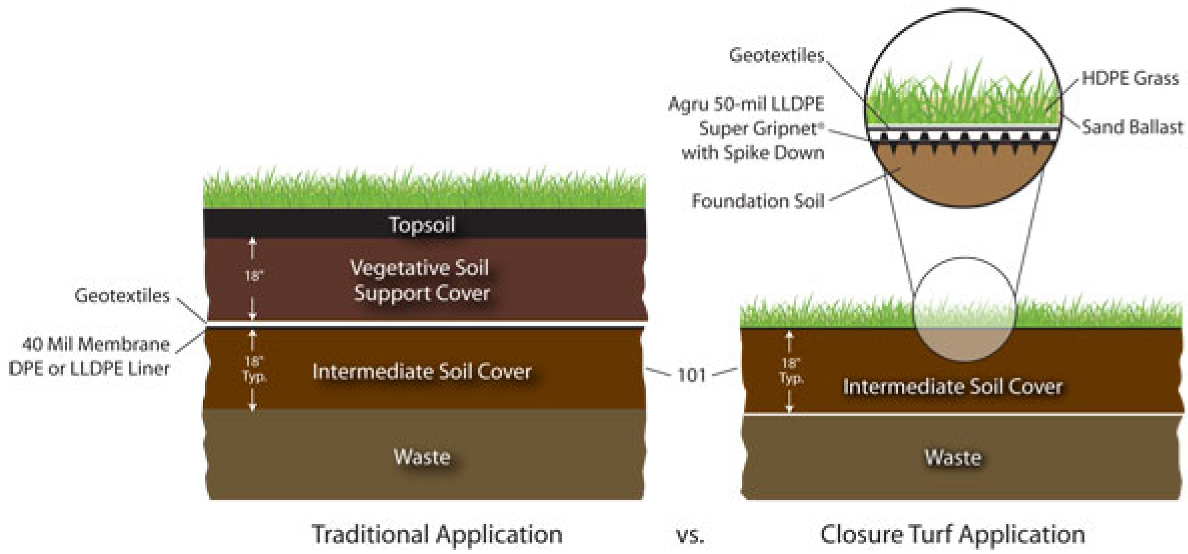

Figure 2b – Installation of Closure Turf

Purpose – The scope of this program was to conduct a full-scale wind tunnel test and experimentally isolate and measure the aerodynamic forces acting on a section of the permeable upper geotextile turf layer alone as installed above the impermeable geomembrane. The wind tunnel install configuration would simulate a wide range of wind speeds flowing over a **flat and level terrain installation** of the Closure Turf ground cover system (Fig 1a-d). The sand ballast requirements needed to counteract the resulting aerodynamic forces could then be determined. The purpose of the ballast is twofold. It serves to prevent both lift-off and tangential motion of the turf material along the geomembrane underlayment **resulting from aerodynamic lift and drag acting on the turf layer**.

Methodology

Model Design – The model represented a full-scale 2D section of the Closure Turf material with a 6.125" chord (stream-wise dimension) with a width of 43" that spanned the tunnel wall to wall. This area constituted the live balance section upon which the total sum of all aerodynamic forces could be measured by a 6 component force balance located under the test section. The model consisted of 4 layers listed below from the lower to uppermost turf layer

1) ¾" Furniture grade plywood support base – This incorporated several pressure taps on the underside in order to measure the ambient pressure (P_{amb}) to determine the vertical force (F_{amb}) due to pressure acting upward on the lower surface of the model.
2) Foam Filler Layer – This represented the soil layer surrounding the lower geomembrane spikes.
3) Impermeable Goemembrane Layer – This was fixed rigidly to the base. An array of static pressure taps was installed on the upper side of this layer, shown schematically in Fig. 1a. These

pressures were integrated numerically to determine the force (F_{geo}) due to pressure acting down on the membrane.

4) Geotextile Turf Layer – The turf was first mounted to a thin wire support frame to maintain the geometry and to provide a safety measure to prevent material from dislodging in the tunnel. The frame was then mounted rigidly on top of the lower construction flush with the top of the geomembrane upper surface studs.

Pitot Static Boundary Layer Probe – In general, pressure variation through the height of the boundary layer is due to viscous forces which cause deficits in the total pressure as the bounding flat and level surface is approached. The static pressure remains constant. However, the unique characteristics of the flexible and permeable turf layer warranted investigating the boundary layer formation on the Closure Turf system. To accomplish this, a traverse system was built into the model to actuate a Pitot static probe vertically through the boundary layer (Fig 1c). This allows the measurement of the total and static pressure as a function of the probe height, defined as h = 0" at the upper surface of the turf HDPE woven mesh. From these measurements the flow velocity distribution was determined. This characterizes the shape of the boundary layer which is by its nature a transition from the no slip condition at the surface ($V = 0$) to free stream conditions ($V = V_{inf}$). The characteristics of this boundary layer profile such as the BL thickness, the height required for the flow to reach free stream velocity, provide valuable insight into the observed results.

Force Balance – An under floor 6 component force balance was utilized to measure the aerodynamic lift (L) and the total drag (D) of the model. These forces were transmitted to the balance through a vertical strut which mounted to the underside of the model base. It should be noted that these forces represent the total sum of all pressure distributions acting on the model resolved vertically and tangentially. As such the isolated vertical force acting on just the turf layer (L_{turf}) is found by Equation 1.

$$L_{turf} = L - L_{amb} + L_{geo} \quad \text{(Eq 1)}$$

Under the confines of this program, it was not feasible to separate the drag acting on just the turf from skin friction and pressure drag acting on the geomembrane. That being the case, the total drag as measured from the force balance was taken as the drag acting on the turf. This results in a conservative overestimation of the actual turf drag force present.

Installation Conditions – Two installation conditions were examined separately. To more accurately simulate the actual installation conditions, both geomembrane and turf layers were installed upstream and downstream of the balance live model (Fig 1b and 1d). This represents an **interior** condition and in this case the model was located approximately 18" inboard of the **perimeter**. It was also suspected that the perimeter, if unaccounted for, could lead to a worse case situation. To determine the nature of this the upstream turf was removed leaving just the geomembrane as a stand in for a typical surface soil roughness that could be expected at the edge of a real world installation. This left the model mounted turf exposed at the leading edge.

Results and Discussion

These results represent the required thickness of sand for the Closure Turf system as installed on **flat and level terrain**. The density of the sand was provided by Closure Turf. If a different material density is to be used as ballast, the results can be recalculated via Equation 2.

In all cases, **the driving parameter for the depth of the sand is tangential slip due to the aerodynamic formation of shear stress**. The sand ballast requirements have been illustrated in Figures 5 and 6 for several assumed representative interface coefficients of static friction (μ_s). The **minimum** required sand ballast height is found by Equation 2.

$$h_{sand}(in) = \frac{1}{\rho_{sand}}\left(\frac{\tau}{\mu_s} + P\right)\frac{12in}{ft} \qquad \text{(Eq 2)}$$

Where:

$$\rho_{sand} = Weight\ Density\ of\ Ballast(sand) = 110\ \frac{lb_f}{ft^3}$$

$$\tau = \frac{D}{Area} = Shear\ Stress, \frac{lb_f}{ft^2}$$

$$P = \frac{L_{turf}}{Area} = Normal\ Force\ Loading, \frac{lb_f(+tve\ up)}{ft^2}$$

The measured data for determining the sand depth are shown in Table I and Table II and plotted in Figures 5 and 6 for the perimeter and interior configurations respectively. The last column of each table gives the resulting sand height requirement, based on Equation 2, for μ_s = 0.93. This value was determined independently from the efforts of this program by Closure Turf affiliates and supplied for use in this analysis.

Perimeter Condition (PC) – The ballast requirement resulting from this configuration are substantially greater than the interior condition. For the given μ_s =0.93 a **minimum** sand height of 0.4" or 3.6 lb_f/ft^2 is needed to provide the ballast based on the resulting shear at 175 ft/s. The lifting pressure will be satisfied by this loading as shown in Figure 4. It should be noted that the required ballast height due to uplift goes from positive to negative at around 115 ft/s. There are several factors contributing to these results.

PC Boundary Layer (BL) – The profile for the perimeter condition is shown in Figure 4 (Red Curve). One characteristic to note is that the boundary layer thickness reaches 99% of free stream velocity at a height of approximately 2". This subjects the turf to up to 89% of the total free stream based on a max vertical blade height of 1.25". This has several resulting effects which can be followed in Figures 3a to 3f. The cascade of effects proceeds as follows.

The blades are subject to higher velocities and thus higher increasing drag as the wind speed increases. The higher drag increases the bending of the blades back onto the mesh substrate. The effect of this has 2 **counteracting effects on the net lift**. At lower velocities (Fig3a-b) the blades are bent slightly with the flow being deflected and accelerated of over the perimeter as shown by the tufts. This flow acceleration increases the **local** velocity and lowers the local static pressure **below** that of free stream static which creates the pressure differential building up in 3a and b Additionally, in this installation, the perimeter exposes the gap between the turf and the geomembrane which allows for some uplift pressure recovery beneath the turf. However, as the free stream velocity increases, the drag is increased further by virtue of greater velocity exposure in the relatively thin boundary layer, the bending angle of the turf also increases (Fig 3b-c). This bending produces an increasing down force reaction which starts to counteract the suction created by the local flow acceleration. Simultaneously, the slightly reduced turf profile geometry (caused by the increased bending) shown in Figure 3c-d begins to reduce the relative local flow acceleration and thus also reduces the suction. This continues until the net vertical force becomes zero at about 110 ft/s (Fig 3d) and continues to decrease through Figure 3f.

Interior Condition (IC) – This condition owes its behavior to the formation of a drastically different boundary layer than the perimeter as shown by the blue profile in Figure 4. Compared to the Perimeter profile it is 25% thicker with no measurable velocity until the height is greater than 50% of the turf length (0.75"). The blades thusly experience a maximum velocity of 45% of free stream. This reduces the drag acting on the turf layer. Furthermore, the static pressure remains constant as a function of height through the BL which effectively prevents the formation of a pressure differential on the flat and level permeable turf membrane.

The cause for the deficient boundary layer is created by longer flow paths over a given surface and all boundaries grow in thickness and increase in turbulence with increasing distance. In the case of Closure Turf, the interaction of the flow with the flexible blades causes this growth to occur quite rapidly. The distance producing the profile in Fig 4 was 18" however, the effect of the growing boundary layer can be seen even in the perimeter condition development in Figures 3a –f. The Model section (highlighted in yellow) is 6.125" wide. It is clearly seen that little to no defection occurs in the turf at a distance just over 6 inches behind the perimeter edge. Thus the boundary layer at further distances than 18" and greater from the perimeter can be expected to have minimal interaction with the turf. Figure 6 shows these results by producing measurements requiring minimal ballast.

Final Comments and Executive Summary

GTRI was contracted by Closure Turf to determine the effective required ballast in terms of sand thickness needed to counteract the aerodynamic forces versus wind velocity acting on a permeable geotextile synthetic turf ground covering material that is to be overlaid onto an impermeable geomembrane underlayment. *It was found that in both perimeter and interior loading conditions, the shear acting on the material serves as the more demanding factor for determining the ballast.*

- **The resulting measurements represent the forces acting on the permeable Turf Layer *only*. The impermeable geomembrane layer was to be assumed immobile as a founding assumption of this program**

- **If it is determined that the static interface friction coefficient (μ_s) between the soil and the lower side of the membrane is lower than that occurring between the turf and the membrane upper surface studs, the lower μ_s should be used in Equation 2 to recalculate the sand depth required by shear. The same shear data given in Tables I & II will apply because, as discussed within the methodology section, the measured shear could not be feasibly separated between the two layers independently and thus represents their combined effect.**
- **The sand ballast depths represented in Figures 5 & 6 and Tables I & II are the Minimum depths required, the proper factor of safety has been left to be determined by Closure Turf, LCC and the authorized building permit issuing agencies.**
- **The perimeter of the turf installation is much more demanding than interior sections.**
- **All measurements were made on a rigidly constrained system. It was not within the scope of this investigation to determine what dynamic effects might occur, including gusts or erosion of sand ballast or any possible unstable perturbations.**
- **All configurations consisted of flat and level terrain installation.**
- **All calculations and measurements assume that the blade length is increased to account for any added ballast material. This is to ensure that the installation matches the conditions as tested.**

