Master Class #1

Advances in Design and Construction with geosynthetics for Hydraulic Structures and Environmental Containment:

Geomembrane Leakage Rates

Speaker: Abigail Gilson

GEOANZ #1 ADVANCES IN GEOSYNTHETICS
7–9 JUNE 2022 | BRISBANE CONVENTION & EXHIBITION CENTRE

Factors in Geomembrane Leakage

- Design choices:
  - Liner cross section components
  - Geomembrane type and thickness
  - Puncture protection
  - Specification of Electrical Leak Location
- Presence and quality of Construction Quality Assurance
- Geomembrane Installer skill/experience/QA procedures
- Type(s) of Electrical Leak Location (ELL) applied and effectiveness of testing
- Cover material placement methods (if applicable)
- Weather during construction
- Site operations

Multitude of factors create large variation in leakage rates

Leakage is caused by holes!

Role of Electrical Leak Location (ELL)

- Provides safety net for leaks at the end of construction activities
- At best, can locate 100% of the leaks before facility is put into operation
- At least, should be able to minimize number and size of leaks to manageable level

BUT

- ELL methods have limitations that must be understood in order to overcome them (to achieve 100%)
- Leaks can form over time during operations if project design or CQA inadequate, or if facility not adequately maintained

How much leakage should I expect?

- Choose leak size and frequency based on published statistics and apply known leakage rate equations

AND/OR

- Look at actual leakage rates from similar projects

BUT

- Leak size and frequency statistics can be biased and are extremely variable
- Calculated leakage rates through known equations can be off by a factor of 1000 if the wrong assumptions are made
- Actual leakage data are not widely published and can be biased

SO

- Use ELL specification to narrow the field of possible outcomes (mitigate risk)
- Use statistics to manage uncertainty (probability of failure analysis)

