Wind-induced Uplift of Exposed Geomembrane Covers: Revised Design Methodology

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Presentation Outline

- Application of exposed geomembrane
- Conventional wind uplift design approach
- Recommended revision to wind uplift design approach
- Design example

INTRODUCTION

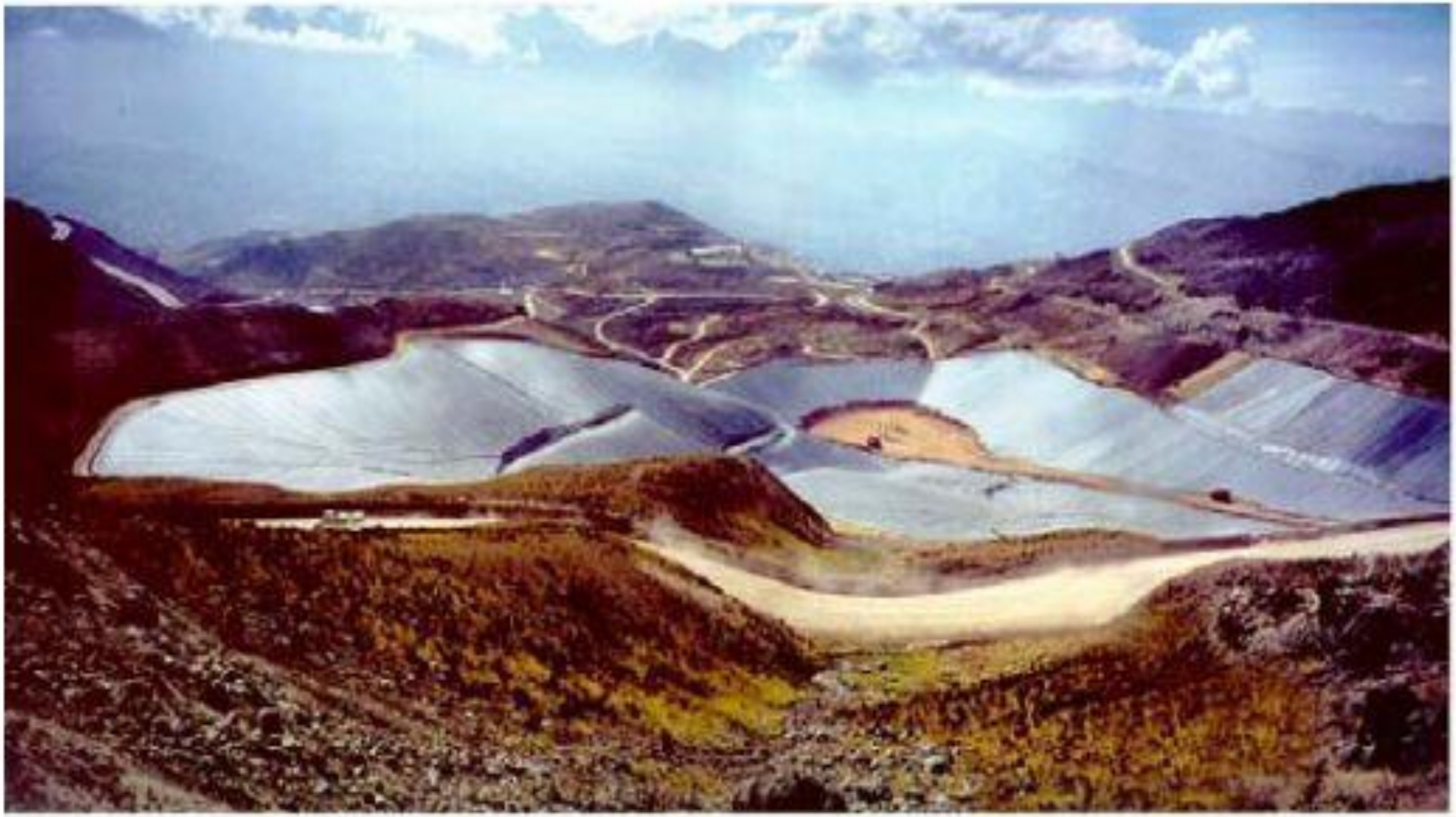
Exposed Geomembrane: Typical Applications

- Cover for landfill or other waste containment system

- Impoundment liner

- Channel liner

Exposed Geomembrane: Typical Applications



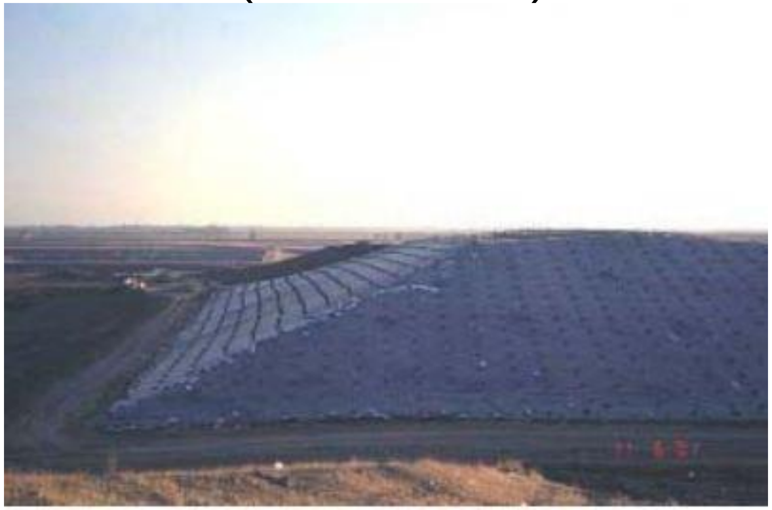
Evaporation Pond and Heap Leaching Pads (mining)

Exposed Geomembrane Covers (EGC)

Delaware Solid Waste Authority, DE 1997 (35-mil fPP)

Sabine Parish, LA 1999 (60-mil HDPE)

Polk County, FL 2001 (LLDPE)



Yolo County, CA 2001(R-fPP)