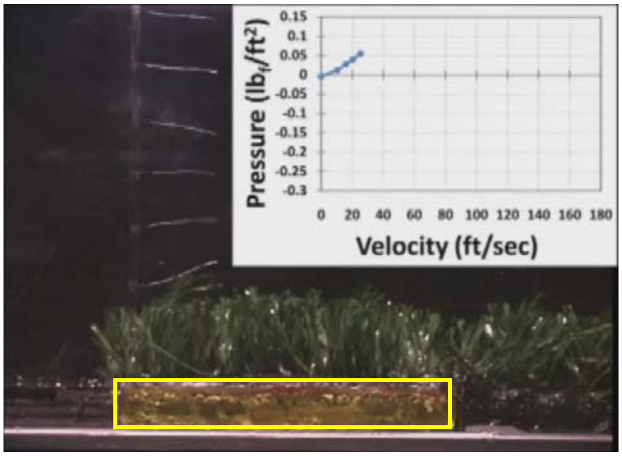

Figure 3a: Vinf = 25 ft/sec

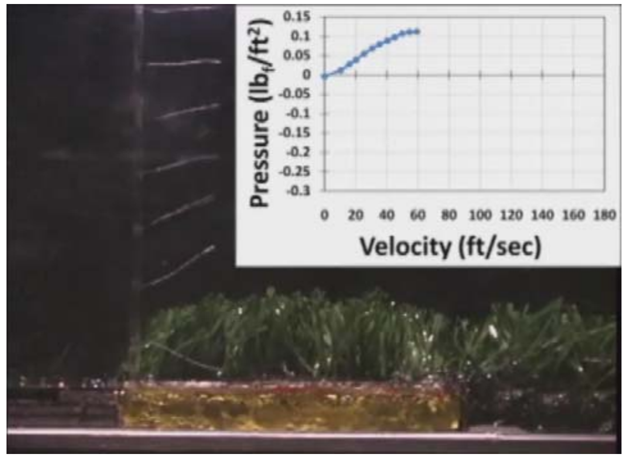

Figure 3b: Vinf = 60 ft/sec

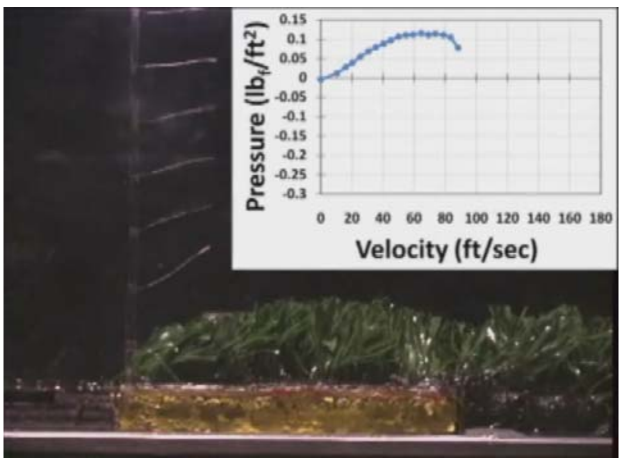

Figure 3c: Vinf = 90 ft/sec

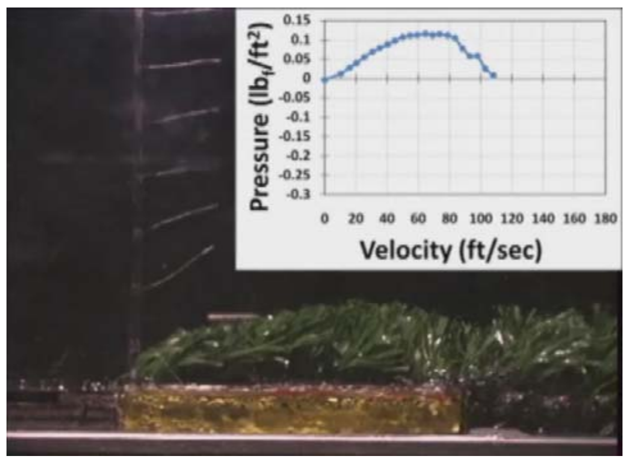

Figure 3d: Vinf = 110 ft/sec

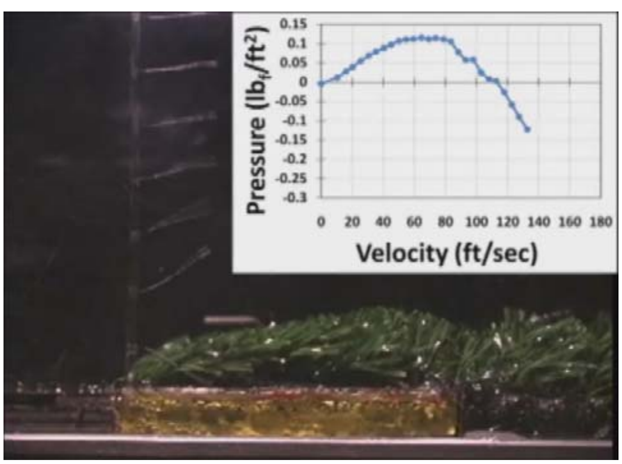

Figure 3e: Vinf = 135 ft/sec

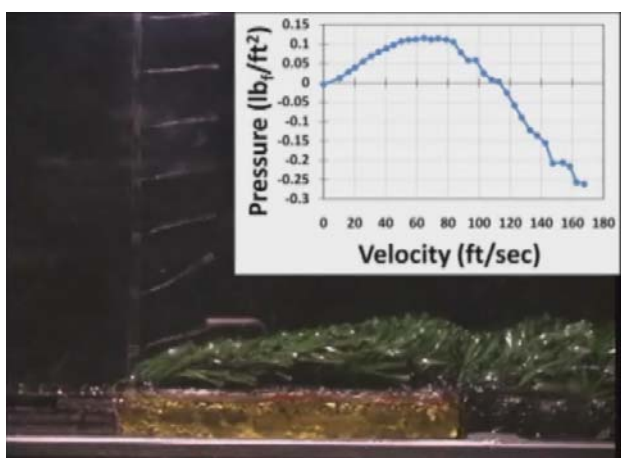

Figure 3f: Vinf = 170 ft/sec

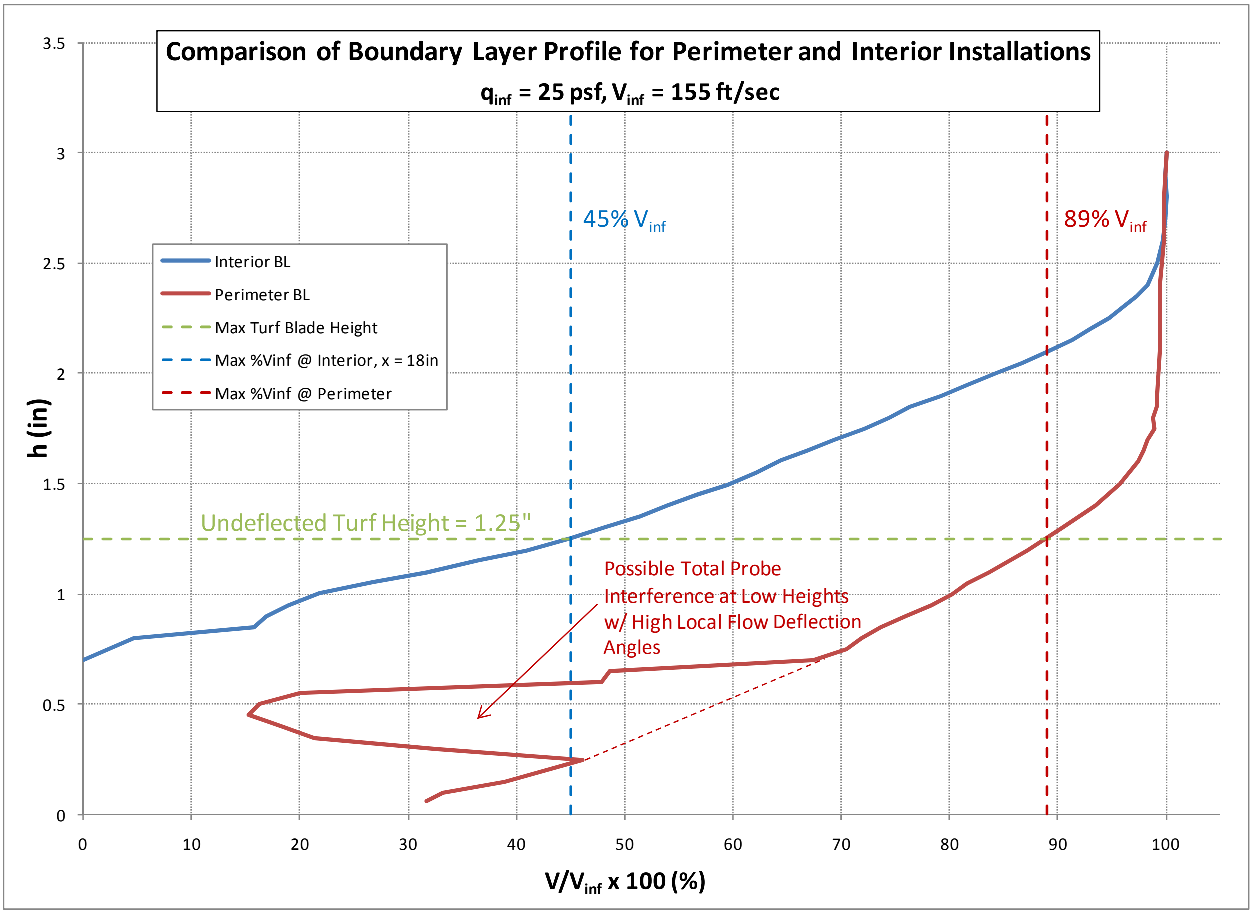

Figure 4 – Non-Dimensional Boundary Layer Profiles for Perimeter and Interior Installations

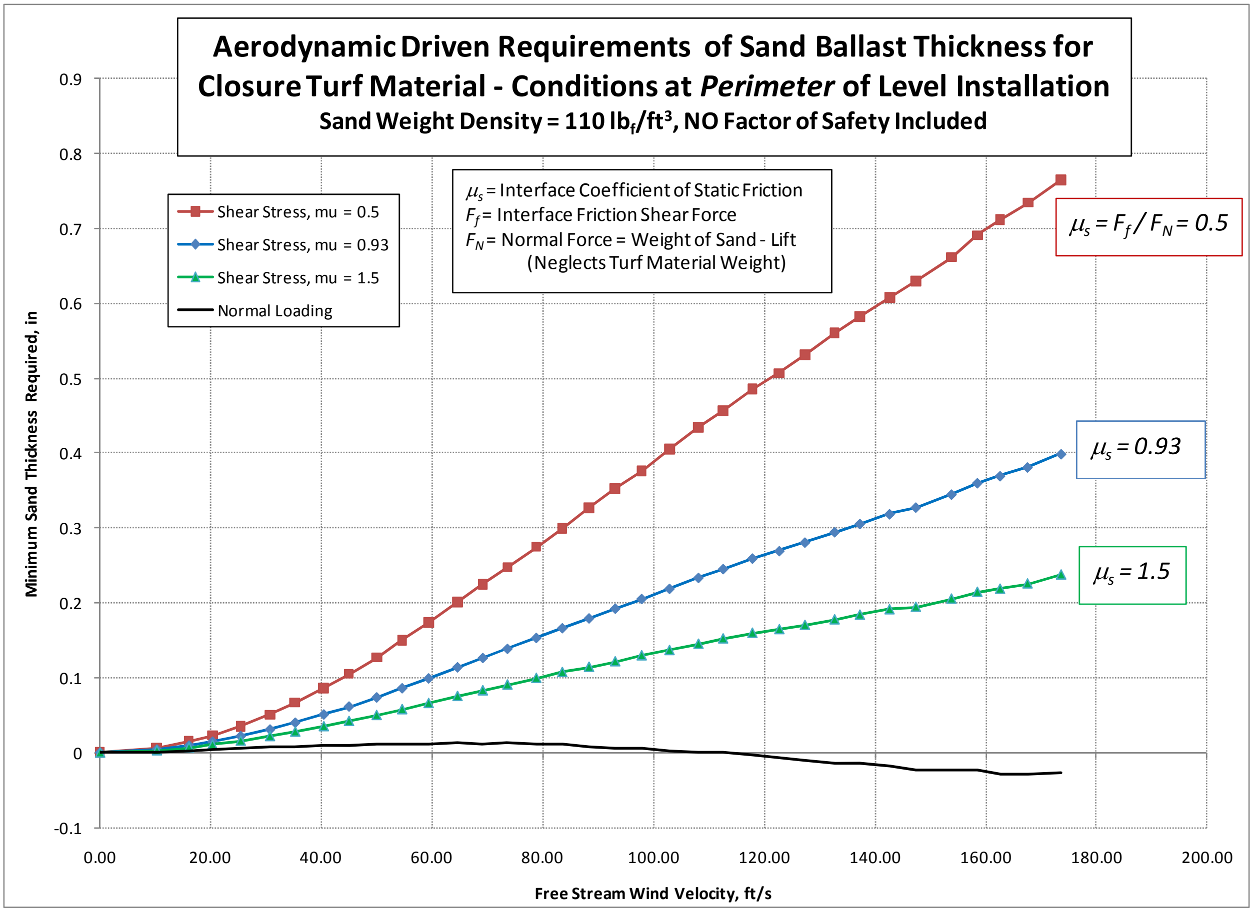

Figure 5 – Sand Ballast Minimum Requirement at the *Perimeter* of Turf Installation

Table I - Perimeter Installation				
Wind Speed (*ft/s*)	Wind Speed (*mi/hr*)	Turf Normal Force Loading (lb_f/ft^2)	Turf Shear Stress (lb_f/ft^2)	Sand Height Due to Shear (*in*)
0.00	0.00	0	0	0
10.26	6.99	0.011689	0.023784	0.0040651
16.06	10.95	0.027798	0.053106	0.009262
20.31	13.84	0.039396	0.086922	0.0144939
25.40	17.32	0.054936	0.136103	0.0219582
30.70	20.93	0.06927	0.198423	0.0308322
35.26	24.04	0.078777	0.266915	0.0399035
40.42	27.56	0.088429	0.351918	0.0509275
44.97	30.66	0.096783	0.434606	0.0615383
49.97	34.07	0.10646	0.529776	0.0737576
54.57	37.21	0.110561	0.630469	0.0860165
59.36	40.47	0.111817	0.741903	0.099225
64.58	44.03	0.115373	0.865046	0.1140578
69.15	47.15	0.111526	0.975305	0.1265718
73.60	50.18	0.114496	1.076528	0.1387694
78.82	53.74	0.111457	1.204017	0.1533926
83.52	56.94	0.104976	1.320714	0.1663744
88.34	60.23	0.077354	1.458158	0.1794835
93.08	63.46	0.057303	1.588598	0.192597
97.86	66.72	0.058201	1.697814	0.2055063
102.89	70.15	0.024978	1.844449	0.2190825
108.12	73.72	0.007601	1.985703	0.2337562
112.58	76.76	0.002646	2.090641	0.2455251
117.87	80.37	-0.026041	2.237684	0.2596441
122.74	83.69	-0.058742	2.352732	0.2695721
127.36	86.84	-0.089852	2.479185	0.2810115
132.72	90.49	-0.122289	2.627843	0.2949108
137.29	93.61	-0.135769	2.734267	0.305924
142.65	97.26	-0.155489	2.863465	0.3189279
147.40	100.50	-0.208034	2.98848	0.3278602
153.84	104.89	-0.206002	3.134988	0.3452676
158.51	108.08	-0.21588	3.274285	0.3605298
162.63	110.88	-0.256805	3.392572	0.3699406
167.59	114.26	-0.261535	3.496667	0.3816351
173.66	118.41	-0.23928	3.626641	0.3993092

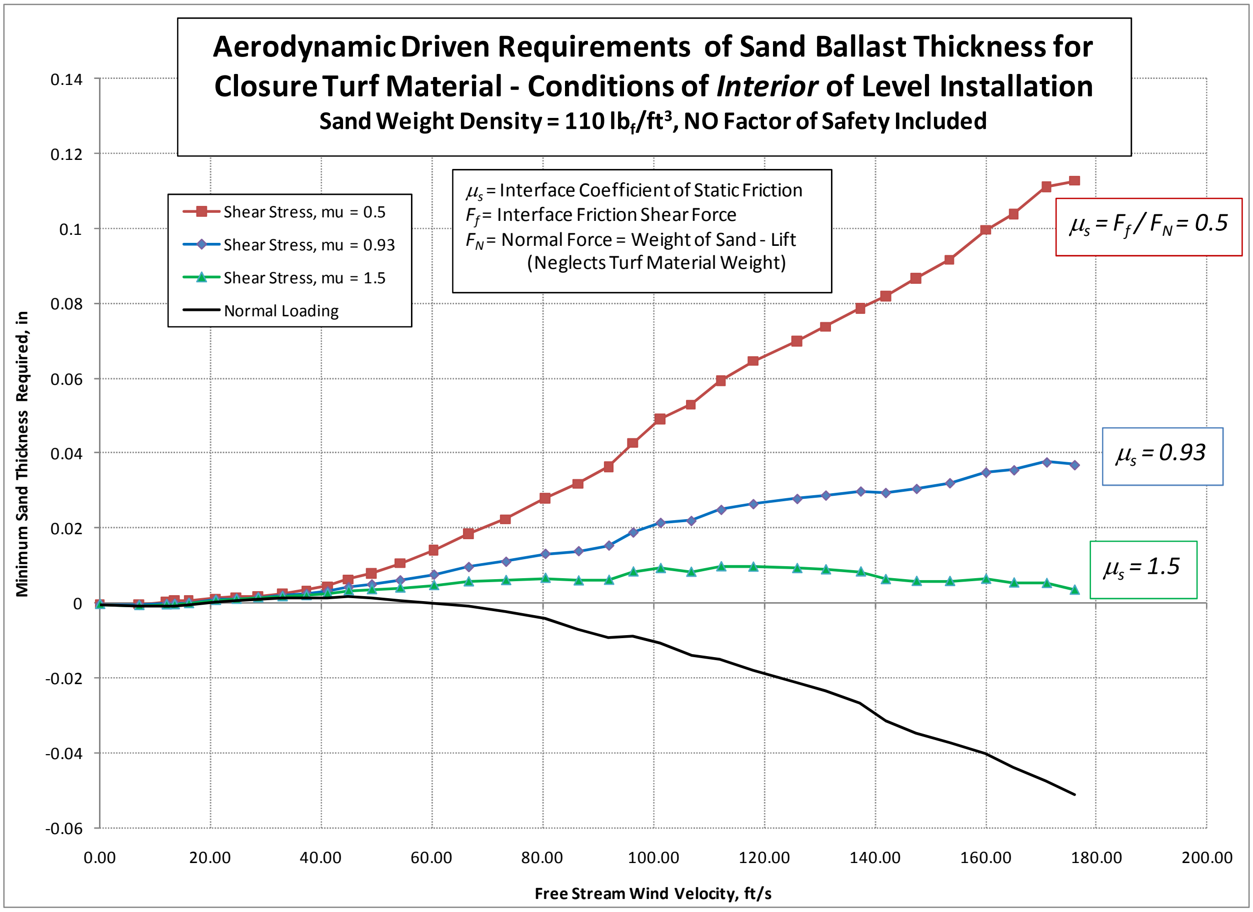

Figure 6 – Minimum Sand Ballast Requirement in the *Interior* of Turf Installation

Table I - Interior Installation				
Wind Speed (ft/s)	Wind Speed (mi/hr)	Turf Normal Force Loading (lb_f/ft^2)	Turf Sheer Stress (lb_f/ft^2)	Sand Height Due to Shear (*in*)
0.00	0.00	-0.00419	0.000471	0
7.07	4.82	-0.00858	0.002819	-0.000605326
12.02	8.20	-0.00858	0.005658	-0.000272305
13.47	9.18	-0.009201	0.006927	-0.000191194
16.05	10.94	-0.005314	0.005174	2.72117E-05
20.91	14.26	0.003753	0.0034	0.000808245
24.64	16.80	0.006062	0.004099	0.00114213
28.56	19.47	0.009925	0.003388	0.001480147
32.94	22.46	0.011669	0.005393	0.001905592
37.27	25.41	0.011221	0.009767	0.002369798
41.09	28.01	0.013608	0.013502	0.003068321
44.90	30.61	0.015886	0.02088	0.004182285
49.08	33.47	0.011842	0.03072	0.004895374
54.21	36.96	0.006407	0.045273	0.006009561
60.31	41.12	-0.000648	0.064883	0.007540218
66.57	45.39	-0.006394	0.087581	0.009575904
73.32	49.99	-0.019878	0.112271	0.01100111
80.43	54.84	-0.037311	0.146631	0.013129826
86.42	58.92	-0.06477	0.178237	0.013841748
91.90	62.66	-0.083261	0.208285	0.01534924
96.30	65.66	-0.081403	0.236369	0.018846242
101.24	69.02	-0.097454	0.273298	0.021427071
106.76	72.79	-0.129489	0.30751	0.021945482
112.17	76.48	-0.138401	0.341067	0.024909568
117.97	80.43	-0.163997	0.378085	0.026459565
125.89	85.83	-0.193612	0.417441	0.027845377
131.07	89.36	-0.215792	0.445855	0.028758761
137.38	93.67	-0.245542	0.482763	0.029842691
141.88	96.73	-0.289393	0.520185	0.029448623
147.46	100.54	-0.317409	0.555461	0.030530279
153.47	104.64	-0.340708	0.59023	0.032067045
159.99	109.08	-0.369093	0.641021	0.034928388
165.05	112.53	-0.4029	0.677722	0.035545455
170.96	116.56	-0.437374	0.727691	0.037646121
176.00	120.00	-0.469865	0.751682	0.036915842

Wind Tunnel Study and Uplift Analysis of Geosynthetic Covers

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ABSTRACT

Geosynthetic covers, including the exposed geomembrane cover and engineered turf cover, have been used as alternatives to conventional soil-geosynthetic covers for closure of landfills and other waste containment facilities. Because the geomembrane component in geosynthetic covers is not overburdened with a soil layer, uplift of geomembrane due to wind loads is of a concern in the design and construction of such covers. A wind tunnel study was performed to evaluate performance of an exposed geomembrane cover and the ClosureTurf engineered turf cover under wind loads on small-scale test models that were built to simulate a landfill cross section. The wind tunnel test results are presented in the form of dimensionless wind pressure coefficients. The wind-induced uplift pressure is found to be affected by the surface roughness of the cover and the slope ratio. The measured maximum uplift pressure coefficient values for the ClosureTurf engineered turf cover are approximately 30% of those for a smooth exposed geomembrane cover, demonstrating significant improvement of wind uplift resistance of the engineered turf cover. An example calculation of the maximum wind uplift pressure on the engineered turf cover is presented.

INTRODUCTION

Landfill covers have been used to protect human and the environment from exposure to the waste. A typical landfill cover prescribed by the federal and state solid waste management regulations in the USA consists of, from bottom to top, a geomembrane barrier layer, a geocomposite drainage layer, and protective and vegetative soil layers. Geosynthetic covers, including the exposed geomembrane cover and engineered turf cover (e.g., ClosureTurf), have been used as alternatives to conventional soil-geosynthetic covers for temporary and final closure of landfills and other waste containment facilities (SWANA 2017).

The exposed geomembrane cover consists of only a geomembrane barrier layer. It eliminates the issues of veneer-type slope instability and soil erosion associated with the prescriptive soil covers. However, since the geomembrane is directly exposed to the environment, it is vulnerable to ultraviolet (UV) damage that limits the design life of the exposed geomembrane cover (Gleason et al. 2001). The engineered turf cover utilizes an engineered synthetic turf layer infilled with sand to cover the underlying geomembrane and protect it from UV degradation (Zhu et al. 2019). Since its first installation in 2009, the engineered turf cover has been

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increasingly used to close municipal solid waste (MSW) landfills, industrial waste landfill and coal combustion residuals (CCR) impoundments and landfills (Abreu R.C. and Franklin J. 2014, Saindon 2019, O'Malley et al. 2019).