EGC: Pros and Cons

Advantages of EGCs

- Can be placed on steep slopes
- Light weight
- Can adapt to settlement
- Reduce hydraulic head on geomembrane barrier
- Less leachate generation potential than soil intermediate cover.
- No cover soil erosion
- Reduced operation and maintenance
  - Does not require mowing, tree removal, weeding/herbicide, frequent erosion damage repair, reseeding, sediment removal from SWM system
  - require only minor patching and seaming, sedimentation reaching the stormwater system from an EGC is minor
- Easier inspection and repair
- Lower cost (~30% of conventional cover)
- Good for future vertical expansion

Disadvantages of EGCs

- Shorter life
- Increased runoff volume and shorter stormwater detention time
- Typically only permitted as intermediate cover

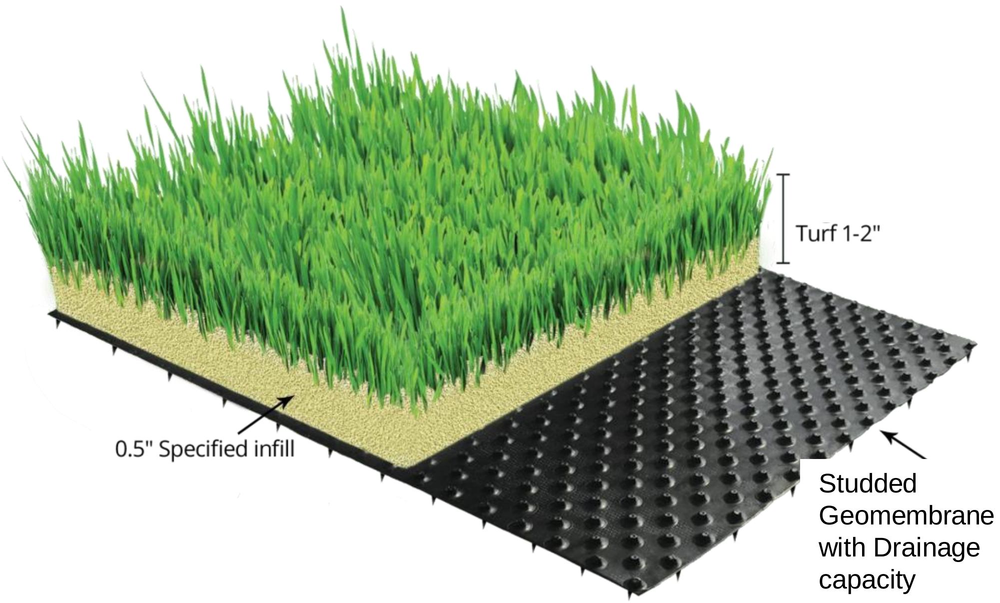
3

Key Issues with Exposed Geomembrane

- **Degradation due to UV exposure**
  - Carbon-black, antioxidants, and stabilizers added to GM
- **Damage due to Temperature Change**
  - Most types of geomembrane can handle high temperature well
  - HDPE is more prone to freeze/thaw cracking than more flexible LLDPE
- **Physical Damage: Puncture/Tear**
  - Add soil cover to high traffic area
  - No large angular particle in contact with GM
- **Chemical Leaching from Geomembrane**
- **Chemical Compatibility**
- **Wind Uplift**
  - Requires anchoring system

To ensure endurance, Specify: Carbon Black Content and Dispersion, Oxidative Induction Time, Oven Aging, UV Resistance

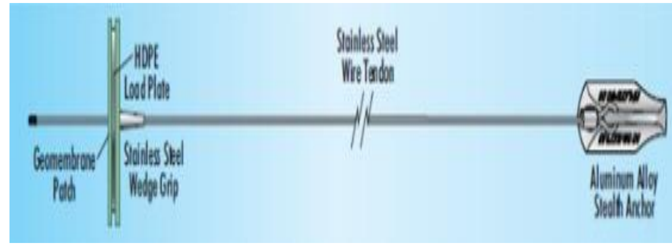
Exposed Geomembrane Covers: Recent Development

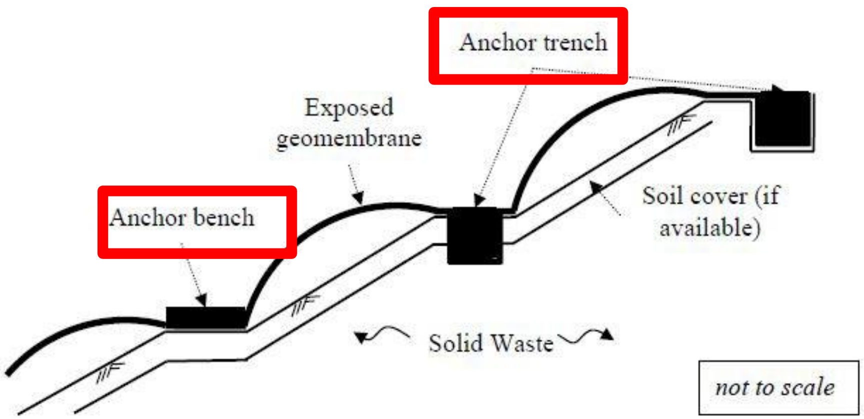


Artificial Turf Cover (patented)

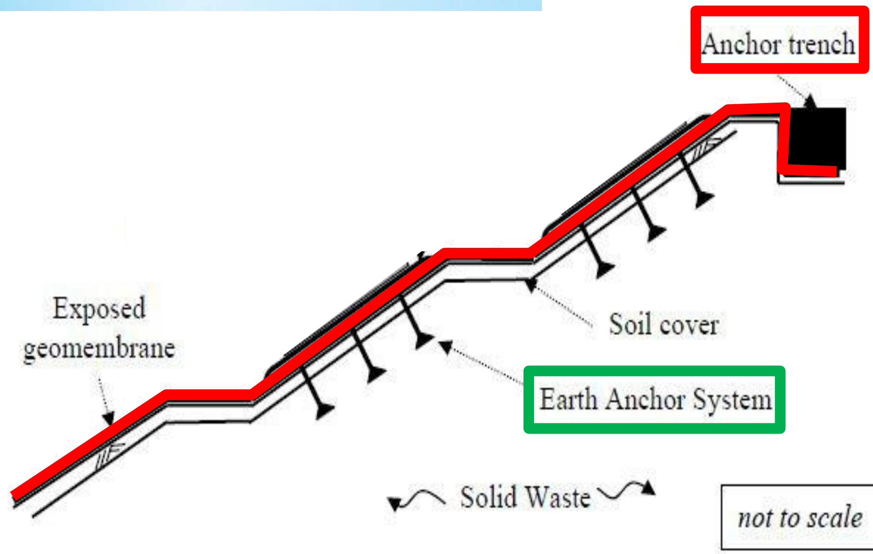
- More aesthetically pleasing
- Reduced wind uplift potential
- Peak runoff flow rate is smaller than regular EGC
- (Advertised) Subtitle D-Compliant Alternative Cover

Anchoring Systems





Conventional

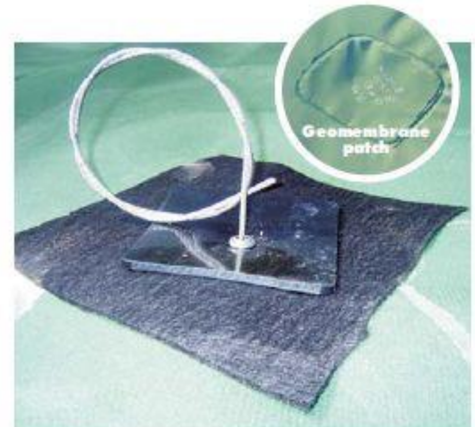


New

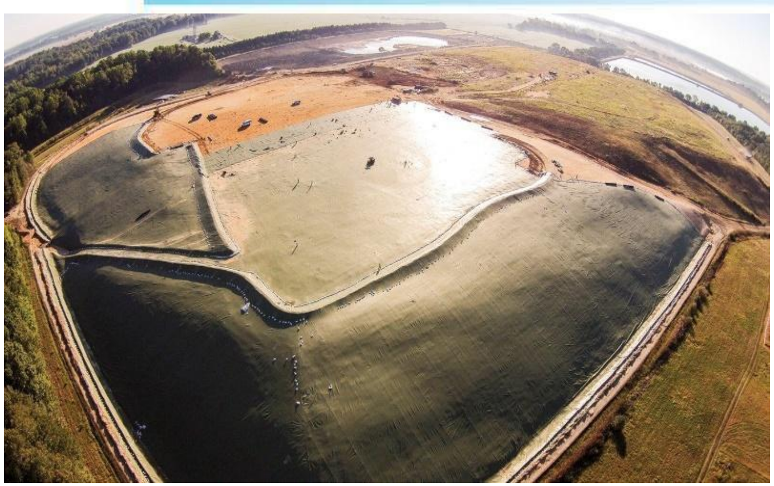
Earth Anchoring System

Drive the Percussive Driven Earth Anchor (PDEA) to depth through the geomembrane.

Loadlock and field verify the applied load to each installed anchor.



Install load plate, wedge grip and weld geomembrane patch.



Midshore Landfill (Maryland, 175 acre) exposed geomembrane cover with earth anchors

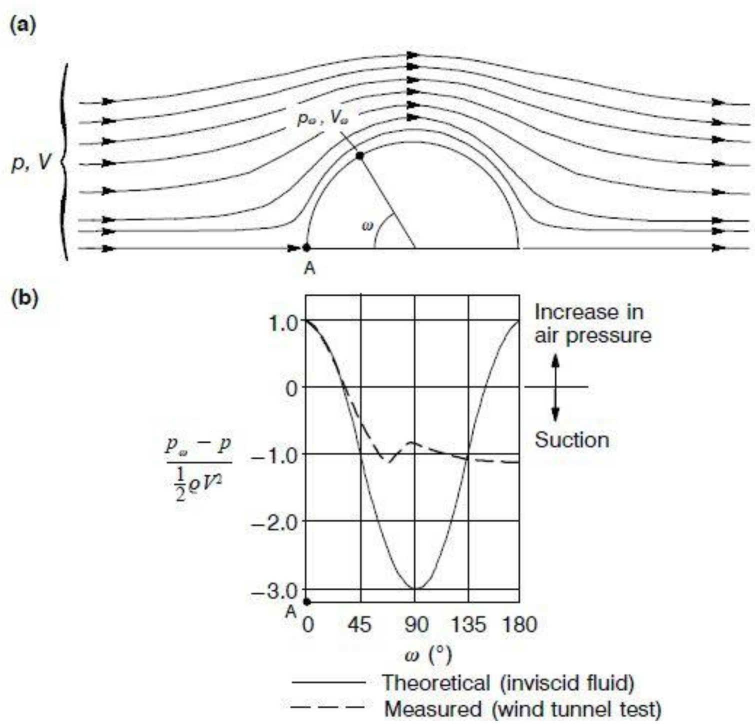
Conventional Design Approach

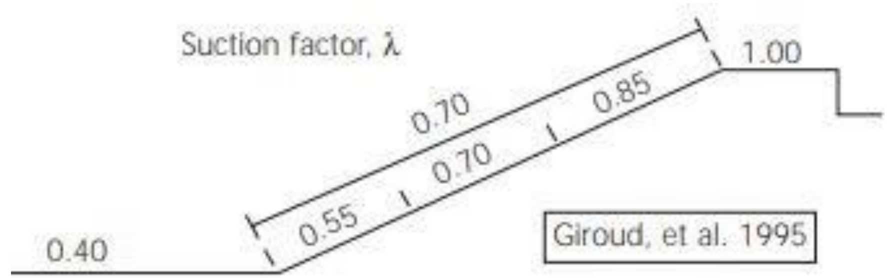
Wind Uplift: Conventional Design Approach

- Giroud et, al. (1995), Zornberg & Giroud (1997)
- Wind-induced Suction, *S*

$$S = 0.05\lambda v^2 exp[-1.252 \times 10^{-4} z]$$

λ = suction factor, v = wind velocity (km/h), z = elevation (m)





Wind Uplift: Conventional Design Approach

- Effective Suction

$$S_e = S - \mu_{GM} g \cos\beta$$

μ_{GM} = mass per unit area, β = slope angle

- Solution for wind-induced strain, ε_w, and uplift angle, θ

Solve Equation to obtain ε_w:

$$\frac{S_e L}{2J\varepsilon_w} = \sin\left[\frac{S_e L}{2J}(1 + 1/\varepsilon_w)\right]$$