Field observations have shown that the exposed geomembrane can be uplifted by wind. Giroud et al. (1995) summarized the study by Dedrick (1973), where wind tunnel tests were conducted on a reduced-scale test model that simulated an empty reservoir. Based on the published wind tunnel test results, Giroud developed the suction factors for the design of exposed geomembrane cover against wind uplift. A method was also presented to calculate the maximum allowable wind velocity for an exposed geomembrane cover when it is not uplifted and the tension and strain of the geomembrane when it is uplifted. The method was later revised by Zornberg and Giroud (1997) to incorporate the influence of slope inclination and a more accurate expression of the tension-strain relationship of geomembrane.

Recently a wind tunnel study was performed by the authors to evaluate performance of the ClosureTurf engineered turf cover under wind loads. Small-scale test models were built to simulate a landfill cross section with a top deck and two side slopes. The models were first covered with the geomembrane to simulate the exposed geomembrane cover. The engineered synthetic turf layer was added later to simulate the engineered turf cover. This paper summarizes the wind tunnel test program and presents the test results for both the exposed geomembrane and ClosureTurf engineered turf covers.

WIND TUNNEL TEST SETUPS

The wind tunnel study was carried out between 2018 and 2020 in the Aerodynamic and Atmospheric Boundary Layer (AABL) Wind and Gust Tunnel located in the Department of Aerospace Engineering at Iowa State University, Ames, Iowa. The purpose of the study was to investigate wind performance of the ClosureTurf engineered turf cover and establish wind pressure distribution profiles through model testing. These profiles can be used to evaluate wind loads, especially wind uplift pressures acting on the ClosureTurf engineered turf cover.

Four test models were constructed with different sizes to simulate a typical landfill cross section that had a side-slope of 3 Horizontal to 1 Vertical (3H:1V) on one side, a flat top deck, and a side-slope of 4H:1V on the other side. The heights of the models varied from 0.15 m (0.5 ft) to 0.46 m (1.5 ft) and the widths varied from 0.46 m (1.5 ft) to 0.76 m (2.5 ft). Each model had two different slopes allowing rotation in the wind tunnel to test two different windward conditions. A velocity probe was used to record point-wise measurements of the upstream wind velocity. Pressure taps were used to measure wind pressures at fifteen locations along the model surface. The pressure taps were connected by flexible vinyl tubes to a pressure scanner module, where data were recorded. The geometry of one of the test models is shown in Figure 1 along with a photo showing the model inside the wind tunnel. Figure 2 illustrates the distribution of measurement points.

The study included tests of both the exposed geomembrane and engineered turf covers. Two types of exposed geomembranes were tested, including a 40-mil (1-mm) thick high-density polyethylene (HDPE) smooth geomembrane and a 50-mil (1.3-mm) thick HDPE structured geomembrane with rough "studded" surface. The engineered turf cover was tested with the engineered synthetic turf layer placed on the 50-mil HDPE structured geomembrane with rough "studded" surface. The geomembrane and engineered turf covers were fixed to the model base in order to measure the wind pressures. No sand infill was applied into the engineered turf during the tests.

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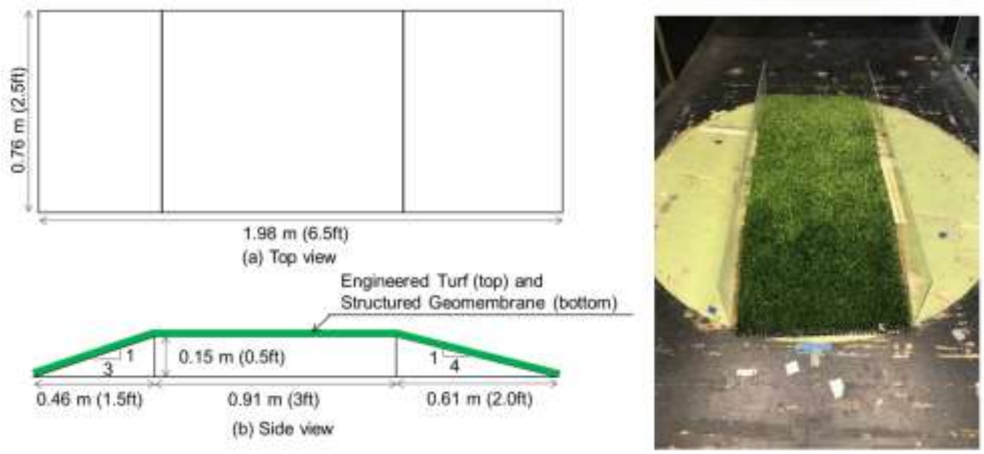

Figure 1. A wind tunnel test model (left - model geometry; right - photo of model inside wind tunnel).

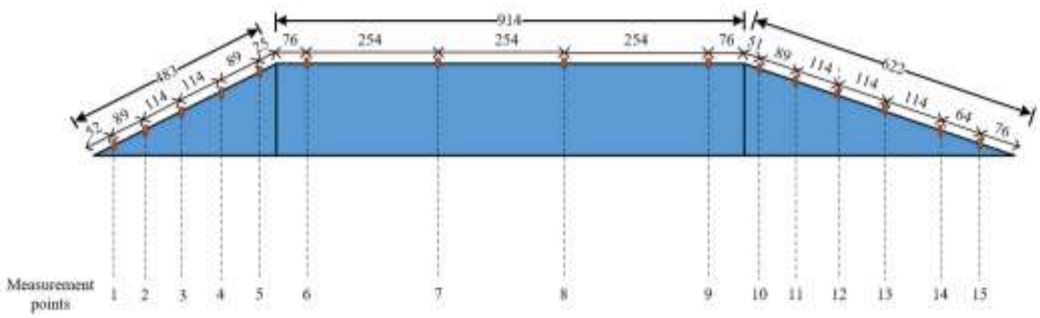

Figure 2. Distribution of wind pressure measurement points (dimension units are in mm).

WIND PRESSURE COEFFICIENT

The wind pressure coefficient is denoted as C_p and defined as follows (Giroud et al. 1995, Zheng et al. 2020):

$$C_p = \frac{\Delta P}{0.5\rho U(H)^2} \quad (1)$$

where, ΔP, psf or N/m^2, is the difference between the pressure on the surface of the model and the static pressure of the upstream flow inside the wind tunnel, which is a function of the wind speed in the tests; ρ is the air density (ρ = 1.225 kg/m^3 or 0.00237 slug/ft^3 at 15ºC and sea level); and U(H) is the upstream mean wind speed at a height equal to the height of the top of the model, ft/s or m/s, with H being the height of the model, ft or m. A positive value of C_p corresponds to the wind load acting toward the surface (i.e., downward pressure) and a negative value of C_p corresponds to the wind load acting away from the surface (i.e., uplift pressure).

The mean wind speed profile upstream of the model was determined by measuring mean wind speeds at several elevations from the wind tunnel floor. The Power-Law (Peterson and Hennessey 1978) is used for modeling the mean wind speed profile upstream of the test models:

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$$\frac{U(z)}{U_{ref}} = \left(\frac{Z}{Z_{ref}}\right)^{\alpha} \quad (2)$$

where, Z is the height above ground; Z_{ref} is the reference height taken as z = H (i.e., at the top of slope model); U_{ref} is the mean wind speed at the reference height taken as U(H); U(z) is the mean wind speed at elevation z; and α is the Power-Law exponent that depends on the terrain over which the wind develops. The value of α was determined as 0.14. Figure 3 shows an example of the measured wind speed profile and the power-law curve fit using α equal to 0.14.

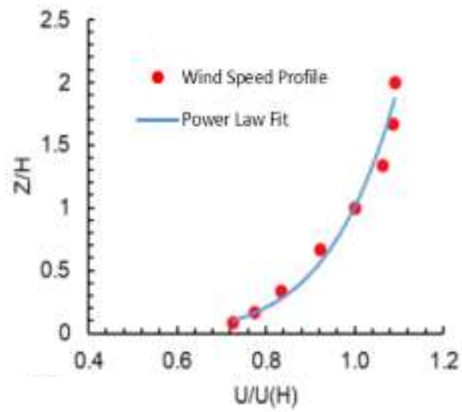

Figure 3. Measured wind speed profile and power-law curve fit (α = 0.14).

A number of test cases were conducted based on combinations of test model, cover type, and wind direction. For each test case, the model was tested for 2 to 3 wind speeds ranging from approximately 5.3 to 22.3 meters per sec (m/s) or 12 to 50 miles per hour (mph). At each wind speed 2 to 3 data runs were taken, resulting in a total of 4 to 9 data sets for each test case. The measured surface pressures were normalized by wind speeds and reported as the dimensionless pressure coefficients according to Eq. 1. The pressure coefficients were found to be consistent and did not show significant variations with respect to the magnitude of wind speed or model sizes. The average C_p values were calculated from the 4 to 9 data sets and reported as the final C_p values for each test case.

WIND TUNNEL TEST RESULTS

Exposed Geomembrane Cover. The measured wind pressure coefficient profiles are plotted in Figure 4 for the smooth and rough geomembranes with wind blowing toward the 3H:1V slope and Figure 5 for the smooth geomembrane with wind blowing toward the 4H:1V slope. In the remainder text of this paper, C_p values are reported as absolute values and the context of the value (i.e., downward or uplift pressure) is made clear. The test results indicate that:

- The windward side slope (i.e., the slope facing toward the wind) was initially under downward pressure. The rest of the model was under uplift pressure.
- The maximum uplift pressures occurred near the slope crests with peaks on both the windward and leeward (i.e., the slope facing away from the wind) side slopes.
- For the smooth geomembrane:

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- When the 3H:1V was on the windward side, the measured maximum uplift C_p values were 1.24 near the crest of the 3H:1V slope and 1.15 near the crest of the 4H:1V slope;
- When the 4H:1V slope was on the windward side, the measured maximum uplift C_p values were 1.13 near the crest of the 4H:1V slope and 1.34 near the crest of the 3H:1V slope; and
- The measured maximum uplift C_p value for 3H:1V slope is approximately 10% greater than that for 4H:1V slope.

- For the rough "studded" geomembrane:
  - For the case of the 3H:1V slope on the windward side, the three models with different sizes yielded reasonably consistent results, indicating that the measured C_p values can be considered independent on the model scale. The average measured maximum uplift C_p values were 0.60 near the crest of the 3H:1V slope and 0.40 near the crest of the 4H:1V slope; and
  - The measured uplift C_p values were significantly lower than those for the smooth geomembrane, indicating that wind uplift pressure decreased as the surface roughness of the cover increased.

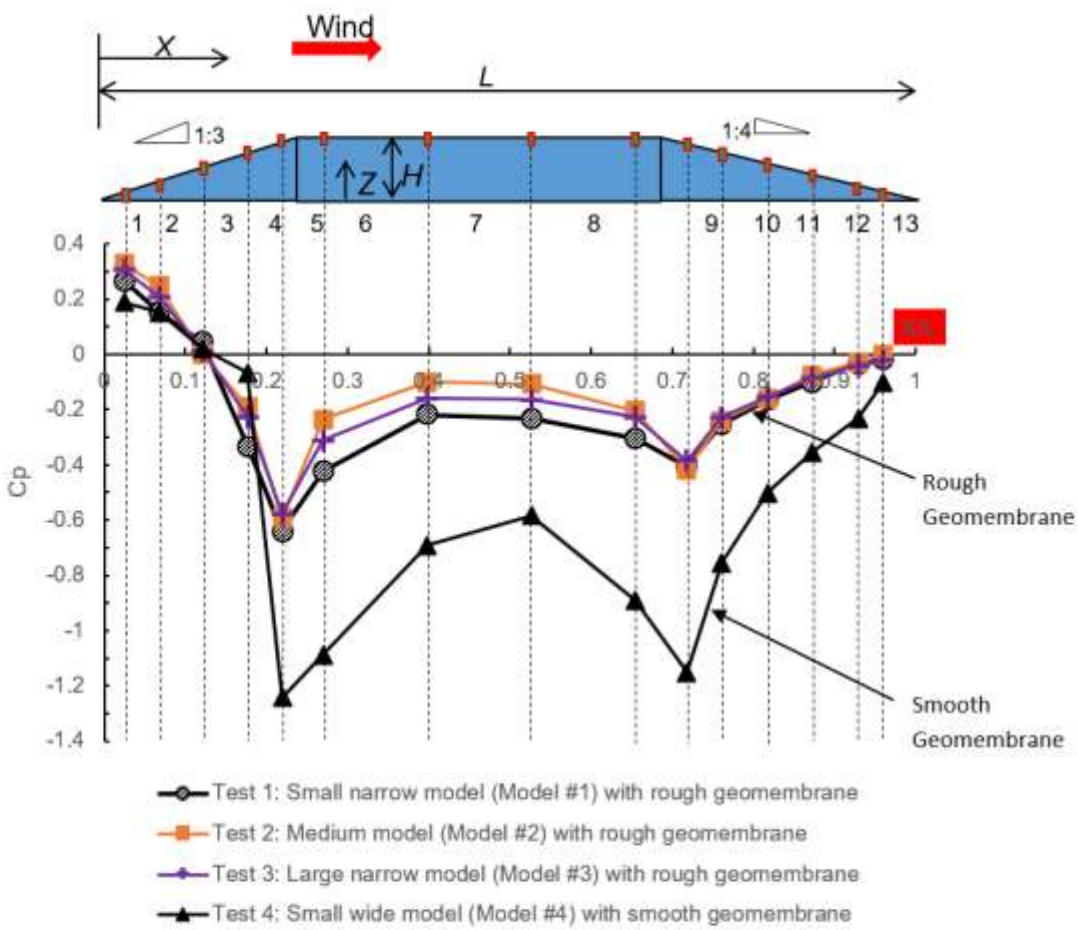

Figure 4. Measured C_p profiles of exposed smooth and rough geomembrane covers. (wind toward 3H:1V slope)

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Giroud et al. (1995) proposed a solution of wind-generated uplift coefficient for geomembrane, which was denoted as the suction factor for design of any slope based on the critical leeward slope. In this solution, the suction factors were recommended to be 1.0 in the top deck of a slope, 0.85 in the top third of a slope, 0.70 in the middle third of a slope and 0.55 in the lower third of a slope. The average suction factor on a slope was 0.70. This solution was later modified (Perera et al. 2011), where the suction factors were decreased by 23% based on field performance of exposed geomembrane covers (e.g., the maximum suction factor was decreased from 1.0 to 0.77 in the top deck of a slope). It should be noted that neither of these solutions accounted for variation in surface roughness of geomembrane nor the slope ratio. With respect to the maximum uplift pressure coefficient, both the original and modified solutions by Giroud and Perera are within the range of coefficients measured in this study. The values of the original solution are closer to these measured for the smooth geomembrane and the values of the modified solution are closer to these measured for the rough, "studded" geomembrane.

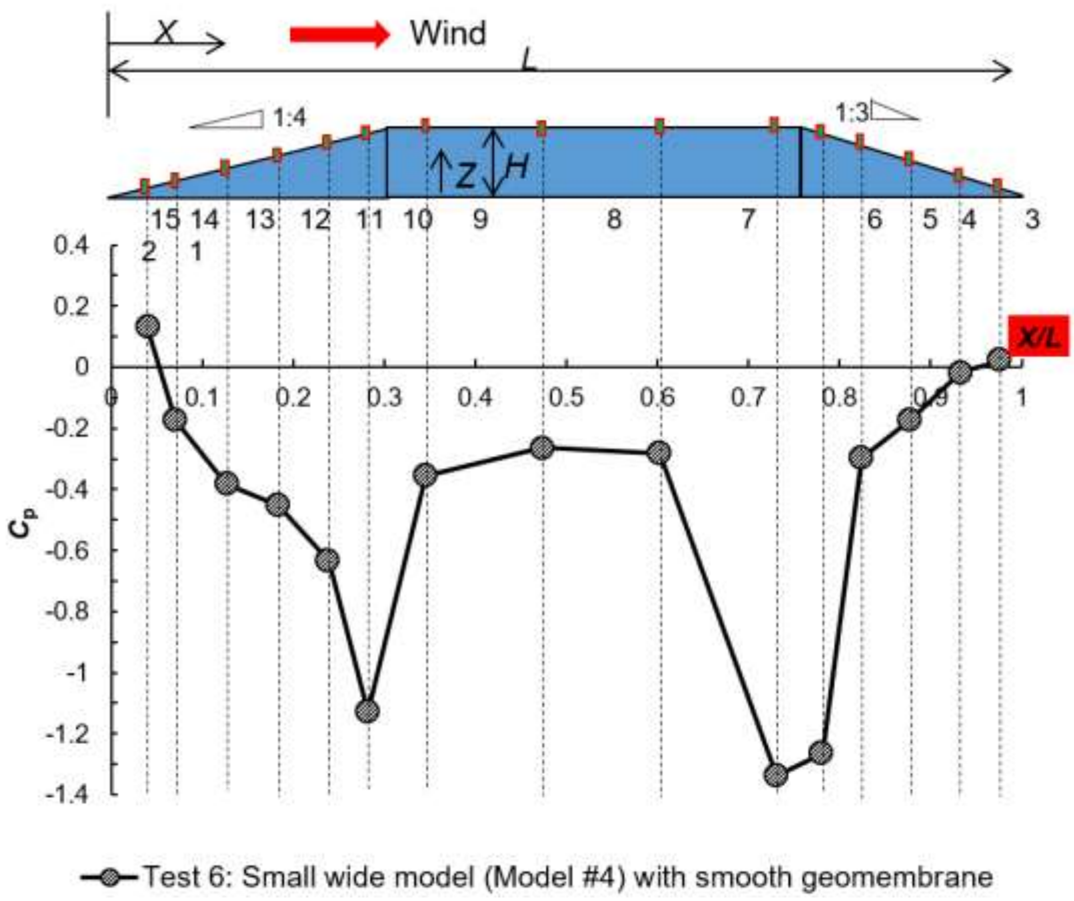

Figure 5. Measured C_p profiles of exposed smooth geomembrane cover. (wind toward 4H:1V slope)

ClosureTurf Engineered Turf Cover. The measured wind pressure coefficient profiles are plotted in Figure 6 for the ClosureTurf engineered turf cover with wind blowing toward the 3H:1V slope and Figure 7 with wind blowing toward the 4H:1V slope. The test results indicate that:

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- Approximately half of the windward side slope was under downward pressure and the rest of the model was under uplift pressure.
- The maximum uplift pressures occurred on the top near the crest of the windward side slope. The second peak near the crest of the leeward side slope was much smaller than that near the crest of the windward side slope.
- For the case of the 3H:1V slope on the windward side, the four models with different sizes yielded reasonably consistent results, indicating that the measured C_p values can be considered independent on the model scale. The average measured maximum uplift C_p value was 0.38 near the crest of the 3H:1V slope and 0.25 near the crest of the 4H:1V slope. These values are approximately 65% of those for the rough, "studded" exposed geomembrane cover and 25% of those for the smooth exposed geomembrane cover.
- When the 4H:1V slope was on the windward side, the measured maximum uplift C_p values were 0.29 near the crest of the 4H:1V slope and 0.18 near the crest of the 3H:1V slope, which are lower than those for the 3H:1V slope.