J = GM stiffness modulus

Approx. Solution from Giroud (2009):

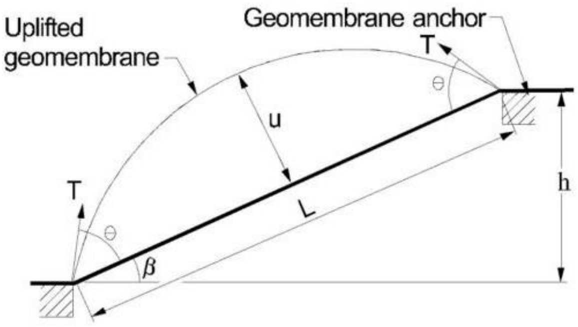
$$\varepsilon_w \approx \frac{0.3467\left(\frac{S_e L}{J}\right)^{2/3}}{1 - 0.3103\left(\frac{S_e L}{J}\right)^{2/3}}$$

$$T = J \cdot \varepsilon_w$$

Uplift angle θ and uplift distance *u* can be calculated as:

$$\theta = \sin^{-1}\left(\frac{S_e L}{2T}\right)$$

$$u = \frac{L}{2}\tan\left(\frac{\theta}{2}\right)$$

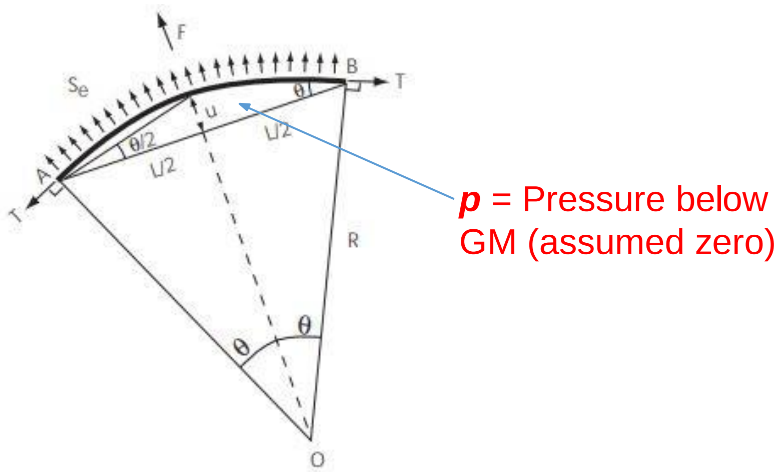


Conservativeness in Conventional Approach

- Our experience
  - Rain tarps held down by sand bags survived Hurricane Sandy (Wind speeds up to 110 mph, 2012)
  - Calculation showed that maximum wind speed it can resist is no more than 30 km/h.
- Several authors (e.g., Kashiwayanagi and Sato, 2006; Thiel et al., non-dated) report that conventional approach yields conservative design based on field performance.

Flaws in Conventional Design Approach

- Pressure below the GM is assumed to be zero by default;



$$S_e = S - \mu_{GM} g \cos\beta + p$$

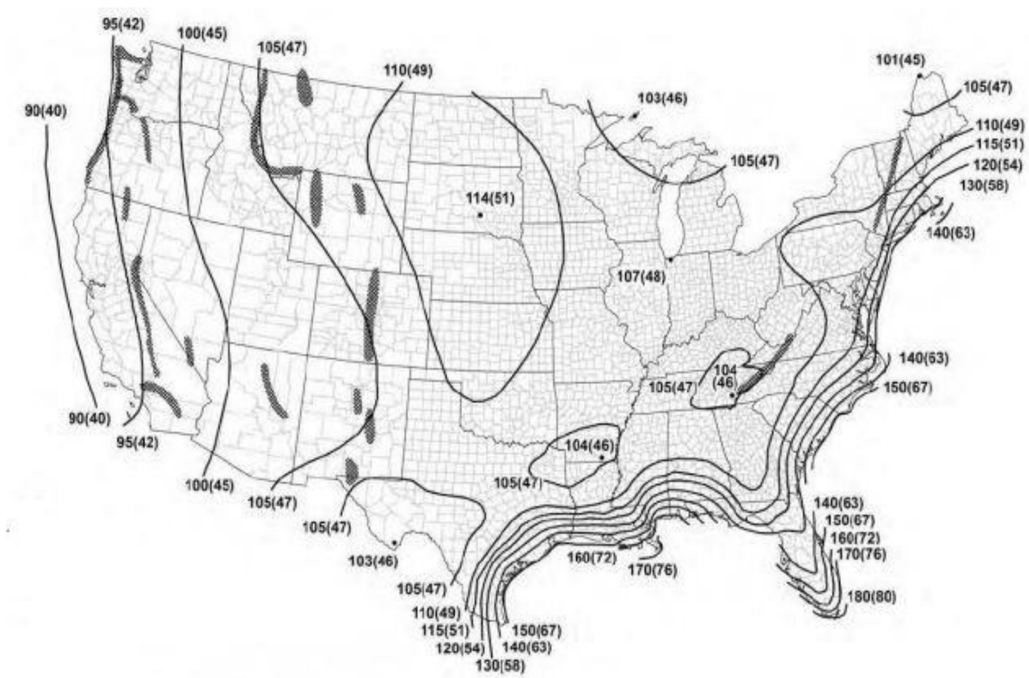
Suction will be created underneath the geomembrane when it is lifted.