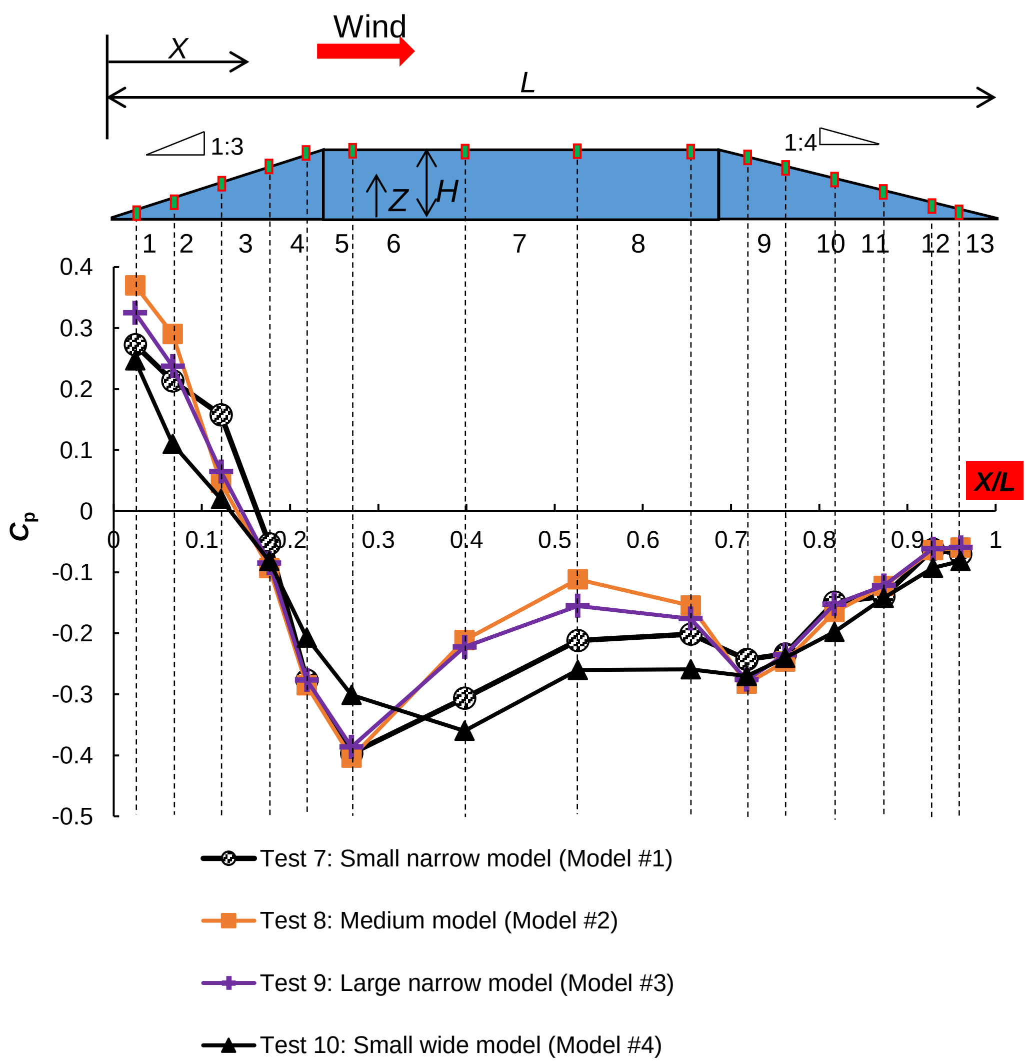

Figure 6. Measured C_p profiles of engineered turf cover. (wind toward 3H:1V slope)

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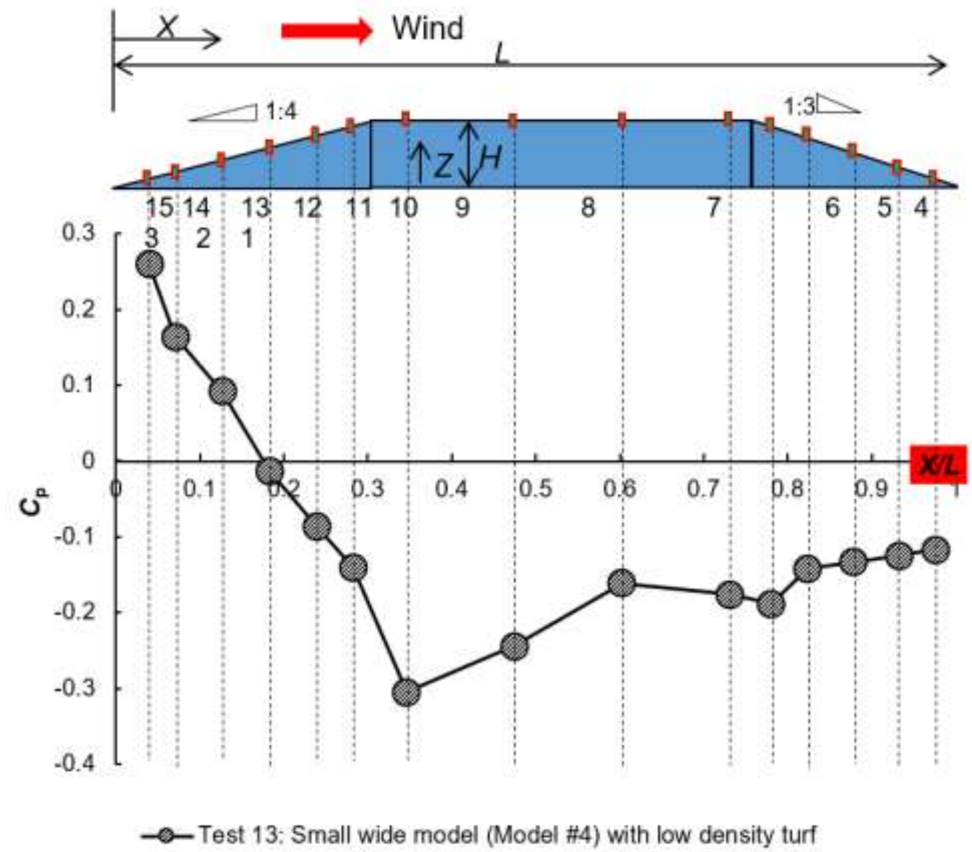

Figure 7. Measured C_P profiles of engineered turf cover. (wind toward 4H:1V slope)

Summary. The measured maximum wind uplift pressure coefficients are summarized in Table 1 below.

Table 1. Measured maximum wind uplift pressure coefficients. (compared with Giroud's solutions)

Cover Type	3H:1V Slope (This study)	4H:1V Slope (This study)	Giroud's Solution	Modified Giroud's Solution
Smooth Exposed Geomembrane Cover	1.24	1.13	1.0	0.77
Rough, "Studded" Exposed Geomembrane Cover	0.60	N/A		
ClosureTurf Engineered Turf Cover	0.38	0.29	N/A	N/A

EXAMPLE WIND UPLIFT CALCULATIONS OF ENGINEERED TURF COVER

A hypothetical landfill located in Ames, Iowa will be closed with the ClosureTurf engineered turf cover, which consists of (from bottom to top) a structured geomembrane, an engineered synthetic turf, and a 0.5-in (12.7-mm) thick sand infill. The landfill is 50 ft (15.24 m) high with a 3H:1V side slope. The design wind speed was assumed to be 83 mph (121.73 ft/s) or 133.58

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km/h (37.10 m/s) for Ames, Iowa based on ASCE 7-16 (https://hazards.atcouncil.org/#/). This corresponds to the 3-second gust speed at 32.8 ft (or 10 m) elevation in open terrain, U_3(32.8ft) or U_3(10m), with a mean recurrence interval (MRI) of 25 years.

Li et al. (2020) presented a detailed study on using the 3-second gust speed divided by a conversion factor to account for the uplift resistance provided by the temporary suction developed below the geomembrane as it is being uplifted. The conversion factor ranges from 1.23 to 1.75 based on varying tropical cyclone conditions and averaging periods (1 minute to 1 hour) (Harper et al. 2008). An example calculation was presented in Li's paper that used the 60-minute (i.e., hourly) average wind speed in the design of the anchor system for an exposed geomembrane cover. To obtain the 60-minute average wind speed, the 3-second gust speed was reduced by a conversion factor of 1.75 that corresponded to an in-land, roughly open terrain.

For the example calculation presented in this paper, the mean hourly wind speed at 32.8-ft (or 10-m) elevation, U(32.8ft) or U(10m), is conservatively calculated from the 3-second gust speed, U_3(32.8ft), using a factor of 1.5 for an open terrain (Vickery and Skerlj 2005):

$$U(32.8\text{ft}) = U_3(32.8\text{ft}) / 1.5 = 121.73\text{ ft/s} / 1.5 = 81.15\text{ ft/s (English Units)}$$

$$U(10\text{m}) = U_3(10\text{m}) / 1.5 = 37.10\text{ m/s} / 1.5 = 24.73\text{ m/s (SI Units)}$$

Using U(32.8 ft) or U(10m) as the reference, the mean hourly wind speed at top of the landfill, U(H) with H = 50 ft (15.24 m), is calculated using Eq. 2:

$$\frac{U(H)}{U(32.8\text{ ft})} = \left(\frac{H}{32.8\text{ ft}}\right)^{0.14};\ \frac{U(H)}{81.15\text{ ft/s}} = \left(\frac{50\text{ ft}}{32.8\text{ ft}}\right)^{0.14};\ U(H) = 86.08\text{ ft/s (English Units)}$$

$$\frac{U(H)}{U(10\text{ m})} = \left(\frac{H}{10\text{ m}}\right)^{0.14};\ \frac{U(H)}{24.73\text{ m/s}} = \left(\frac{15.24\text{ m}}{10\text{ m}}\right)^{0.14};\ U(H) = 26.23\text{ m/s (SI Units)}$$

The maximum mean wind uplift pressure is calculated according to Eq. 1 using the maximum uplift C_p value of 0.38 for a 3H:1V slope:

$$P_{max} = C_p \times 0.5\rho U(H)^2 = 0.38 \times 0.5 \times 0.00237 \times 86.08^2 = 3.34\text{ psf (English Units)}$$

$$P_{max} = C_p \times 0.5\rho U(H)^2 = 0.38 \times 0.5 \times 1.225 \times 26.23^2 = 160.14\text{ N/m}^2\text{ (SI Units)}$$

The weight of the ClosureTurf engineered turf cover per unit area is about 5.4 psf (258.6 N/m^2) with a 0.5-in (12.7-mm) thickness of sand infill. The factor of safety (FS) for wind uplift is calculated to be 1.6 (i.e., 5.4 psf/3.34 psf or 258.6 N/m^2/160.14 N/m^2) for the assumed landfill cross section. Therefore, the engineered turf cover is considered to have adequate wind resistance under the design wind loads. If a higher design wind speed is used and the maximum uplift pressure exceeds the weight per unit area of engineered turf cover, further calculations may be required to evaluate whether the tension induced by the wind loads is acceptable; or thicker sand infill, anchor trenches or other means can be used to further secure/ballast the cover. Note that these additional measures would only be needed in those portions of the cover where the predicted FS is deemed not adequate.

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CONCLUSION

The wind tunnel study is presented that was carried out to evaluate wind uplift of the exposed geomembrane and ClosureTurf engineered turf landfill covers. The wind tunnel tests were performed on scaled slope models with different slope ratios, surface roughness, and wind speeds. The test results showed that:

- The wind-induced uplift pressure is mainly affected by the surface roughness of the cover. The measured maximum uplift pressure coefficient decreases as the roughness increases from smooth geomembrane to rough “studded” geomembrane to rougher engineered turf. The measured maximum uplift pressure coefficient values for the engineered turf cover are approximately 60% of those for the rough, “studded” exposed geomembrane cover and 30% of those for the smooth exposed geomembrane cover, which demonstrates the effect of the engineered synthetic turf layer on protecting the underlying geomembrane from wind uplift.
- The wind pressure is also affected by the slope ratio. Compared with a 4H:1V slope, the measured maximum uplift pressure coefficient values of a 3H:1V slope increase by approximately 10% and 30%, respectively, for the smooth exposed geomembrane and engineered turf covers; and
- The distributions of the measured wind pressure coefficients have been found to be reasonably consistent with respect to varying wind speeds and model sizes, which confirms that the dimensionless coefficients measured on small-scale models tested under wind speeds in the wind tunnel facility can be scaled up and used for full-scale landfill cross section subject to higher design wind speeds.

The wind pressure coefficient profiles presented in this paper can be used to evaluate whether the geosynthetic landfill covers, i.e., the exposed geomembrane and engineered turf covers, have sufficient resistance against wind uplift under the selected design wind speed.

ACKNOWLEDGEMENT

This study was funded by Watershed Geosynthetics. The authors want to thank Hantao He and Zhen Zhang of Iowa State University and Carl Davis of Watershed Geosynthetics for helping with building the test models and performing the wind tunnel tests, and Dr. Rudolph Bonaparte of Geosyntec Consultants and Dr. Bryan Scholl of Watershed Geosynthetics for providing technical view of the wind tunnel test report.

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ATTACHMENT D2
AMENDMENT #1

ASCE 7-15 (http://hazards.atcouncil.org/#/

25-year		80	mph	=	117.36 ft/s
	33	ft	3-second gust speed height - need to check from ASCE 7-16		
	Uplift Resistance				
U(1.5)		1.5		78.24 ft/s	Mean Hourly Windspeed

$$\frac{U(H)}{U(\text{3s Gust Speed Height})} = \left(\frac{H}{(\text{3s Gust Speed Height})}\right)^{0.14}$$

H =	225	Height of Landfill	
U(H) =	Wind Speed at height of Landfill		
U(H)	=	102.36 ft/s	@U(1.5)

C_p =	0.29	-Wind Pressure Coefficient - 4:1 slope (windward), 3:1 slope (leeward)
ρ=	0.00237	slug/ft3 air density @ 15C

P_{max} =	mean wind uplift pressure		
P_{max} =	3.60	psf	@U(1.5)

Closure Turf cover per unit area = 5.4 psf

Factor of Safety

FS=	1.50	@U(1.5)

Attachment E

ClosureTurf Integrity Study

Revision 1 – 4/15/22

ATTACHMENT E
AMENDMENT #1

INTERFACE DIRECT SHEAR TEST RESULTS

ATTACHMENT E
AMENDMENT #1

40mil Textured LLDPE to Turf
Peak Friction Angle of 23 Degrees

(1)

$$\sigma_n = \frac{W \cos\alpha}{4A} \quad (1)$$

α =	14	degrees
σ_n =		
W =	8000	lbs
A=	78.53982	in^2

where:

α = the slope angle;

σ_n = contact normal stress between the tire and sand;

W = total gravity force of equipment; and

A = contact area between a tire and sand layer.

(2) $\sigma_n = \frac{8000\cos\alpha}{4*78.54}$ = 25.5 cosα

Flat	α =	0	σ_n =	25.5
4:1 Slope	α =	14	σ_n =	24.74254
3:1 Slope	α =	18.4	σ_n =	24.19634
2:1 Slope	α =	26.6	σ_n =	22.80093

Assuming: (i) the tire-soil contact area is approximately equivalent to a 10 inch diameter circular area and (ii) the total weight of a RTCE is 8000 lbs, then the contact normal stress in the unit of psi is:

$$\sigma_n = \frac{8000\cos\alpha}{4(3.14)(5^2)} = 25.5\cos\alpha \quad (2)$$

(3)

α =	14	degrees	0.244346	radians	
σ_n =	24.74254				
δ =	23	degrees	0.401426	radians	-Lab Results from Agru
W =	8000				
A=	78.53982				

FS = 1.7

$$FS = \frac{A\sigma_n \tan\delta}{0.25(W)\sin\alpha} \quad (3)$$

where:

α = the slope angle;

σ_n = contact normal stress between the tire and sand;

δ = the peak friction angle of the Closure Turf system;

W = total gravity force of equipment; and

A = contact area between a tire and sand layer.

(4)

α =	14	degrees		0.244346	radians
δ =	23	degrees	From Agru testing	0.401426	radians

FS= 1.7

Substituting Equation (1) into (3), Equation (3) is reduced to:

$$FS = \frac{\tan\delta}{\tan\alpha} \quad (4)$$

40mil Textured LLDPE to Turf
Peak Friction Angle of 20.5 Degrees

(1)

$$\sigma_n = \frac{W \cos \alpha}{4A} \quad (1)$$

α =	14	degrees
σ_n =		
W =	8000	lbs
A=	78.53982	in^2

where:

α = the slope angle;

σ_n = contact normal stress between the tire and sand;

W = total gravity force of equipment; and

A = contact area between a tire and sand layer.

(2) $\sigma_n = \frac{8000\cos\alpha}{4*78.54} = 25.5 \cos\alpha$

Flat	α =	0	σ_n =	25.5
4:1 Slope	α =	14	σ_n =	24.74254
3:1 Slope	α =	18.4	σ_n =	24.19634
2:1 Slope	α =	26.6	σ_n =	22.80093

Assuming: (i) the tire-soil contact area is approximately equivalent to a 10 inch diameter circular area and (ii) the total weight of a RTCE is 8000 lbs, then the contact normal stress in the unit of psi is:

$$\sigma_n = \frac{8000\cos\alpha}{4(3.14)(5^2)} = 25.5\cos\alpha \quad (2)$$

(3)

α =	14	degrees	0.244346	radians	
σ_n =	24.74254				
δ =	20.5	degrees	0.357792	radians	-Lab Results from Agru
W =	8000				
A=	78.53982				

FS = 1.5

$$FS = \frac{A\sigma_n \tan\delta}{0.25(W)\sin\alpha} \quad (3)$$

where:

α = the slope angle;

σ_n = contact normal stress between the tire and sand;

δ = the peak friction angle of the Closure Turf system;

W = total gravity force of equipment; and

A = contact area between a tire and sand layer.

(4)

α =	14	degrees		0.244346	radians
δ =	20.5	degrees	From Agru testing	0.357792	radians

FS= 1.5

Substituting Equation (1) into (3), Equation (3) is reduced to:

$$FS = \frac{\tan\delta}{\tan\alpha} \quad (4)$$

40mil Textured LLDPE to Turf
Peak Friction Angle of 19 Degrees

(1)

$$\sigma_n = \frac{W \cos\alpha}{4A} \quad (1)$$

α =	14	degrees
σ_n =		
W =	8000	lbs
A=	78.53982	in^2

where:

α = the slope angle;

σ_n = contact normal stress between the tire and sand;

W = total gravity force of equipment; and

A = contact area between a tire and sand layer.

(2) σ_n = $\frac{8000\cos\alpha}{4*78.54}$ = 25.5 cosα

Flat	α =	0	σ_n =	25.5
4:1 Slope	α =	14	σ_n =	24.74254
3:1 Slope	α =	18.4	σ_n =	24.19634
2:1 Slope	α =	26.6	σ_n =	22.80093

Assuming: (i) the tire-soil contact area is approximately equivalent to a 10 inch diameter circular area and (ii) the total weight of a RTCE is 8000 lbs, then the contact normal stress in the unit of psi is:

$$\sigma_n = \frac{8000\cos\alpha}{4(3.14)(5^2)} = 25.5\cos\alpha \quad (2)$$

(3)

α =	14	degrees	0.244346	radians	
σ_n =	24.74254				
δ =	19	degrees	0.331613	radians	-Lab Results from Agru
W =	8000				
A=	78.53982				

FS = 1.4

$$FS = \frac{A\sigma_n \tan\delta}{0.25(W)\sin\alpha} \quad (3)$$

where:

α = the slope angle;

σ_n = contact normal stress between the tire and sand;

δ = the peak friction angle of the Closure Turf system;

W = total gravity force of equipment; and

A = contact area between a tire and sand layer.

(4)

α =	14	degrees		0.244346	radians
δ =	19	degrees	From Agru testing	0.331613	radians

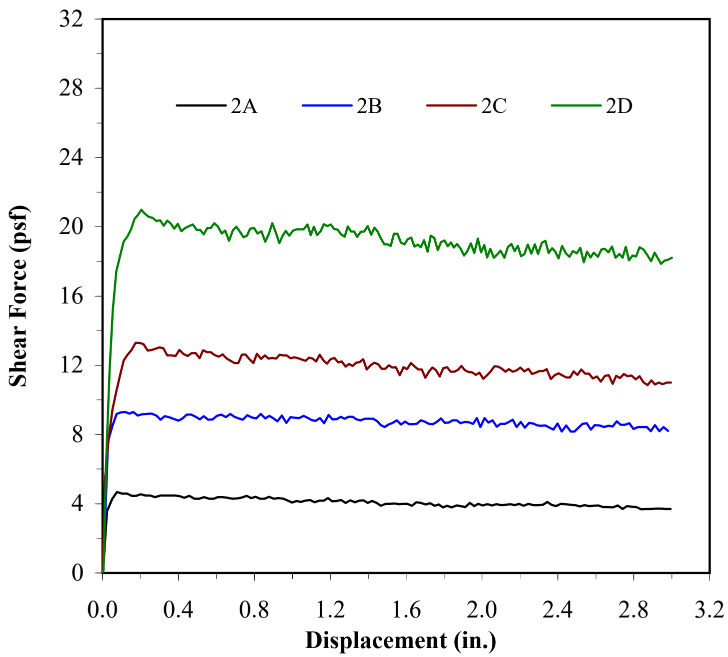
FS= 1.4

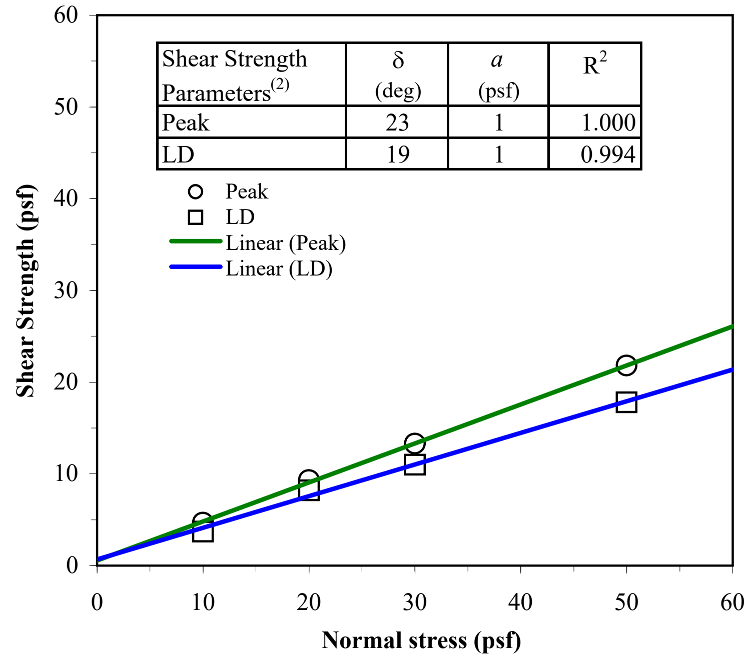
Substituting Equation (1) into (3), Equation (3) is reduced to:

$$FS = \frac{\tan\delta}{\tan\alpha} \quad (4)$$

WATERSHED GEOSYNTHETICS LLC
INTERFACE DIRECT SHEAR TESTING (ASTM D 5321)

Upper Shear Box: Concrete sand
CT32 Synthetic Turf with base geotextile side down against
Agru 40-mil Microspike LLDPE geomembrane with dull side up
Lower Shear Box: Concrete sand





Test No.	Shear Box Size (in. x in.)	Normal Stress (psf)	Shear Rate (in./min)	Soaking Stress (psf)	Soaking Time (hour)	Consolidation Stress (psf)	Consolidation Time (hour)	Lower Soil γ_d (pcf)	Lower Soil ω_i (%)	Lower Soil ω_f (%)	Upper Soil γ_d (pcf)	Upper Soil ω_i (%)	Upper Soil ω_f (%)	Soil Shear Strength ϕ (deg)	Soil Shear Strength c (psf)	Shear Strengths τ_P (psf)	Shear Strengths τ_{LD} (psf)	Failure Mode
2A	12 x 12	10	0.04	10	24	-	-	-	-	-	-	-	-	-	-	4.7	3.7	(1)
2B	12 x 12	20	0.04	20	24	-	-	-	-	-	-	-	-	-	-	9.3	8.2	(1)
2C	12 x 12	30	0.04	30	24	-	-	-	-	-	-	-	-	-	-	13.3	11.0	(1)
2D	12 x 12	50	0.04	50	24	-	-	-	-	-	-	-	-	-	-	21.8	17.8	(1)

NOTES:
(1) Sliding (i.e., shear failure) occurred at the interface between the geotextile side of heavy closure turf and the dull side of agru 40-mil microspike LLDPE geomembrane.
(2) The reported total-stress parameters of friction angle and adhesion were determined from a best-fit line drawn through the test data. Caution should be exercised in using these strength parameters for applications involving normal stresses outside the range of the stresses covered by the test series. The large-displacement (LD) shear strength was calculated using the shear force measured at the end of the test.

DATE OF TEST:	5/6/2019
FIGURE NO.	1
PROJECT NO.	SGI19014
DOCUMENT NO.	
FILE NO.	

SGI TESTING SERVICES, LLC

Attachment I

Hydrologic **Evaluation of Landfill**

Performance (HELP) Model Analysis

Revision 1 – 4/15/22

HELP Model Comparison
Engineered Turf / Traditional Cover

Rev. 0 - November 2021

Rev. 1 - April 2022

Prepared by:

CTI and Associates, Inc.
34705 West 12 Mile Rd, Suite 230
Farmington Hills, MI 48331
Phone: (248) 560-0725

CALCULATION SHEET

		Project No.:			
Client:	US Ecology – Wayne Disposal	Calculated By:	BME	Date:	4/7/22
Project:	Engineered Turf Equivalency Demonstration Report	Checked By:	JLM	Date:	4/8/22
Calculation	HELP Model – Cover Comparison	Approved By:		Date:	

Table of Contents

Attachments

CALCULATION SHEET

		Project No.:			
Client:	US Ecology – Wayne Disposal	Calculated By:	BME	Date:	4/7/22
Project:	Engineered Turf Equivalency Demonstration Report	Checked By:	JLM	Date:	4/8/22
Calculation	HELP Model – Cover Comparison	Approved By:		Date:	

1.0 Objective

CTI and Associates has prepared this report to demonstrate the hydrologic equivalency of engineered turf to the traditional cover system requirements specified by 40 Code of Federal Regulations (CFR) §264.310 which in part requires the final cover to in part

- Provide long-term minimization of migration of liquids through the closed landfill
- Promote drainage of the cover
- Have a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present.

In addition to prescriptive requirements for the final cover over a hazardous waste landfill, Michigan Administrative Code R 299.9619(6)(a) also states the owner or operator can: Substitute an equivalent design which shall include a flexible membrane liner component with a minimum thickness of 1 mm (40 mil), depending on the type of material selected, and demonstrates to the director that it provides equivalent environmental protection.

ClosureTurf, which is an engineered turf designed to be used for landfill cover systems, already includes the 40 mil minimum geomembrane. It is the most developed and tested of the commercially available engineered turf products and is the subject of this comparison. Other aspects of environmental protection can be demonstrated through various performance demonstrations. To demonstrate the hydrologic performance of ClosureTurf, the Hydrologic Evaluation of Landfill Performance (HELP) Model, was used to compare the amount of percolation through the cover system expected for each system.

2.0 Final Cover Comparison Methodology

The HELP Model was developed by USEPA specifically to compare the hydrologic performance of different cover designs while considering a variety of environmental, soil, and design variables (Schroeder et al., 1994). Version 4.0.1 was used for this evaluation. The results of the HELP Model provide a detailed look at daily, monthly, and annual contact water amounts expected to be generated for a given cover design. Therefore, the efficacy of each cover evaluated can be directly compared by the amount of contact water generated. A detailed engineering manual discussing the basis for the model is available online at the following location: https://www.epa.gov/land-research/hydrologic-evaluation-landfill-performance-help-model. Updated information on version 4.0 from USEPA used in this analysis can be found here: https://www.epa.gov/land-research/hydrologic-evaluation-landfill-performance-help-model.

2.1. HELP Model Parameters

The HELP Model requires four different types of climate data to execute including: evapotranspiration, precipitation, temperature, and solar radiation. Each data group is based on a specific location and can either be synthetically generated using the HELP Model or manually entered. For this analysis, the most important parameter is precipitation because it directly correlates to the amount of contact water generated. For all four groups, the program was used to generate 100 years of synthetic data based on the default database associated with the closest weather station to the site, Detroit Metro Airport, which is approximately 12 miles east of the site. The synthetic precipitation data was back checked with the National Oceanic and Atmospheric Administration's (NOAA) Summary of Monthly Normals for precipitation to determine if the actual climate values were consistent with the model data. It was determined that they were in good agreement for purposes of this analysis. This comparison is included in the calculations in Attachment A.

The remaining model parameters included site geometry and material characteristics. A standard of one acre was used for each analysis. Representative slope lengths and grades were also used as depicted in the summary Tables 1 and 2. With the exception of the cover system materials modeled, all other inputs into the model were held constant to facilitate a fair comparison. For purposes of the comparison, each final cover system was input into the model and the amount of contact water measured after 100 years was compared. The model presents peak daily results and average annual results over the 100-year simulation period. Input parameters are included in the output files contained in Attachments B1 and B2. Climate data are included in Attachment C.

2.2. Model Assumptions

The following assumptions were made in performing the HELP Model Analysis. For reference, the HELP Model User's Guide For Version 4 can be found online at: https://www.epa.gov/land-research/help-40-user-manual.

- The geosynthetics materials are assumed to be constructed with good quality workmanship and in accordance with the project CQA Plan. An industry standard defect area of 0.0001 m^2 was assumed in the analysis with a placement quality of "good". This represents one pinhole-type defect and four pinhole installation defects per acre. Both designs include a 40 mil geomembrane underlain by a GCL. Geomembrane hydraulic conductivity was modeled as $4.0x10^{-13}$ cm/sec while GCL hydraulic conductivity was modeled as $3.0x10^{-9}$ cm/sec

- The initial water contents of all layers were manually set equal to the default HELP specified field capacity of the material, which represents the water content of the material after a prolonged period of gravity drainage. However, it should be noted that for the purpose of calculating hydraulic flow through the landfill system, the HELP Model conservatively assumes that all barrier layers (final cover barrier layer) are saturated.

- The HELP Model was utilized to synthetically generate temperature, precipitation, evapotranspiration, and solar radiation data based on Detroit Metro, Michigan. The evaporative zone depth was conservatively reduced from the default value based on the given cover system.

- The HELP Model results are independent of the landfill area. A one acre area was considered for the analysis. Therefore, cover system leakage results are presented as cubic feet per acre per time period (annual or daily). Results were converted to gallons per acre per time period using the conversion factor listed below:

$$\frac{ft^3}{time\ period} \times \frac{7.48\ gallons}{ft^3} \times \frac{time\ period}{\#\ of\ days}$$

2.3. Standard Soil Cover System Material Textures

Cover materials for the OAC prescribed Standard Soil Cover System used in the HELP Model were modeled as follows:

- The Infiltration Layer was modeled consistent with past analyses as follows:
  - Porosity: 0.471
  - Wilting Point: 0.21
  - Saturated Hydraulic Conductivity: 5.0×10^{-4} cm/sec.
- The geocomposite drainage Layer was modeled as HELP default texture 20 with effective saturated hydraulic conductivity of 10 cm/s.

2.4. Engineered Turf Cover System Material Textures

The engineered turf was modeled as recommended by the manufacturer of ClosureTurf and based on the published characteristics of the materials.

- The sand infill material was modeled as follows:
  - Porosity: 0.437
  - Wilting Point: 0.024
  - Saturated Hydraulic Conductivity: 2.5×10^{-2} cm/sec
- The lateral drainage characteristics were modeled with an effective Saturated Hydraulic Conductivity of 31.6 cm/s.

3.0 Results

The HELP model output files for the required and proposed cover systems are provided in Appendix B. The key results of the HELP Model comparison depicting the hydraulic performance of each cover system are included in Table 1 and Table 2 below. Note that these results are presented for comparative purposes and may not represent accurate estimates of actual leakage through the constructed cover system.

CALCULATION SHEET

Client:	US Ecology – Wayne Disposal	Project No.:	
Project:	Engineered Turf Equivalency Demonstration Report	Calculated By: BME	Date: 4/7/22
Calculation	HELP Model – Cover Comparison	Checked By: JLM	Date: 4/8/22
		Approved By:	Date:

Table 1: Rainfall/Runoff/Infiltration of standard cover system versus Engineered Turf Cover System

Final Cover Systems	Slope	Slope Length (ft)	Average Annual Precipitation (in)	Average Annual Runoff (in)	Average Annual Perc. Through Membrane (in)
Rule Required Cover System	4%	625	31.7	3.037	4E-6
Engineered Turf	4%	625	31.7	8.0	1E-6
Rule Required Cover System	25%	200	31.7	2.225	4E-6
Engineered Turf	25%	820	31.7	7.9	1E-6

Table 2: Hydraulic Performance of the Rule Required Cover System versus Engineered Turf Cover System

Final Cover Systems	Slope	Slope Length (ft)	Average Daily Leakage Rate (Gal/Acre/Day)	Peak Daily Leakage Rate (Gal/Acre/Day)	Average Annual Leakage Rate (Gal/Acre/Year)
Rule Required Cover System	4%	625	3.3E-4	3.1E-5	0.12
Engineered Turf	4%	625	8.1E-5	4.4E-4	0.03
Rule Required Cover System	25%	200	3.0E-4	2.0E-5	0.11
Engineered Turf	25%	820	8.6E-5	2.3E-4	0.03

4.0 CONCLUSIONS

The results in Table 1 and Table 2 provide a side-by-side comparison of the 40 CFR §264.310 rule required design standard versus engineered turf which shows that the proposed alternate cover system will result in similar rates and sheds much more water than a traditional cover system. Although percolation rates are mathematically different, this likely is due to limitations in the model for handling such small values relative to the overall resolution of the model. In any case, it shows that both cover systems allow for negligible flow through the geosynthetic composite cover. From a hydrologic standpoint, the proposed alternate material meets the criteria for being at least as protective to the environment as the rule required cover system.