- v = 100 km/h; Suction Induced, S = 490 Pa (101,325 – 490 = 100,835 in absolute pressure)
- Initial Volume of Void, V_0 ,
- Void Volume Increased Required to Generate 490 Pa of Suction: $\Delta V = 0.00486\, V_0$

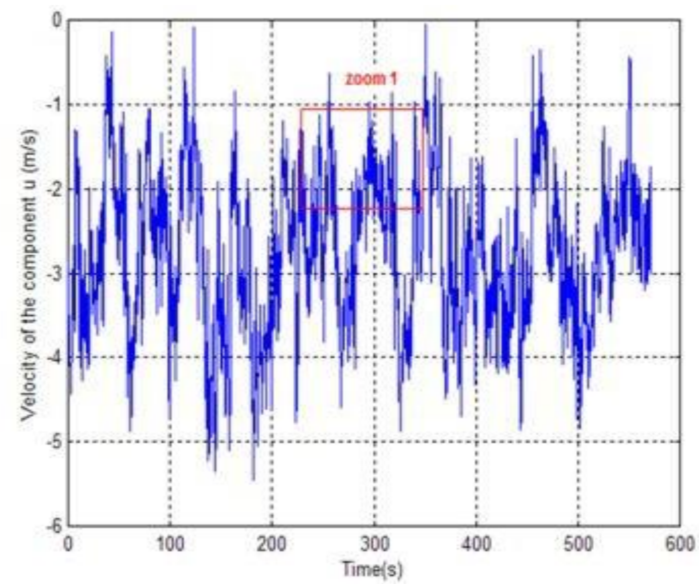
Ideal Gas Law: $p_{abs}V = nRT$

Flaws in Conventional Design Approach

- Wind speed varied with duration
- Unclear on wind velocity selection



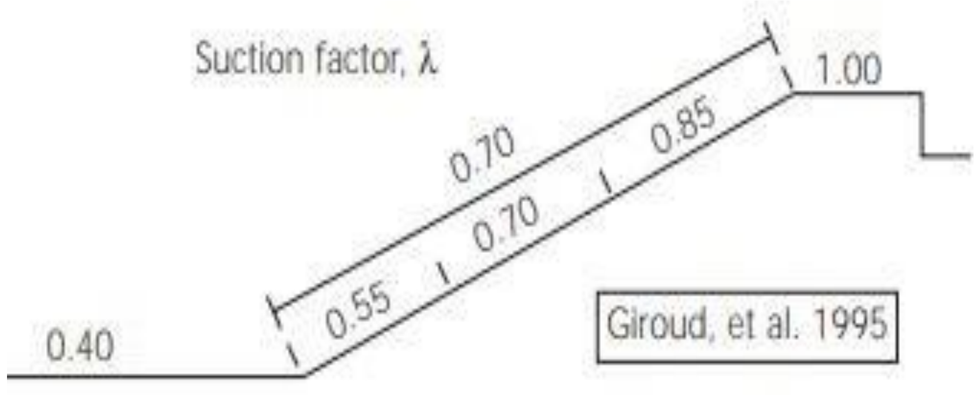
Wind Velocity Contour Map (3-second gust speed) from ASCE 7-16 Manual



Question: Is 3-second gust speed appropriate for exposed geomembrane design?

Recent Research Progress for Suction Factor, λ

- From original Giroud et al. (1995)

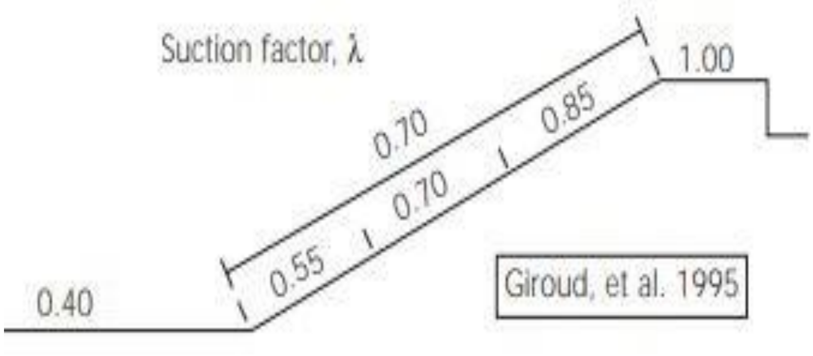


- Recent development
  - Botelho, et al., (2013) conducted computational fluid dynamics (CFD) modeling
  - Perera et al., (2011) recommended to reduce the wind suction coefficient by 23% to account for the effect of negative air pressure under the geomembrane.
  - Zhu et al., (2022) conducted wind tunnel study

Suction Factor from Wind Tunnel Experimental Study

- Material Tested
  - Smooth HDPE geomembrane
  - Studded HDPE geomembrane
  - Artificial turf cover

- Measured suction factor



From Giroud et al. (1995)

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		
Turf Engineered Turf Cover	0.38	0.29	N/A	N/A

Source: Zhu, M., Sarkar, P., Hou, F., & Junxing, Z. Wind Tunnel Study and Uplift Analysis of Geosynthetic Covers. In *Geo-Congress 2022* (pp. 543-553).

Recommended Revision to Conventional Design Approach

Wind Uplift: Modified Design Approach

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Wind-induced uplift of exposed geomembrane covers: A proposed revision to conventional design approaches

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ABSTRACT

Conventional approach for exposed geomembrane design assumes that the geomembrane is subjected to an uplift pressure induced by wind above the geomembrane, and the pressure below the geomembrane is kept constant at atmospheric pressure by default. In reality, the exposed geomembrane is typically anchored into subgrade, which limits the exchange of air above and below the geomembrane. Therefore, when the geomembrane is being uplifted, suction will be generated temporarily below the geomembrane. This temporary suction provides significant resistance to uplift during short-duration wind gust. This paper recommended revisions to the current design approach. An average wind velocity within a selected period, instead of the 3-s gust speed, is recommended to be used for design. This period can be selected based on evaluation of how fast air can enter the voids below the geomembrane.

1. Introduction

The use of an exposed geomembrane cover (EGC) as a temporary or permanent waste containment solution for landfills and other waste disposal sites is becoming increasingly popular (e.g., Richardson, 2000; Germain et al., 2001; Thiel et al.,.2003; Hullings, 2017). EGCs can satisfy regulatory requirements for closure while offering significant cost savings over prescriptive cover designs due to the elimination of soil components. They also afford flexibility where resumption of waste disposal or other site redevelopments may occur in the future. Additionally, exposed geomembrane has also widely used as liner of ponds to reduce percolation into the foundation (e.g., Rowe et al., 2003). Under an empty pond condition, the geomembrane will experience similar loading condition as the EGC for waste containment facilities. Although the advantages of EGC systems are numerous, as have been well described in the literature (e.g., Koerner, 2012; Hullings, 2017), an EGC design must overcome several challenges, such as providing adequate anchorage, managing intensive runoff during a storm, and protection of the geomembrane for long-term integrity. A significant issue to be considered in design is potential uplift of the EGC due to wind loads, which is the focus of this paper.