Attachment A
Final Cover Comparison Calculations

28001 Cabot Dr.
Novi, MI 48377
Tel. (248) 486-5100

USE/WDI

Final Cover Comparison
2021 WDI Permit Mod

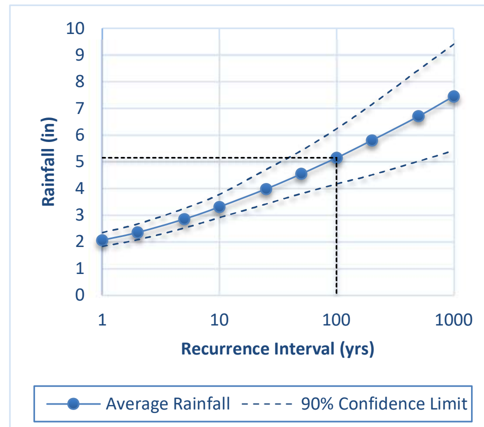
JOB	**1208070066**		
SHT NO	**1**	OF	**3**
CALC BY	**JLM**	DATE	**10/03/21**
CHK BY	**XZ**	DATE	

Review climate data for the site and determine total normal precip, monthly extreme values, and 100 yr/24 hr storm based on local NOAA Data

National Environmental Satellite, Data, and Information Service: Climate Normals 1981-2010
Station Data: DETROIT MET. AIRPORT, MI US USW00094847 Lat 42.2313° N Long -83.3308° W

Normal Precipitation

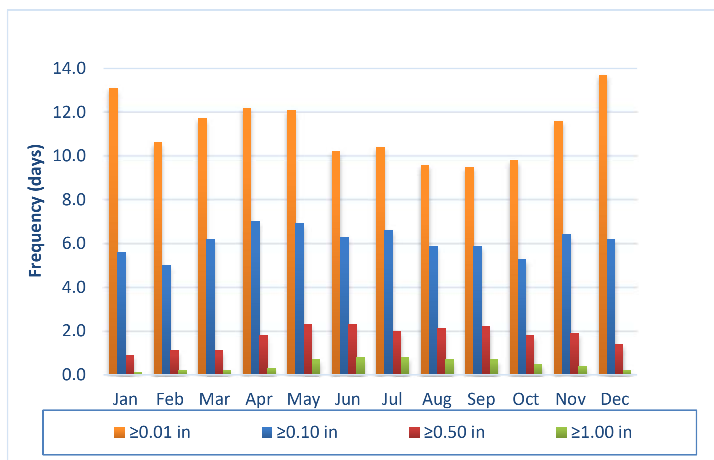
Month	Rainfall (in)	Snowfall (in)	Extreme Daily Rainfall.* (in)	Extreme Daily Rainfall.* Year	24-hr Storm Duration Rainfall: Recurrence Interval (yr)	24-hr Storm Duration Rainfall: Precip. (in)
Jan	1.96	12.5	2.06	11/2020		0
Feb	2.02	10.2	2.41	09/1876	1	2.06
Mar	2.28	6.9	1.97	30/2017	2	2.35
Apr	2.90	1.7	3.58	20/2000	5	2.85
May	3.38	0.0	2.56	26/1968	10	3.31
Jun	3.52	0.0	3.07	06/1903	25	3.98
Jul	3.37	0.0	4.74	31/1925	50	4.55
Aug	3.00	0.0	4.57	11/2014	100	5.15
Sep	3.27	0.0	3.71	11/2000	200	5.8
Oct	2.52	0.1	3.29	Mar-54	500	6.71
Nov	2.79	1.5	2.59	22/1909	1000	7.45
Dec	2.46	9.6	2.17	21/1967		
Year	33.47	42.50				



*Extreme data from 1874 through 2021

Frequency Distribution for Daily Precipitation (1981-2010)

Mth/Rain	≥0.01 in	≥0.10 in	≥0.50 in	≥1.00 in
Jan	13.1	5.6	0.9	0.1
Feb	10.6	5.0	1.1	0.2
Mar	11.7	6.2	1.1	0.2
Apr	12.2	7.0	1.8	0.3
May	12.1	6.9	2.3	0.7
Jun	10.2	6.3	2.3	0.8
Jul	10.4	6.6	2.0	0.8
Aug	9.6	5.9	2.1	0.7
Sep	9.5	5.9	2.2	0.7
Oct	9.8	5.3	1.8	0.5
Nov	11.6	6.4	1.9	0.4
Dec	13.7	6.2	1.4	0.2
Year	134.5	73.3	20.9	5.6



28001 Cabot Dr.
Novi, MI 48377
Tel. (248) 486-5100

USE/WDI

Final Cover Comparison
2021 WDI Permit Mod

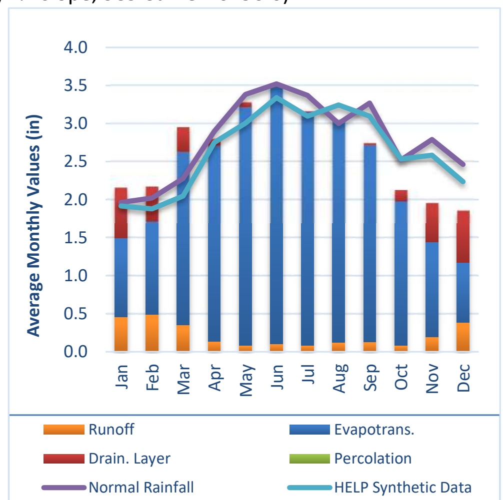
JOB	**1208070066**		
SHT NO	**2**	OF	**3**
CALC BY	**JLM**	DATE	**10/03/21**
CHK BY	**XZ**	DATE	

Compare climate data and HELP model results. Determine average daily precipitation, stormwater runoff, and leachate generation due to percolation through the infiltration layer based on HELP model data.

HELP Model Average Monthly Precipitation & Leachate Data

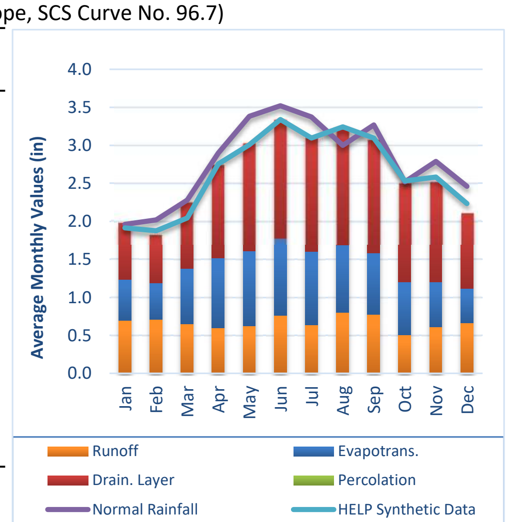
HELP Model - 100 yrs of Synthetic Weather Data - (Permitted Cover System, 1 Acre, 625 ft/4% slope, SCS Curve No. 90.0)

Average Month	Rainfall in	Runoff in	Evapotrans. in	Evap. Zone in	Drain. Layer in	Percolation in
Jan	1.91	0.457	1.038	0.344	0.660	0.000
Feb	1.88	0.488	1.217	0.332	0.464	0.000
Mar	2.05	0.350	2.274	0.305	0.327	0.000
Apr	2.76	0.137	2.564	0.283	0.092	0.000
May	3.01	0.083	3.125	0.275	0.067	0.000
Jun	3.34	0.101	3.386	0.268	0.013	0.000
Jul	3.10	0.084	3.059	0.258	0.016	0.000
Aug	3.24	0.124	2.912	0.267	0.007	0.000
Sep	3.10	0.128	2.582	0.280	0.030	0.000
Oct	2.53	0.084	1.890	0.293	0.149	0.000
Nov	2.58	0.196	1.245	0.322	0.514	0.000
Dec	2.24	0.387	0.790	0.340	0.678	0.000
Year	31.73	2.62	26.08		3.02	0.000
Peak Daily	2.40	2.20			0.342	0.000



HELP Model - 100 yrs of Synthetic Weather Data - (CT Cover System, 1 Acre, 625 ft/4% slope, SCS Curve No. 96.7)

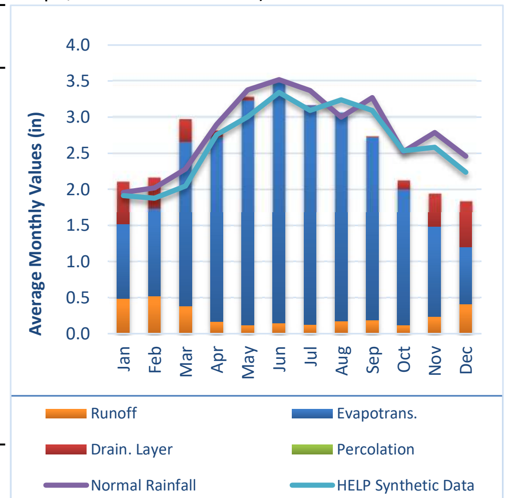
Average Month	Rainfall in	Runoff in	Evapotrans. in	Evap. Zone in	Drain. Layer in	Percolation in
Jan	1.91	0.698	0.536	0.130	0.750	0.000
Feb	1.88	0.707	0.481	0.100	0.637	0.000
Mar	2.05	0.655	0.726	0.088	0.871	0.000
Apr	2.76	0.597	0.923	0.080	1.223	0.000
May	3.01	0.624	0.986	0.076	1.419	0.000
Jun	3.34	0.762	1.008	0.079	1.569	0.000
Jul	3.10	0.640	0.964	0.076	1.496	0.000
Aug	3.24	0.800	0.894	0.075	1.550	0.000
Sep	3.10	0.777	0.811	0.072	1.487	0.000
Oct	2.53	0.505	0.697	0.073	1.299	0.000
Nov	2.58	0.612	0.586	0.081	1.320	0.000
Dec	2.24	0.664	0.449	0.111	0.998	0.000
Year	31.73	8.04	9.06		14.62	0.000
Peak Daily	2.4	2.44			0.591	0.000



	USE/WDI	
28001 Cabot Dr. Novi, MI 48377 **Tel. (248) 486-5100**	Final Cover Comparison 2021 WDI Permit Mod	JOB **1208070066** SHT NO **3** OF **3** CALC BY **JLM** DATE **10/03/21** CHK BY **XZ** DATE

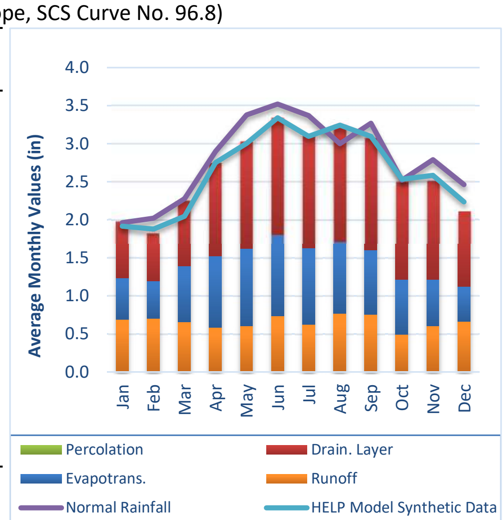
HELP Model - 100 yrs of Synthetic Weather Data - (Permit Cover System, 1 Acre, 200 ft/4:1 slope, SCS Curve No. 90.9)

Average Month	Rainfall in	Runoff in	Evapotrans. in	Evap. Zone in	Drain. Layer in	Percolation in
Jan	1.91	0.486	1.037	0.350	0.585	0.000
Feb	1.88	0.519	1.217	0.339	0.430	0.000
Mar	2.05	0.383	2.272	0.311	0.316	0.000
Apr	2.76	0.169	2.552	0.288	0.090	0.000
May	3.01	0.122	3.105	0.279	0.052	0.000
Jun	3.34	0.149	3.357	0.272	0.009	0.000
Jul	3.10	0.123	3.030	0.262	0.010	0.000
Aug	3.24	0.177	2.881	0.269	0.001	0.000
Sep	3.10	0.186	2.535	0.283	0.013	0.000
Oct	2.53	0.119	1.880	0.296	0.126	0.000
Nov	2.58	0.242	1.241	0.325	0.461	0.000
Dec	2.24	0.415	0.790	0.344	0.635	0.000
Year	31.73	3.09	25.90		2.73	0.000
Peak Daily	2.40	2.21			0.250	0.000



HELP Model - 100 yrs of Synthetic Weather Data - (CT Cover System, 1 Acre, 820 ft/4:1 slope, SCS Curve No. 96.8)

Average Month	Rainfall in	Runoff in	Evapotrans. in	Evap. Zone in	Drain. Layer in	Percolation in
Jan	1.91	0.693	0.542	0.344	0.749	0.000
Feb	1.88	0.705	0.486	0.332	0.632	0.000
Mar	2.05	0.653	0.736	0.305	0.867	0.000
Apr	2.76	0.586	0.939	0.283	1.222	0.000
May	3.01	0.602	1.020	0.275	1.407	0.000
Jun	3.34	0.733	1.068	0.268	1.537	0.000
Jul	3.10	0.622	1.001	0.258	1.477	0.000
Aug	3.24	0.768	0.945	0.267	1.531	0.000
Sep	3.10	0.754	0.848	0.280	1.473	0.000
Oct	2.53	0.496	0.721	0.293	1.283	0.000
Nov	2.58	0.603	0.609	0.322	1.300	0.000
Dec	2.24	0.663	0.461	0.340	0.990	0.000
Year	31.73	7.88	9.38		14.47	0.000
Peak Daily	2.40	2.44			0.642	0.000



Conclusions:

Overall, the HELP synthetic data correlates well with the available monthly climate normals data from NOAA. It underpredicts rainfall by a little over an inch. As the primary objective of the HELP model is to demonstrate the Engineered Turf cover system has an equivalent or better hydrologic performance compared to the permitted soil cover system, this HELP model is sufficient for comparison purposes.

The final cover comparison shows that the Engineered Turf barrier used in the alternate cover system prevents infiltration as effectively as the permitted cover which is to say the both effectively prevent infiltration when installed properly. The biggest difference as illustrated by the results is the soil component of the traditional cover holds a large portion of the surface water while the engineered turf sheds that water.

R 299.9619(6)(a) states the owner or operator can substitute an equivalent design which shall include a flexible membrane liner component with a minimum thickness of 1 mm (40 mil), depending on the type of material selected, and demonstrates to the director that it provides equivalent environmental protection. ClosureTurf includes the geomembrane, it also offers equivalent environmental protection as it relates surface water infiltration and percolation through the cover system.

Attachment B1
Rule Required Cover System HELP Model Output

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

Title:	MC Cell VI-F&G Rule Req. Cover	Simulated On:	4/7/2022 21:57

Layer 1
Type 1 - Vertical Percolation Layer (Cover Soil)
WDI Veg/Infiltration Layer
Material Texture Number 43

Thickness	=	36	inches
Porosity	=	0.471	vol/vol
Field Capacity	=	0.342	vol/vol
Wilting Point	=	0.21	vol/vol
Initial Soil Water Content	=	0.3411	vol/vol
Effective Sat. Hyd. Conductivity	=	1.00E-04	cm/sec

Layer 2
Type 2 - Lateral Drainage Layer
Drainage Net (0.5 cm)
Material Texture Number 20

Thickness	=	0.2	inches
Porosity	=	0.85	vol/vol
Field Capacity	=	0.01	vol/vol
Wilting Point	=	0.005	vol/vol
Initial Soil Water Content	=	0.0113	vol/vol
Effective Sat. Hyd. Conductivity	=	1.00E+01	cm/sec
Slope	=	25	%
Drainage Length	=	200	ft

Layer 3
Type 4 - Flexible Membrane Liner
HDPE Membrane
Material Texture Number 35

Thickness	=	0.04	inches
Effective Sat. Hyd. Conductivity	=	2.00E-13	cm/sec
FML Pinhole Density	=	1	Holes/Acre
FML Installation Defects	=	4	Holes/Acre
FML Placement Quality	=	3	Good

Layer 4
Type 3 - Barrier Soil Liner

CL - Clay Loam (Moderate)
Material Texture Number 25

Thickness	=	36	inches
Porosity	=	0.437	vol/vol
Field Capacity	=	0.373	vol/vol
Wilting Point	=	0.266	vol/vol
Initial Soil Water Content	=	0.437	vol/vol
Effective Sat. Hyd. Conductivity	=	3.60E-06	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	=	90.9	
Fraction of Area Allowing Runoff	=	100	%
Area projected on a horizontal plane	=	1	acres
Evaporative Zone Depth	=	16	inches
Initial Water in Evaporative Zone	=	5.219	inches
Upper Limit of Evaporative Storage	=	7.536	inches
Lower Limit of Evaporative Storage	=	3.36	inches
Initial Snow Water	=	0	inches
Initial Water in Layer Materials	=	28.015	inches
Total Initial Water	=	28.015	inches
Total Subsurface Inflow	=	0	inches/year

Note: SCS Runoff Curve Number was calculated by HELP.

Evapotranspiration and Weather Data

Station Latitude	=	42.18	Degrees
Maximum Leaf Area Index	=	3.5	
Start of Growing Season (Julian Date)	=	90	days
End of Growing Season (Julian Date)	=	216	days
Average Wind Speed	=	9	mph
Average 1st Quarter Relative Humidity	=	70	%
Average 2nd Quarter Relative Humidity	=	72	%
Average 3rd Quarter Relative Humidity	=	80	%
Average 4th Quarter Relative Humidity	=	77	%

Note: Evapotranspiration data was obtained for Belleville, Michigan

Normal Mean Monthly Precipitation (inches)

Jan/Jul	Feb/Aug	Mar/Sep	Apr/Oct	May/Nov	Jun/Dec
1.913949	1.878746	2.045516	2.755274	3.005731	3.34107
3.096216	3.243099	3.096181	2.533399	2.583786	2.235743

Note: Precipitation was simulated based on HELP V4 weather simulation for:
Lat/Long: 42.18/-83.49

Normal Mean Monthly Temperature (Degrees Fahrenheit)

Jan/Jul	Feb/Aug	Mar/Sep	Apr/Oct	May/Nov	Jun/Dec
29.7	30.4	42.7	54.8	68.5	78.1
81.5	79	68.8	56.2	44	31.5

Note: Temperature was simulated based on HELP V4 weather simulation for:
Lat/Long: 42.18/-83.49
Solar radiation was simulated based on HELP V4 weather simulation for:
Lat/Long: 42.18/-83.49

Average Annual Totals Summary

Title: MC Cell VI-F&G Rule Req. Cover
Simulated on: 4/7/2022 22:02

	Average Annual Totals for Years 1 - 100*			
	(inches)	[std dev]	(cubic feet)	(percent)
Precipitation	31.73	[3.35]	115,175.2	100.00
Runoff	3.037	[1.286]	11,025.3	9.57
Evapotranspiration	25.683	[2.72]	93,229.4	80.95
Subprofile1				
Lateral drainage collected from Layer 2	3.0027	[1.3809]	10,899.9	9.46
Percolation/leakage through Layer 4	0.000004	[0.000002]	0.0145	0.00
Average Head on Top of Layer 3	0.0001	[0.0001]	---	---
Water storage				
Change in water storage	0.0057	[0.8045]	20.6	0.02

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

Peak Values Summary

Title: MC Cell VI-F&G Rule Req. Cover
Simulated on: 4/7/2022 22:02

	Peak Values for Years 1 - 100*	
	(inches)	(cubic feet)
Precipitation	2.40	8,721.4
Runoff	2.224	8,073.1
Subprofile1		
Drainage collected from Layer 2	0.2831	1,027.7
Percolation/leakage through Layer 4	0.000000	0.0010
Average head on Layer 3	0.0042	---
Maximum head on Layer 3	0.0085	---
Location of maximum head in Layer 2	0.00	(feet from drain)
Other Parameters		
Snow water	4.1439	15,042.2
Maximum vegetation soil water	0.4307	(vol/vol)
Minimum vegetation soil water	0.2100	(vol/vol)

Final Water Storage in Landfill Profile at End of Simulation Period

Title: MC Cell VI-F&G Rule Req. Cover
Simulated on: 4/7/2022 22:02
Simulation period: 100 years

	Final Water Storage	
Layer	(inches)	(vol/vol)
1	12.8492	0.3569
2	0.0022	0.0109
3	0.0000	0.0000
4	15.7320	0.4370
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: Rule Cover System_MinSlope **Simulated On:** 4/8/2022 15:06

Layer 1
Type 1 - Vertical Percolation Layer (Cover Soil)
WDI Veg/Infiltration Layer
Material Texture Number 43

Thickness	=	36	inches
Porosity	=	0.471	vol/vol
Field Capacity	=	0.342	vol/vol
Wilting Point	=	0.21	vol/vol
Initial Soil Water Content	=	0.3428	vol/vol
Effective Sat. Hyd. Conductivity	=	1.00E-04	cm/sec

Layer 2
Type 2 - Lateral Drainage Layer
Drainage Net (0.5 cm)
Material Texture Number 20

Thickness	=	0.2	inches
Porosity	=	0.85	vol/vol
Field Capacity	=	0.01	vol/vol
Wilting Point	=	0.005	vol/vol
Initial Soil Water Content	=	0.0104	vol/vol
Effective Sat. Hyd. Conductivity	=	1.00E+01	cm/sec
Slope	=	25	%
Drainage Length	=	200	ft

Layer 3
Type 4 - Flexible Membrane Liner
HDPE Membrane
Material Texture Number 35

Thickness	=	0.04	inches
Effective Sat. Hyd. Conductivity	=	2.00E-13	cm/sec
FML Pinhole Density	=	1	Holes/Acre
FML Installation Defects	=	4	Holes/Acre
FML Placement Quality	=	3	Good

Layer 4
Type 3 - Barrier Soil Liner

CL - Clay Loam (Moderate)
Material Texture Number 25

Thickness	=	36	inches
Porosity	=	0.437	vol/vol
Field Capacity	=	0.373	vol/vol
Wilting Point	=	0.266	vol/vol
Initial Soil Water Content	=	0.437	vol/vol
Effective Sat. Hyd. Conductivity	=	3.60E-06	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	=	86.5	
Fraction of Area Allowing Runoff	=	100	%
Area projected on a horizontal plane	=	1	acres
Evaporative Zone Depth	=	16	inches
Initial Water in Evaporative Zone	=	5.219	inches
Upper Limit of Evaporative Storage	=	7.536	inches
Lower Limit of Evaporative Storage	=	3.36	inches
Initial Snow Water	=	0	inches
Initial Water in Layer Materials	=	28.075	inches
Total Initial Water	=	28.075	inches
Total Subsurface Inflow	=	0	inches/year

Note: SCS Runoff Curve Number was calculated by HELP.

Evapotranspiration and Weather Data

Station Latitude	=	42.18	Degrees
Maximum Leaf Area Index	=	3.5	
Start of Growing Season (Julian Date)	=	90	days
End of Growing Season (Julian Date)	=	216	days
Average Wind Speed	=	9	mph
Average 1st Quarter Relative Humidity	=	70	%
Average 2nd Quarter Relative Humidity	=	72	%
Average 3rd Quarter Relative Humidity	=	80	%
Average 4th Quarter Relative Humidity	=	77	%

Note: Evapotranspiration data was obtained for Belleville, Michigan

Normal Mean Monthly Precipitation (inches)

Jan/Jul	Feb/Aug	Mar/Sep	Apr/Oct	May/Nov	Jun/Dec
1.913949	1.878746	2.045516	2.755274	3.005731	3.34107
3.096216	3.243099	3.096181	2.533399	2.583786	2.235743

Note: Precipitation was simulated based on HELP V4 weather simulation for:
Lat/Long: 42.18/-83.49

Normal Mean Monthly Temperature (Degrees Fahrenheit)

Jan/Jul	Feb/Aug	Mar/Sep	Apr/Oct	May/Nov	Jun/Dec
29.7	30.4	42.7	54.8	68.5	78.1
81.5	79	68.8	56.2	44	31.5

Note: Temperature was simulated based on HELP V4 weather simulation for:
Lat/Long: 42.18/-83.49
Solar radiation was simulated based on HELP V4 weather simulation for:
Lat/Long: 42.18/-83.49

Average Annual Totals Summary

Title: Rule Cover System_MinSlope
Simulated on: 4/8/2022 15:11

	Average Annual Totals for Years 1 - 100*			
	(inches)	[std dev]	(cubic feet)	(percent)
Precipitation	31.73	[3.35]	115,175.2	100.00
Runoff	2.225	[1.235]	8,075.2	7.01
Evapotranspiration	26.078	[2.81]	94,664.5	82.19
Subprofile1				
Lateral drainage collected from Layer 2	3.4207	[1.5505]	12,417.0	10.78
Percolation/leakage through Layer 4	0.000004	[0.000002]	0.0162	0.00
Average Head on Top of Layer 3	0.0001	[0.0001]	---	---
Water storage				
Change in water storage	0.0051	[0.8178]	18.4	0.02

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

Peak Values Summary

Title: Rule Cover System_MinSlope
Simulated on: 4/8/2022 15:11

	Peak Values for Years 1 - 100*		
	(inches)		(cubic feet)
Precipitation	2.40		8,721.4
Runoff	2.224		8,073.0
Subprofile1			
Drainage collected from Layer 2	0.4261		1,546.9
Percolation/leakage through Layer 4	0.000000		0.0015
Average head on Layer 3	0.0064		---
Maximum head on Layer 3	0.0128		---
Location of maximum head in Layer 2	0.00	(feet from drain)	
Other Parameters			
Snow water	4.1439		15,042.2
Maximum vegetation soil water	0.4414	(vol/vol)	
Minimum vegetation soil water	0.2100	(vol/vol)	

Final Water Storage in Landfill Profile at End of Simulation Period

Title: Rule Cover System_MinSlope
Simulated on: 4/8/2022 15:11
Simulation period: 100 years

	Final Water Storage	
Layer	(inches)	(vol/vol)
1	12.8487	0.3569
2	0.0022	0.0109
3	0.0000	0.0000
4	15.7320	0.4370
Snow water	0.0000	---

Attachment B2
Engineered Turf Cover System HELP Model Output

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

Title: MC Cell VI-F&G Engineered Turf **Simulated On:** 10/7/2021 16:03

Layer 1
Type 1 - Vertical Percolation Layer (Cover Soil)
Engineered Turf
Material Texture Number 44

Thickness	=	0.5	inches
Porosity	=	0.437	vol/vol
Field Capacity	=	0.062	vol/vol
Wilting Point	=	0.024	vol/vol
Initial Soil Water Content	=	0.024	vol/vol
Effective Sat. Hyd. Conductivity	=	2.50E-02	cm/sec

Layer 2
Type 2 - Lateral Drainage Layer
Studded Drainage Layer
Material Texture Number 123

Thickness	=	0.13	inches
Porosity	=	0.85	vol/vol
Field Capacity	=	0.01	vol/vol
Wilting Point	=	0.005	vol/vol
Initial Soil Water Content	=	0.01	vol/vol
Effective Sat. Hyd. Conductivity	=	3.16E+01	cm/sec
Slope	=	25	%
Drainage Length	=	820	ft

Layer 3
Type 4 - Flexible Membrane Liner
HDPE Membrane
Material Texture Number 35

Thickness	=	0.04	inches
Effective Sat. Hyd. Conductivity	=	2.00E-13	cm/sec
FML Pinhole Density	=	1	Holes/Acre
FML Installation Defects	=	1	Holes/Acre
FML Placement Quality	=	3	Good

Layer 4
Type 3 - Barrier Soil Liner

Bentonite (High)
Material Texture Number 17

Thickness	=	0.5	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

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	=	96.8	
Fraction of Area Allowing Runoff	=	100	%
Area projected on a horizontal plane	=	1	acres
Evaporative Zone Depth	=	0.5	inches
Initial Water in Evaporative Zone	=	0.012	inches
Upper Limit of Evaporative Storage	=	0.218	inches
Lower Limit of Evaporative Storage	=	0.012	inches
Initial Snow Water	=	0	inches
Initial Water in Layer Materials	=	0.388	inches
Total Initial Water	=	0.388	inches
Total Subsurface Inflow	=	0	inches/year

Note: SCS Runoff Curve Number was calculated by HELP.

Evapotranspiration and Weather Data

Station Latitude	=	42.18	Degrees
Maximum Leaf Area Index	=	1	
Start of Growing Season (Julian Date)	=	90	days
End of Growing Season (Julian Date)	=	216	days
Average Wind Speed	=	9	mph
Average 1st Quarter Relative Humidity	=	70	%
Average 2nd Quarter Relative Humidity	=	72	%
Average 3rd Quarter Relative Humidity	=	80	%
Average 4th Quarter Relative Humidity	=	77	%

Note: Evapotranspiration data was obtained for Belleville, Michigan

Normal Mean Monthly Precipitation (inches)

Jan/Jul	Feb/Aug	Mar/Sep	Apr/Oct	May/Nov	Jun/Dec
1.913949	1.878746	2.045516	2.755274	3.005731	3.34107
3.096216	3.243099	3.096181	2.533399	2.583786	2.235743

Note: Precipitation was simulated based on HELP V4 weather simulation for:
Lat/Long: 42.18/-83.49

Normal Mean Monthly Temperature (Degrees Fahrenheit)

Jan/Jul	Feb/Aug	Mar/Sep	Apr/Oct	May/Nov	Jun/Dec
29.7	30.4	42.7	54.8	68.5	78.1
81.5	79	68.8	56.2	44	31.5

Note: Temperature was simulated based on HELP V4 weather simulation for:
Lat/Long: 42.18/-83.49
Solar radiation was simulated based on HELP V4 weather simulation for:
Lat/Long: 42.18/-83.49

Average Annual Totals Summary

Title: MC Cell VI-F&G Engineered Turf
Simulated on: 10/7/2021 16:09

	Average Annual Totals for Years 1 - 100*			
	(inches)	[std dev]	(cubic feet)	(percent)
Precipitation	31.73	[3.35]	115,175.2	100.00
Runoff	7.879	[1.761]	28,601.5	24.83
Evapotranspiration	9.378	[1.156]	34,041.5	29.56
Subprofile1				
Lateral drainage collected from Layer 2	14.4711	[1.3463]	52,530.2	45.61
Percolation/leakage through Layer 4	0.000001	[0]	0.0042	0.00
Average Head on Top of Layer 3	0.0008	[0.0001]	---	---
Water storage				
Change in water storage	0.0006	[0.5254]	2.1126	0.00

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

Peak Values Summary

Title: MC Cell VI-F&G Engineered Turf
Simulated on: 10/7/2021 16:10

	Peak Values for Years 1 - 100*	
	(inches)	(cubic feet)
Precipitation	2.40	8,721.4
Runoff	2.440	8,855.5
Subprofile1		
Drainage collected from Layer 2	0.6423	2,331.7
Percolation/leakage through Layer 4	0.000000	0.0000
Average head on Layer 3	0.0125	---
Maximum head on Layer 3	0.0250	---
Location of maximum head in Layer 2	0.00 (feet from drain)	
Other Parameters		
Snow water	4.1439	15,042.2
Maximum vegetation soil water	0.4370 (vol/vol)	
Minimum vegetation soil water	0.0240 (vol/vol)	

Final Water Storage in Landfill Profile at End of Simulation Period

Title: MC Cell VI-F&G Engineered Turf
Simulated on: 10/7/2021 16:10
Simulation period: 100 years

	Final Water Storage	
Layer	(inches)	(vol/vol)
1	0.0702	0.1404
2	0.0013	0.0100
3	0.0000	0.0000
4	0.3749	0.7499
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: MC Cell VI-F&G Engineered Turf **Simulated On:** 10/7/2021 16:47

Layer 1
Type 1 - Vertical Percolation Layer (Cover Soil)
Engineered Turf
Material Texture Number 44

Thickness	=	0.5	inches
Porosity	=	0.437	vol/vol
Field Capacity	=	0.062	vol/vol
Wilting Point	=	0.024	vol/vol
Initial Soil Water Content	=	0.024	vol/vol
Effective Sat. Hyd. Conductivity	=	2.50E-02	cm/sec

Layer 2
Type 2 - Lateral Drainage Layer
Studded Drainage Layer
Material Texture Number 123

Thickness	=	0.13	inches
Porosity	=	0.85	vol/vol
Field Capacity	=	0.01	vol/vol
Wilting Point	=	0.005	vol/vol
Initial Soil Water Content	=	0.01	vol/vol
Effective Sat. Hyd. Conductivity	=	3.16E+01	cm/sec
Slope	=	4	%
Drainage Length	=	625	ft

Layer 3
Type 4 - Flexible Membrane Liner
HDPE Membrane
Material Texture Number 35

Thickness	=	0.04	inches
Effective Sat. Hyd. Conductivity	=	2.00E-13	cm/sec
FML Pinhole Density	=	1	Holes/Acre
FML Installation Defects	=	1	Holes/Acre
FML Placement Quality	=	3	Good

Layer 4
Type 3 - Barrier Soil Liner

Bentonite (High)
Material Texture Number 17

Thickness	=	0.5	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

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	=	96.7	
Fraction of Area Allowing Runoff	=	100	%
Area projected on a horizontal plane	=	1	acres
Evaporative Zone Depth	=	0.5	inches
Initial Water in Evaporative Zone	=	0.012	inches
Upper Limit of Evaporative Storage	=	0.218	inches
Lower Limit of Evaporative Storage	=	0.012	inches
Initial Snow Water	=	0	inches
Initial Water in Layer Materials	=	0.388	inches
Total Initial Water	=	0.388	inches
Total Subsurface Inflow	=	0	inches/year

Note: SCS Runoff Curve Number was calculated by HELP.