Wind uplift calculations are typically performed using the methodology developed by Giroud et al. (1995) and extended by Zornberg and Giroud (1997). The basis of this methodology is the calculation of uplift pressure induced by the wind and resulting geomembrane strain. Based on the calculated uplift pressure, anchor trenches or ground anchors are typically designed to hold down the EGC under the design wind storm. Ballast weight are also used for temporary EGC. However, this methodology inherently assumes that the air pressure below the geomembrane is at atmospheric pressure. In addition, no guidance is provided regarding selection of the design wind speed. A commonly used design approach is to use the 3-s gust speed (basic wind speed) obtained from design codes intended for structural design of buildings and similar structures. This conservative approach often leads to designs that specify dense anchor spacing and significant anti-uplift ballast.

In the authors' experience, the uplift potential estimated from the conventional design methodology is significantly over-estimated. This is supported by the observed behavior of temporary EGCs with relatively light anti-uplift ballast. For example, a temporary rain tarp was used for protecting a large embankment slope area against erosion at a landfill in the northeastern U.S. in 2010. The tarp was held down using only 18 kg sandbags at 3 m spacings on a square grid. The authors were requested to conduct a wind uplift evaluation, and our calculation using conventional methodology predicted that uplift of the installed rain tarp would start occurring at wind speeds above 25 km/h. However, the rain tarp has far outlasted its expected service life and has survived several large storm events, including Hurricane Sandy in October 2012,

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EGC at Midshore Landfill (Maryland)

Main Considerations for Modifying the Wind Uplift Design Approach

- Pressure below EGC is not constant at zero
- Suction can develop below EGC as it is being lifted
  - Absolute pressure p_{abs} reduces as volume V increases $p_{abs}V = nRT$
  - Less than 0.5% volume increase will generate enough suction to counteract uplift by wind velocity of 100 km/h.
- Suction will decrease gradually as air infiltrates through GM defects and subsurface

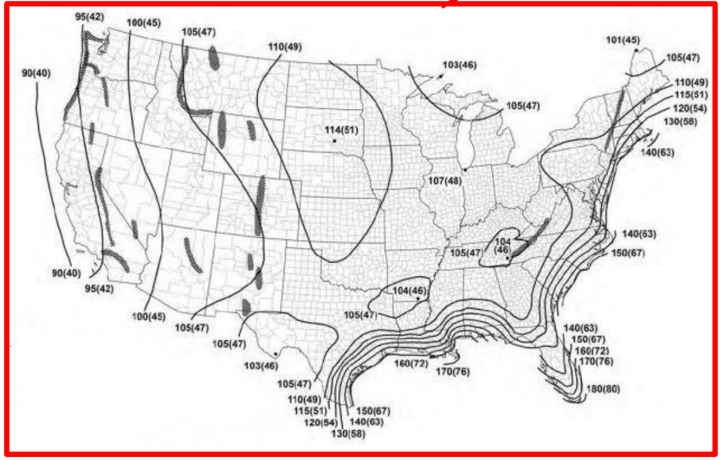
Recommended Design Approach

- Suction below EGC will help counteract uplift induced by short-duration wind gusts. So we will use average wind speed over a longer duration as design wind speed.
- Estimate how long suction below GM can be maintained (T^*)
- Use average wind speed over time T^* for uplift design

Recommended Modified Design Approach

- Convert 3-second wind gust speed to wind speed at longer time to determine gust factor.

Design wind speed = 3-second gust speed/Gust factor



Select basic wind speed (3-second gust) (from structural design code)

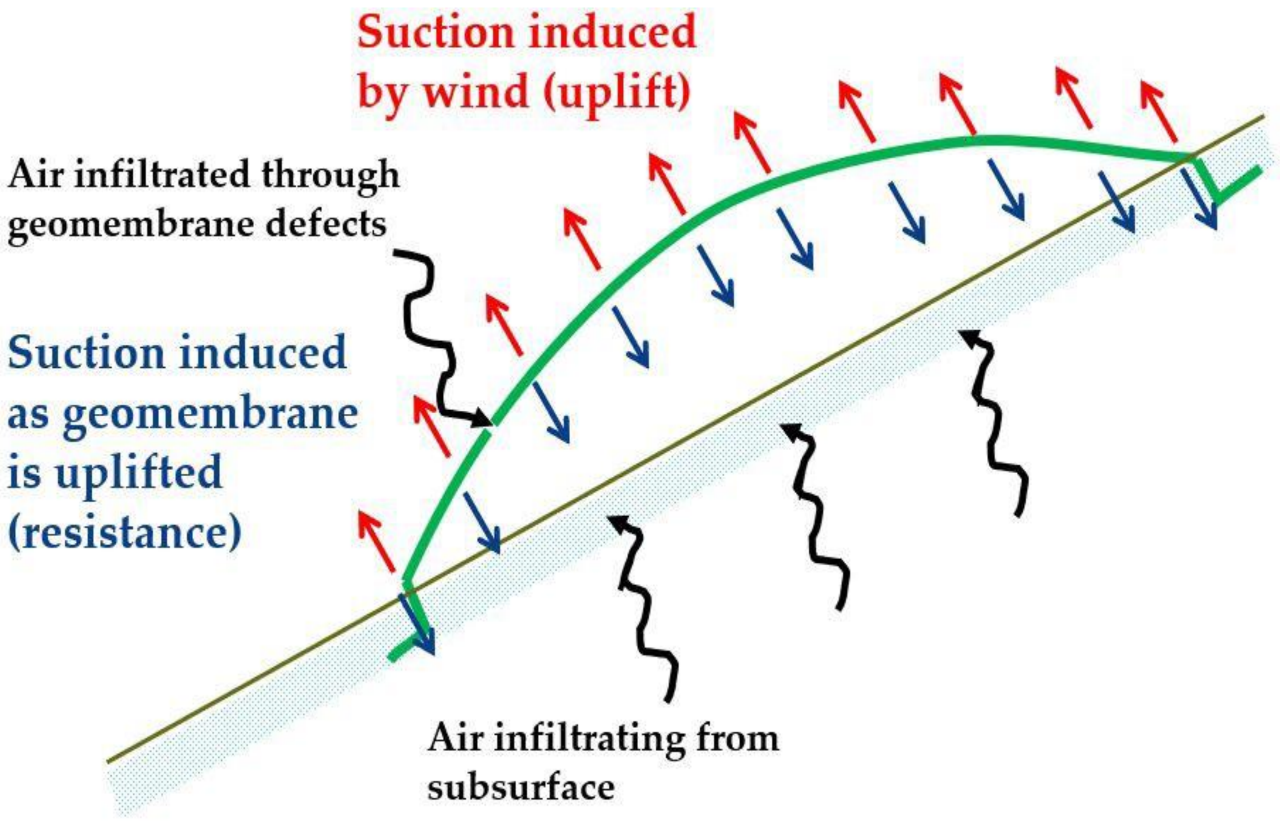
Table 2
Recommended wind speed conversion factor for tropical cyclone condition (after Harper et., al. (2008).