Evapotranspiration and Weather Data

Station Latitude	=	42.18	Degrees
Maximum Leaf Area Index	=	1	
Start of Growing Season (Julian Date)	=	90	days
End of Growing Season (Julian Date)	=	216	days
Average Wind Speed	=	9	mph
Average 1st Quarter Relative Humidity	=	70	%
Average 2nd Quarter Relative Humidity	=	72	%
Average 3rd Quarter Relative Humidity	=	80	%
Average 4th Quarter Relative Humidity	=	77	%

Note: Evapotranspiration data was obtained for Belleville, Michigan

Normal Mean Monthly Precipitation (inches)

Jan/Jul	Feb/Aug	Mar/Sep	Apr/Oct	May/Nov	Jun/Dec
1.913949	1.878746	2.045516	2.755274	3.005731	3.34107
3.096216	3.243099	3.096181	2.533399	2.583786	2.235743

Note: Precipitation was simulated based on HELP V4 weather simulation for:
Lat/Long: 42.18/-83.49

Normal Mean Monthly Temperature (Degrees Fahrenheit)

Jan/Jul	Feb/Aug	Mar/Sep	Apr/Oct	May/Nov	Jun/Dec
29.7	30.4	42.7	54.8	68.5	78.1
81.5	79	68.8	56.2	44	31.5

Note: Temperature was simulated based on HELP V4 weather simulation for:
Lat/Long: 42.18/-83.49
Solar radiation was simulated based on HELP V4 weather simulation for:
Lat/Long: 42.18/-83.49

Average Annual Totals Summary

Title: MC Cell VI-F&G Engineered Turf
Simulated on: 10/7/2021 16:52

	Average Annual Totals for Years 1 - 100*			
	(inches)	[std dev]	(cubic feet)	(percent)
Precipitation	31.73	[3.35]	115,175.2	100.00
Runoff	8.042	[1.78]	29,191.4	25.35
Evapotranspiration	9.064	[1.106]	32,901.7	28.57
Subprofile1				
Lateral drainage collected from Layer 2	14.6223	[1.3618]	53,078.9	46.09
Percolation/leakage through Layer 4	0.000001	[0]	0.0040	0.00
Average Head on Top of Layer 3	0.0036	[0.0003]	---	---
Water storage				
Change in water storage	0.0009	[0.5232]	3.2043	0.00

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

Peak Values Summary

Title: MC Cell VI-F&G Engineered Turf
Simulated on: 10/7/2021 16:53

	Peak Values for Years 1 - 100*	
	(inches)	(cubic feet)
Precipitation	2.40	8,721.4
Runoff	2.440	8,855.5
Subprofile1		
Drainage collected from Layer 2	0.5917	2,147.8
Percolation/leakage through Layer 4	0.000000	0.0001
Average head on Layer 3	0.0517	---
Maximum head on Layer 3	0.1032	---
Location of maximum head in Layer 2	0.50 (feet from drain)	
Other Parameters		
Snow water	4.1439	15,042.2
Maximum vegetation soil water	0.4370 (vol/vol)	
Minimum vegetation soil water	0.0240 (vol/vol)	

Final Water Storage in Landfill Profile at End of Simulation Period

Title: MC Cell VI-F&G Engineered Turf
Simulated on: 10/7/2021 16:53
Simulation period: 100 years

	Final Water Storage	
Layer	(inches)	(vol/vol)
1	0.1003	0.2005
2	0.0013	0.0100
3	0.0000	0.0000
4	0.3750	0.7500
Snow water	0.0000	---

Attachment C
Climate Data Information

U.S. Department of Commerce
National Oceanic & Atmospheric Administration
National Environmental Satellite, Data, and Information Service

Summary of Monthly Normals
1981-2010
Generated on 10/03/2021

National Centers for Environmental Information
151 Patton Avenue
Asheville, North Carolina 28801

Current Location: Elev: 631 ft. Lat: 42.2313° N Lon: -83.3308° W
Station: **DETROIT METROPOLITAN AIRPORT, MI US USW00094847**

Temperature (°F)																						
Mean							Cooling Degree Days Base (above)						Heating Degree Days Base (above)				Mean Number of Days					
Month	Daily Max	Daily Min	Mean	Long Term Max Std Dev	Long Term Min Std Dev	Long Term Avg Std Dev	55	57	60	65	70	72	55	57	60	65	Max >= 100	Max >= 90	Max >= 50	Max <= 32	Min <= 32	Min <= 0
01	32.0	19.1	25.6	4.7	5.7	5.1	-7777	-7777	0	0	0	0	913	975	1068	1223	0.0	0.0	1.6	15.7	26.7	2.0
02	35.2	21.0	28.1	4.1	4.3	4.1	-7777	-7777	-7777	-7777	0	0	753	809	893	1033	0.0	0.0	2.0	10.6	24.3	0.8
03	45.8	28.6	37.2	3.8	3.0	3.3	6	4	2	-7777	-7777	0	558	618	709	862	0.0	0.0	10.3	3.5	20.3	-7777
04	59.1	39.4	49.2	3.1	2.4	2.6	47	34	20	6	1	-7777	220	266	342	479	0.0	0.0	23.8	0.1	5.6	0.0
05	69.9	49.4	59.7	3.8	3.4	3.5	186	145	97	42	13	7	42	63	108	208	0.0	0.4	30.7	0.0	0.2	0.0
06	79.3	59.5	69.4	2.7	2.4	2.4	434	376	291	167	75	50	2	4	9	35	-7777	2.4	30.0	0.0	0.0	0.0
07	83.4	63.9	73.6	2.7	2.3	2.3	578	516	423	271	137	95	0	-7777	-7777	2	-7777	4.5	31.0	0.0	0.0	0.0
08	81.4	62.6	72.0	2.7	2.6	2.6	527	465	373	225	103	68	-7777	-7777	1	8	0.0	2.5	31.0	0.0	0.0	0.0
09	74.0	54.7	64.4	2.8	1.9	2.2	294	244	175	84	29	16	14	23	44	104	0.0	0.5	30.0	0.0	0.0	0.0
10	61.6	43.3	52.4	3.0	2.8	2.8	69	49	27	8	2	1	148	190	261	397	0.0	0.0	27.3	0.0	1.9	0.0
11	48.8	34.3	41.5	3.7	2.9	3.1	8	4	1	-7777	0	0	412	468	555	704	0.0	0.0	13.2	0.9	12.5	0.0
12	36.1	24.1	30.1	5.1	5.2	5.0	1	-7777	-7777	0	0	0	773	834	927	1082	0.0	0.0	2.6	10.5	23.9	0.7
Summary	58.9	41.7	50.3	3.5	3.2	3.2	2150	1837	1409	803	360	237	3835	4250	4917	6137	0.0	10.3	233.5	41.3	115.4	3.5

-7777: a non-zero value that would round to zero

Empty or blank cells indicate data is missing or insufficient occurrences to compute value

U.S. Department of Commerce
National Oceanic & Atmospheric Administration
National Environmental Satellite, Data, and Information Service

Summary of Monthly Normals 1981-2010

Generated on 10/03/2021

National Centers for Environmental Information
151 Patton Avenue
Asheville, North Carolina 28801

Current Location: Elev: 631 ft. Lat: 42.2313° N Lon: -83.3308° W

Station: **DETROIT METROPOLITAN AIRPORT, MI US USW00094847**

Precipitation (in.)								
	Totals	**Mean Number of Days**				**Precipitation Probabilities Probability that precipitation will be equal to or less than the indicated amount**		
	Means	**Daily Precipitation**				**Monthly Precipitation vs. Probability Levels**		
Month	**Mean**	**>= 0.01**	**>= 0.10**	**>= 0.50**	**>= 1.00**	**0.25**	**0.50**	**0.75**
01	1.96	13.1	5.6	0.9	0.1	1.28	1.80	2.80
02	2.02	10.6	5.0	1.1	0.2	0.89	1.83	3.02
03	2.28	11.7	6.2	1.1	0.2	1.46	2.15	3.18
04	2.90	12.2	7.0	1.8	0.3	2.11	2.72	3.85
05	3.38	12.1	6.9	2.3	0.7	2.20	3.00	4.61
06	3.52	10.2	6.3	2.3	0.8	2.35	3.37	4.91
07	3.37	10.4	6.6	2.0	0.8	2.43	3.22	4.38
08	3.00	9.6	5.9	2.1	0.7	1.60	3.07	4.19
09	3.27	9.5	5.9	2.2	0.7	1.74	2.86	4.28
10	2.52	9.8	5.3	1.8	0.5	1.56	2.15	3.54
11	2.79	11.6	6.4	1.9	0.4	1.78	2.68	3.31
12	2.46	13.7	6.2	1.4	0.2	1.61	2.39	2.91
Summary	33.47	134.5	73.3	20.9	5.6	21.01	31.24	44.98

-7777: a non-zero value that would round to zero

Empty or blank cells indicate data is missing or insufficient occurrences to compute value

U.S. Department of Commerce
National Oceanic & Atmospheric Administration
National Environmental Satellite, Data, and Information Service

Summary of Monthly Normals
1981-2010
Generated on 10/03/2021

National Centers for Environmental Information
151 Patton Avenue
Asheville, North Carolina 28801

Current Location: Elev: 631 ft. Lat: 42.2313° N Lon: -83.3308° W
Station: **DETROIT METROPOLITAN AIRPORT, MI US USW00094847**

Snow (in.)												
	Totals	**Mean Number of Days**								**Snow Probabilities Probability that snow will be equal to or less than the indicated amount**		
	Means	**Snowfall >= Thresholds**					**Snow Depth >= Thresholds**			**Monthly Snow vs. Probability Levels Values derived from the incomplete gamma distribution.**		
Month	**Snowfall Mean**	**0.01**	**1.0**	**3.0**	**5.00**	**10.00**	**1**	**3**	**5**	**10**	**.25**	**.50**	**.75**
01	12.5	10.4	3.7	1.1	0.4	0.2	17.4	11.0	5.9	1.3	7.0	9.9	17.9
02	10.2	8.3	3.2	1.2	0.4	0.0	12.7	7.5	3.7	0.9	4.9	9.0	14.6
03	6.9	5.4	2.1	0.7	0.3	0.0	5.6	3.1	1.6	0.0	3.4	5.8	9.7
04	1.7	1.6	0.4	0.2	0.1	0.0	0.5	0.3	0.1	0.0	0.0	0.6	2.0
05	-7777	-7777	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
07	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
08	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
09	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.1	0.2	-7777	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	1.5	2.3	0.5	-7777	0.0	0.0	1.0	0.2	0.0	0.0	0.1	0.9	2.2
12	9.6	8.5	3.2	0.9	0.4	0.0	8.7	5.4	3.4	0.3	4.9	7.8	13.2
Summary	42.5	36.7	13.1	4.1	1.6	0.2	45.9	27.5	14.7	2.5	20.3	34.0	59.6

-7777: a non-zero value that would round to zero

Empty or blank cells indicate data is missing or insufficient occurrences to compute value

U.S. Department of Commerce
National Oceanic & Atmospheric Administration
National Environmental Satellite, Data, and Information Service

Summary of Monthly Normals
1981-2010

Generated on 10/03/2021

National Centers for Environmental Information
151 Patton Avenue
Asheville, North Carolina 28801

Current Location: Elev: 631 ft. Lat: 42.2313° N Lon: -83.3308° W

Station: **DETROIT METROPOLITAN AIRPORT, MI US USW00094847**

Growing Degree Units (Monthly)

Base	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
40	10	12	84	298	609	882	1043	992	731	390	132	21
45	3	3	41	185	456	732	888	837	581	254	66	9
50	1	1	17	100	310	582	733	682	433	144	26	3
55	-7777	-7777	6	47	186	434	578	527	294	69	8	1
60	0	-7777	2	20	97	291	423	373	175	27	1	-7777
Growing Degree Units for Corn (Monthly)												
50/86	3	6	48	163	352	576	713	671	449	202	57	8

Growing Degree Units (Accumulated Monthly)

Base	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
40	10	22	106	404	1013	1895	2938	3930	4661	5051	5183	5204
45	3	6	47	232	688	1420	2308	3145	3726	3980	4046	4055
50	1	2	19	119	429	1011	1744	2426	2859	3003	3029	3032
55	0	0	6	53	239	673	1251	1778	2072	2141	2149	2150
60	0	0	2	22	119	410	833	1206	1381	1408	1409	1409
Growing Degree Units for Corn (Monthly Accumulated)												
50/86	3	9	57	220	572	1148	1861	2532	2981	3183	3240	3248

Note: For corn, temperatures below 50 are set to 50, and temperatures above 86 are set to 86.

-7777: a non-zero value that would round to zero.

Empty or blank cells indicate data is missing or insufficient occurrences to compute value.

NOAA Atlas 14, Volume 8, Version 2 DETROIT METRO AP
Station ID: 20-2103
Location name: Detroit, Michigan, USA*
Latitude: 42.2314°, Longitude: -83.3308°
Elevation:
Elevation (station metadata): 631 ft**
* source: ESRI Maps
** source: USGS

POINT PRECIPITATION FREQUENCY ESTIMATES

Sanja Perica, Deborah Martin, Sandra Pavlovic, Ishani Roy, Michael St. Laurent, Carl Trypaluk, Dale Unruh, Michael Yekta, Geoffery Bonnin

NOAA, National Weather Service, Silver Spring, Maryland

PF_tabular | PF_graphical | Maps_&_aerials

PF tabular

PDS-based point precipitation frequency estimates with 90% confidence intervals (in inches)[1]

Duration	Average recurrence interval (years)									
	1	2	5	10	25	50	100	200	500	1000
5-min	0.312 (0.271-0.367)	0.369 (0.319-0.434)	0.463 (0.400-0.545)	0.543 (0.466-0.642)	0.656 (0.544-0.794)	0.745 (0.604-0.909)	0.835 (0.654-1.04)	0.929 (0.698-1.18)	1.06 (0.763-1.36)	1.15 (0.812-1.50)
10-min	0.457 (0.396-0.537)	0.540 (0.468-0.635)	0.678 (0.585-0.799)	0.795 (0.682-0.939)	0.960 (0.797-1.16)	1.09 (0.884-1.33)	1.22 (0.958-1.52)	1.36 (1.02-1.72)	1.55 (1.12-1.99)	1.69 (1.19-2.20)
15-min	0.557 (0.483-0.655)	0.658 (0.570-0.774)	0.827 (0.714-0.974)	0.970 (0.832-1.15)	1.17 (0.972-1.42)	1.33 (1.08-1.62)	1.49 (1.17-1.85)	1.66 (1.25-2.10)	1.88 (1.36-2.43)	2.06 (1.45-2.68)
30-min	0.764 (0.662-0.898)	0.902 (0.781-1.06)	1.13 (0.979-1.34)	1.33 (1.14-1.57)	1.61 (1.34-1.95)	1.83 (1.48-2.24)	2.05 (1.61-2.55)	2.29 (1.72-2.90)	2.60 (1.88-3.36)	2.85 (2.01-3.71)
60-min	0.974 (0.844-1.14)	1.15 (0.996-1.35)	1.45 (1.25-1.71)	1.70 (1.46-2.01)	2.07 (1.72-2.51)	2.36 (1.92-2.89)	2.66 (2.09-3.31)	2.97 (2.24-3.77)	3.40 (2.46-4.39)	3.73 (2.63-4.87)
2-hr	1.18 (1.03-1.38)	1.40 (1.22-1.63)	1.76 (1.53-2.06)	2.08 (1.79-2.44)	2.53 (2.11-3.05)	2.89 (2.36-3.51)	3.26 (2.58-4.04)	3.66 (2.77-4.61)	4.20 (3.06-5.39)	4.62 (3.28-5.98)
3-hr	1.31 (1.15-1.53)	1.55 (1.35-1.80)	1.95 (1.69-2.27)	2.29 (1.98-2.68)	2.80 (2.35-3.37)	3.20 (2.63-3.89)	3.63 (2.88-4.48)	4.08 (3.10-5.12)	4.70 (3.44-6.01)	5.19 (3.69-6.69)
6-hr	1.55 (1.36-1.79)	1.80 (1.58-2.08)	2.24 (1.96-2.60)	2.64 (2.29-3.06)	3.21 (2.72-3.85)	3.69 (3.05-4.45)	4.19 (3.35-5.14)	4.73 (3.63-5.91)	5.48 (4.04-6.97)	6.07 (4.36-7.78)
12-hr	1.80 (1.59-2.07)	2.06 (1.82-2.37)	2.53 (2.22-2.90)	2.94 (2.57-3.39)	3.57 (3.05-4.26)	4.09 (3.41-4.92)	4.65 (3.75-5.68)	5.26 (4.06-6.53)	6.11 (4.54-7.74)	6.80 (4.91-8.65)
24-hr	2.06 (1.83-2.35)	2.35 (2.08-2.67)	2.85 (2.52-3.25)	3.31 (2.91-3.78)	3.98 (3.42-4.71)	4.55 (3.81-5.42)	5.15 (4.17-6.24)	5.80 (4.51-7.15)	6.71 (5.02-8.44)	7.45 (5.42-9.41)
2-day	2.35 (2.10-2.66)	2.69 (2.40-3.04)	3.27 (2.90-3.70)	3.78 (3.34-4.29)	4.52 (3.89-5.29)	5.12 (4.30-6.04)	5.75 (4.68-6.90)	6.42 (5.02-7.85)	7.35 (5.54-9.16)	8.09 (5.93-10.2)
3-day	2.58 (2.31-2.90)	2.93 (2.62-3.30)	3.54 (3.15-3.99)	4.06 (3.60-4.60)	4.82 (4.16-5.61)	5.44 (4.58-6.38)	6.08 (4.96-7.25)	6.75 (5.30-8.21)	7.69 (5.81-9.53)	8.42 (6.20-10.5)
4-day	2.78 (2.49-3.12)	3.14 (2.82-3.53)	3.76 (3.36-4.23)	4.30 (3.82-4.85)	5.07 (4.38-5.88)	5.70 (4.81-6.66)	6.34 (5.19-7.55)	7.03 (5.53-8.52)	7.97 (6.04-9.85)	8.71 (6.43-10.9)
7-day	3.29 (2.97-3.67)	3.69 (3.32-4.12)	4.36 (3.91-4.88)	4.94 (4.41-5.54)	5.77 (5.00-6.64)	6.43 (5.45-7.46)	7.11 (5.84-8.40)	7.82 (6.18-9.41)	8.79 (6.70-10.8)	9.55 (7.09-11.8)
10-day	3.75 (3.39-4.17)	4.18 (3.77-4.65)	4.90 (4.41-5.46)	5.51 (4.93-6.16)	6.39 (5.55-7.31)	7.08 (6.02-8.18)	7.79 (6.42-9.15)	8.52 (6.76-10.2)	9.52 (7.28-11.6)	10.3 (7.68-12.7)
20-day	5.10 (4.63-5.62)	5.61 (5.09-6.19)	6.46 (5.84-7.14)	7.16 (6.44-7.95)	8.15 (7.11-9.23)	8.91 (7.62-10.2)	9.69 (8.02-11.3)	10.5 (8.35-12.4)	11.5 (8.87-14.0)	12.3 (9.26-15.1)
30-day	6.27 (5.71-6.89)	6.87 (6.25-7.56)	7.86 (7.13-8.65)	8.66 (7.82-9.57)	9.75 (8.53-11.0)	10.6 (9.07-12.0)	11.4 (9.47-13.2)	12.2 (9.78-14.4)	13.3 (10.3-16.0)	14.1 (10.6-17.2)
45-day	7.79 (7.12-8.53)	8.56 (7.81-9.37)	9.76 (8.88-10.7)	10.7 (9.70-11.8)	12.0 (10.5-13.4)	12.9 (11.1-14.6)	13.8 (11.5-15.8)	14.6 (11.7-17.2)	15.7 (12.1-18.8)	16.5 (12.5-20.0)
60-day	9.13 (8.36-9.96)	10.1 (9.20-11.0)	11.5 (10.5-12.6)	12.6 (11.4-13.8)	14.0 (12.3-15.6)	15.0 (12.9-16.9)	16.0 (13.3-18.2)	16.8 (13.5-19.6)	17.9 (13.8-21.3)	18.6 (14.1-22.5)

[1] Precipitation frequency (PF) estimates in this table are based on frequency analysis of partial duration series (PDS).

Numbers in parenthesis are PF estimates at lower and upper bounds of the 90% confidence interval. The probability that precipitation frequency estimates (for a given duration and average recurrence interval) will be greater than the upper bound (or less than the lower bound) is 5%. Estimates at upper bounds are not checked against probable maximum precipitation (PMP) estimates and may be higher than currently valid PMP values.

Please refer to NOAA Atlas 14 document for more information.

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