Condition	Gust Factor for Various Averaging Period[a]					
	3s	60s	120s	180s	600s	3600s
In-land, roughly open terrain	1	1.49	1.55	1.58	1.66	1.75
Off-land, offshore at a coastline	1	1.36	1.42	1.44	1.52	1.60
Off-sea, onshore at a coastline	1	1.23	1.28	1.31	1.38	1.45

Select Gust Factor based on how long suction below GM can last (from World Meteorological Organization publication)

Potential Leakage

- Air flow through GM defects
- Air flow through subsurface soils



Estimation of Air Flow Rate Through Defects

- Air flow rate through GM defects

Table 1
Estimated air flow rate through orifice at varying differential pressure.

Orifice diameter (mm)	Air flow rate (in normal m^3/min) at varying differential pressure (in Pa)[a]					
	100	200	300	500	750	1000
0.1	4.18E-06	5.90E-06	7.22E-06	9.32E-06	1.14E-05	1.31E-05
1	4.17E-04	5.90E-04	7.22E-04	9.32E-04	1.14E-03	1.31E-03
2	1.67E-03	2.36E-03	2.89E-03	3.73E-03	4.56E-03	5.26E-03
5	1.04E-02	1.47E-02	1.81E-02	2.33E-02	2.85E-02	3.29E-02
10	4.17E-02	5.90E-02	7.22E-02	9.32E-02	1.14E-01	1.31E-01
50	1.04E+00	1.47E+00	1.81E+00	2.32E+00	2.85E+00	3.29E+00
100	4.17E+00	5.90E+00	7.22E+00	9.32E+00	1.14E+01	1.31E+01

[a] Assumed air temperature = 20 °C.

Based on Air Flow through Orifice Theory

Estimation of Air Flow Rate through Soil

- Air flow through subsurface material (Darcy's law for air flow)

$$v = \frac{K_{gas}}{\gamma_g}\frac{\Delta u_g}{\Delta L}$$

v = air flow velocity, γ_g = unit weight of air; Δu_g = pressure difference over distance of ΔL, K_{gas} = permeability of soil to air.

- Estimating permeability of soil to air (K_{gas}) using permeability to water (K_{water})

$$K_{gas,dry} = \frac{K_{water} \cdot \mu_w \gamma_g}{\mu_g \gamma_w}$$

$$K_{gas} = K_{gas,dry}(1 - s_e)^2(1 - s_e^{(2+\chi)/\chi})$$

$$s_e = \frac{s - s_r}{1 - s_r}$$

where: K_{water} = coefficient of permeability of waste to water under saturated conditions; μ_w = dynamic (absolute) viscosity of water; μ_g = dynamic (absolute) viscosity of air; and γ_w = unit weight of water; χ = pore-size distribution index; and s_e = effective degree of saturation: s = degree of saturation; and s_r = residual degree of saturation at which point an increase in matrix suction does not produce an appreciable change in the degree of saturation.

Recommended design procedure

- Obtain basic wind speed (3-second gust) for Site
- Select averaging period (*T**) by assuming how long suction below EGC will last
- Select design wind speed
- Calculate wind induced uplift distance and angle, similar to conventional approach
- Estimate volume of voids below GM (*V*)
- Estimate air flow rates into voids below GM
    - Air flow rates through GM defects, Q_{GM}
    - Air flow rates through subsurface material, Q_{soil}
- Estimate time duration to lose suction $T^* = V/ (Q_{GM} + Q_{soil})$
- Check if calculated *T** is close to assumed value. If not, repeat above steps

Design Example

Design Example

- Landfill site on east coast USA
- Site is in-land roughly open terrain
- Basic wind speed (3-second gust) is 100 mph
- 3H:1V sideslope, slope angle β = 18.3 deg

Wind-induced Suction Calculation

- Assume $T^* = 1$ hr (3600 sec).
- Average wind speed over time T^*:
  - v = 100 / 1.75 = 57 mph = 92 km/h

Table 2
Recommended wind speed conversion factor for tropical cyclone condition (after Harper et., al. (2008).

Condition	Gust Factor for Various Averaging Period[a]					
	3s	60s	120s	180s	600s	3600s
In-land, roughly open terrain	1	1.49	1.55	1.58	1.66	1.75
Off-land, offshore at a coastline	1	1.36	1.42	1.44	1.52	1.60
Off-sea, onshore at a coastline	1	1.23	1.28	1.31	1.38	1.45

- Wind induced suction:
  - S = 0.05 x 0.77 x 92 x 92 x 1 = 326 pa

$$S = 0.05\lambda v^2 exp[-1.252 \times 10^{-4} z]$$

  - S_e = 326- 0.91x 9.8 x cos18.3° = 317 pa

$$S_e = S - \mu_{GM} g cos\beta$$

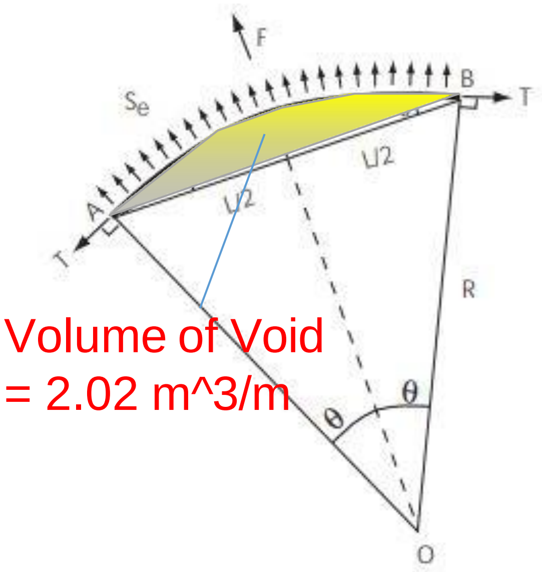
Volume of Voids and Induced Strain

- 60-mil HDPE geomembrane (the stiffness modulus J = 1,015 lb/in or 177 kN/m)
- Spacing of anchorage (L) = 20 ft (6.1 m)
- Wind induced strain

$$\varepsilon_w \approx \frac{0.3467\left(\frac{S_e L}{J}\right)^{2/3}}{1 - 0.3103\left(\frac{S_e L}{J}\right)^{2/3}}$$

= 1.7% < less than allowable strain 4~5 %

Tension T = 0.017x177 = 3.01 kN/m



- Uplift angle θ and distance u

$$\theta = sin^{-1}(\frac{S_e L}{2T})$$ = 18.7 deg

$$u = \frac{L}{2} tan\,(\frac{\theta}{2})$$ =0.50 m

- Volume of void below GM calculated to be 2.02 m^3/m

Estimate *T** (time duration to lose the suction)

- Air flow through geomembrane defects
  - Assume 1 1-cm diameter hole per acre
  - Driving air pressure difference = *S*/2 (160 pa)

Table 1
Estimated air flow rate through orifice at varying differential pressure.

Orifice diameter (mm)	Air flow rate (in normal m^3/min) at varying differential pressure (in Pa)[a]			
	100	200	300	500
0.1	4.18E-06	5.90E-06	7.22E-06	9.32E-06
1	4.17E-04	5.90E-04	7.22E-04	9.32E-04
2	1.67E-03	2.36E-03	2.89E-03	3.73E-03
5	1.04E-02	1.47E-02	1.81E-02	2.33E-02
10	4.17E-02	5.90E-02	7.22E-02	9.32E-02
50	1.04E+00	1.47E+00	1.81E+00	2.32E+00
100	4.17E+00	5.90E+00	7.22E+00	9.32E+00

[a] Assumed air temperature = 20 °C.

Estimated flow rate = 0.0521 m3/min/ac = 1.28E-5 m/min

Estimate T^* (time duration to lose suction)

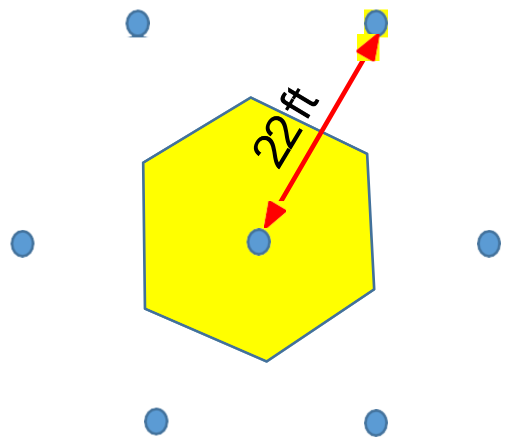
- Air flow through subsurface soils
  - 2-ft of silt K_{water} = 1 E-4 cm/sec (K_{gas} = 1E-5 cm/sec or 1E-7 m/sec)
  - Underneath the cover soil, there is a 1000 pa pressure buildup. Driving air pressure difference = 1160 pa. Gas unit weight = 12 N/m3

$$v = \frac{K_{gas}}{\gamma_g}\frac{\Delta u_g}{\Delta L}$$ = (1E-7)(1160)/[(12)(0.61)] = 1.58E-5 m/sec = 9.51E-4 m/min

- Time T^* = 2.02/[6.1(9.51E-4+ 1.28E-5)] = 343 min > assumed 60 min
- (There is no wind gust factor provided for averaging period greater than 60 min. It is safe to use the assumed design wind speed)

Anchorage System Design

- Option 1: Anchor trench
  Anchor trench should provide pullout resistance of 3.01 kN/m with proper factor of safety
- Option 2: Ground anchor
  Ground anchor arranged in triangular pattern with 22 ft center-to-center spacing (equivalent to 20.5 ft by 20.5 ft in square pattern in area). Each anchor will be responsible for 420 sf. Each anchor should provide designed pullout resistance equal to (S_e x responsible area) with proper factor of safety, which is 2,780 lbs.
- The modified design approach allows 67% savings in anchoring system.



Design Implication

- It is beneficial to maintain suction below GM as long as possible
- More airtight EGC will allow use of lower wind velocity for design, leading to more cost-effective design
- Maintaining EGC during service life to retain suction is critical to avoid wind damage

Questions??

Thank you for attending!!!

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Mobilized Interface Strengths on Geosynthetic Lined Slopes

Tuesday, October 18, 2022 at Noon CDT

Free to Industry Professionals

1.0 PDH

Presenters:

Timothy D. Stark, Ph.D., P.E.

Jiale Lin, Ph.D.

Check out the FGI's Website

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FGI at Geosynthetics 2023 Conference

Wednesday, February 5-8, 2023
Kansas City, MO

Tuesday, February 7, 2023

1:30–3 pm **-** Round Table Discussion: Women in Geosynthetics

Wednesday, February 8, 2023

8-9:30 am **-** Technical Session 1: Fabricated Geosynthetics for Water Retention Projects

9:45–11:15 am **-** Panel Discussion 1: Importance of Operation & Maintenance Manuals

1:30–3 pm **-** Technical Session 2: Applications of Fabricated Geosynthetics

3:45–5:15 pm **-** Panel Discussion 2: How to Write a Good Geomembrane Specification

Register Today: geosyntheticsconference.com