Leak Frequency Statistics

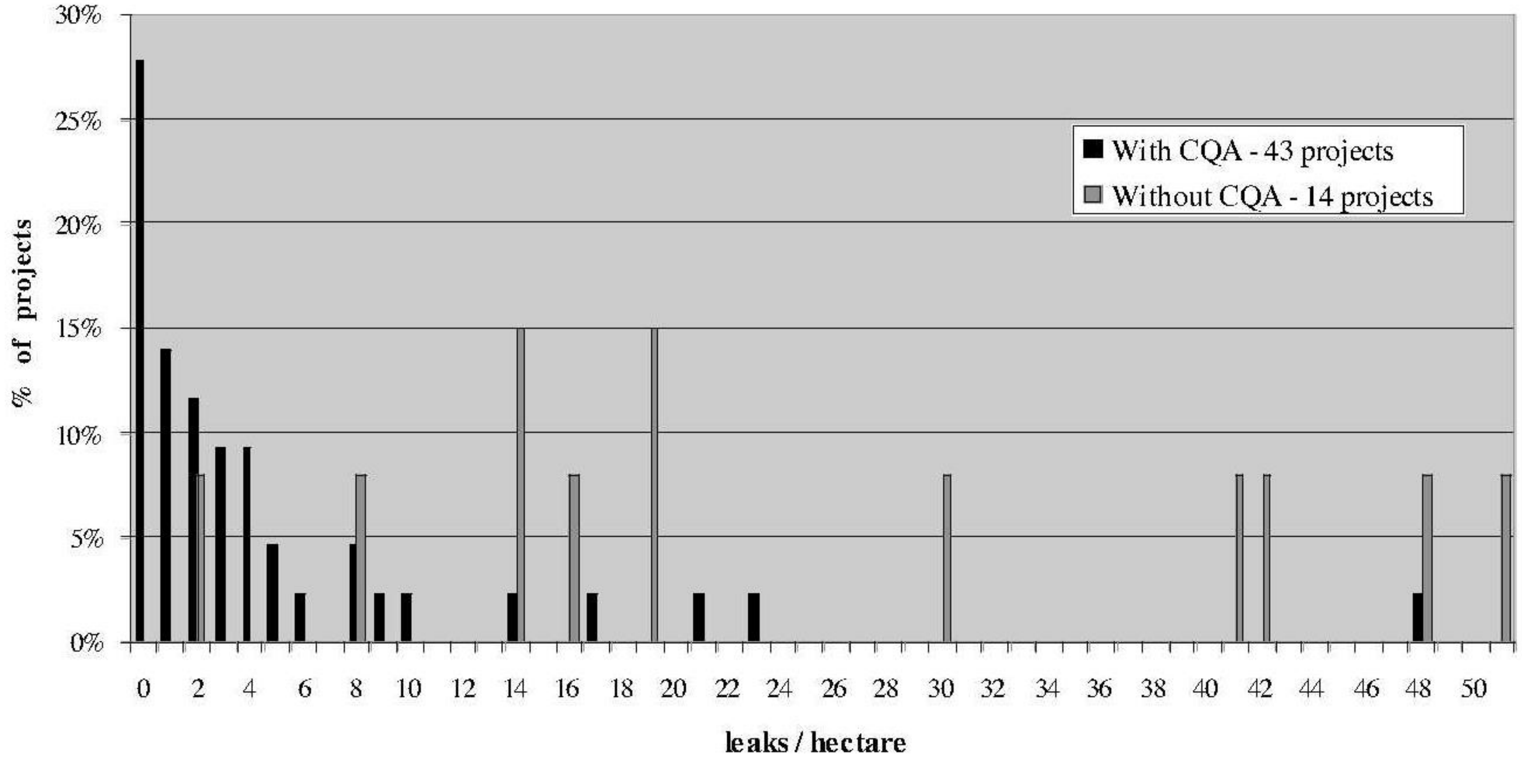
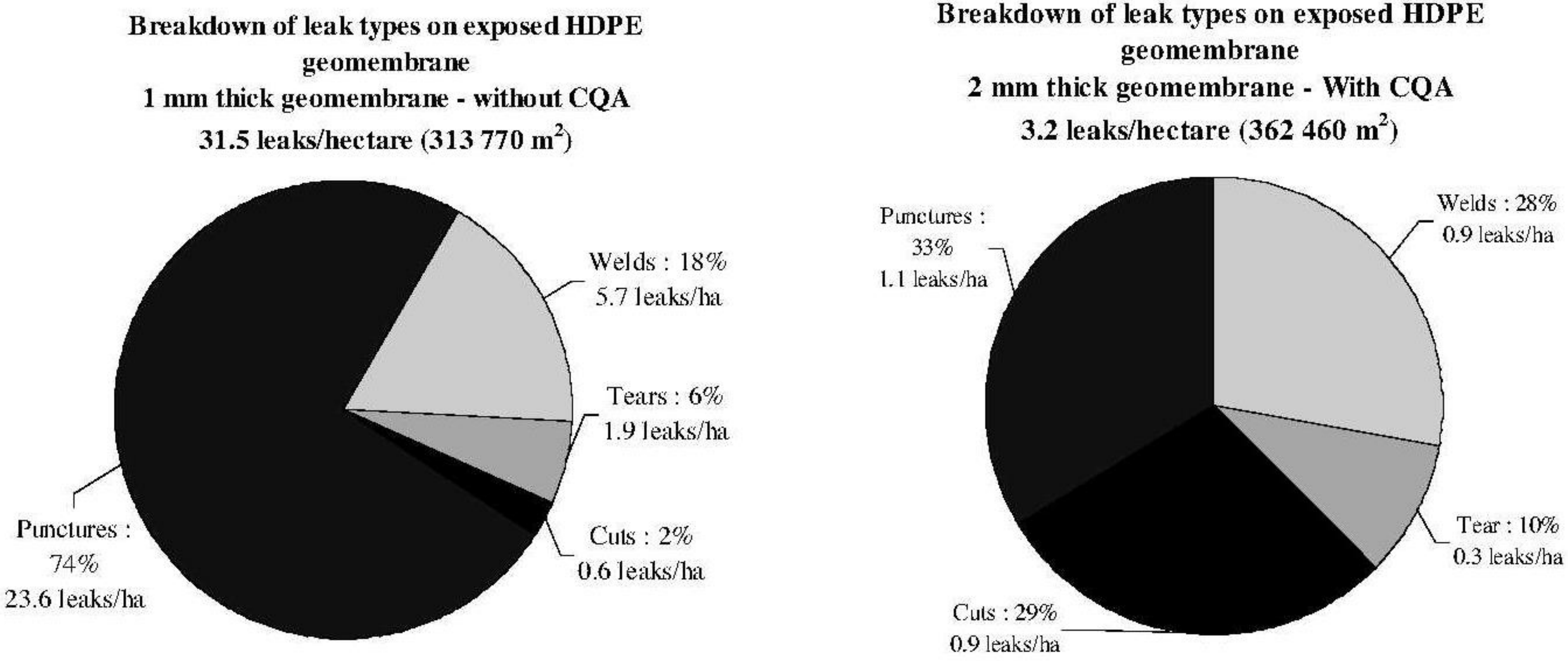


Figure 3. Leak Densities – With and Without a Rigorous CQA Program (Exposed Geomembranes).

Source: Forget et. al. (2005). “Lessons Learned from 10 Year so Leak Detection Surveys on Geomembranes”, Proceedings of the Sardinia Conference.

Leak Frequency Statistics



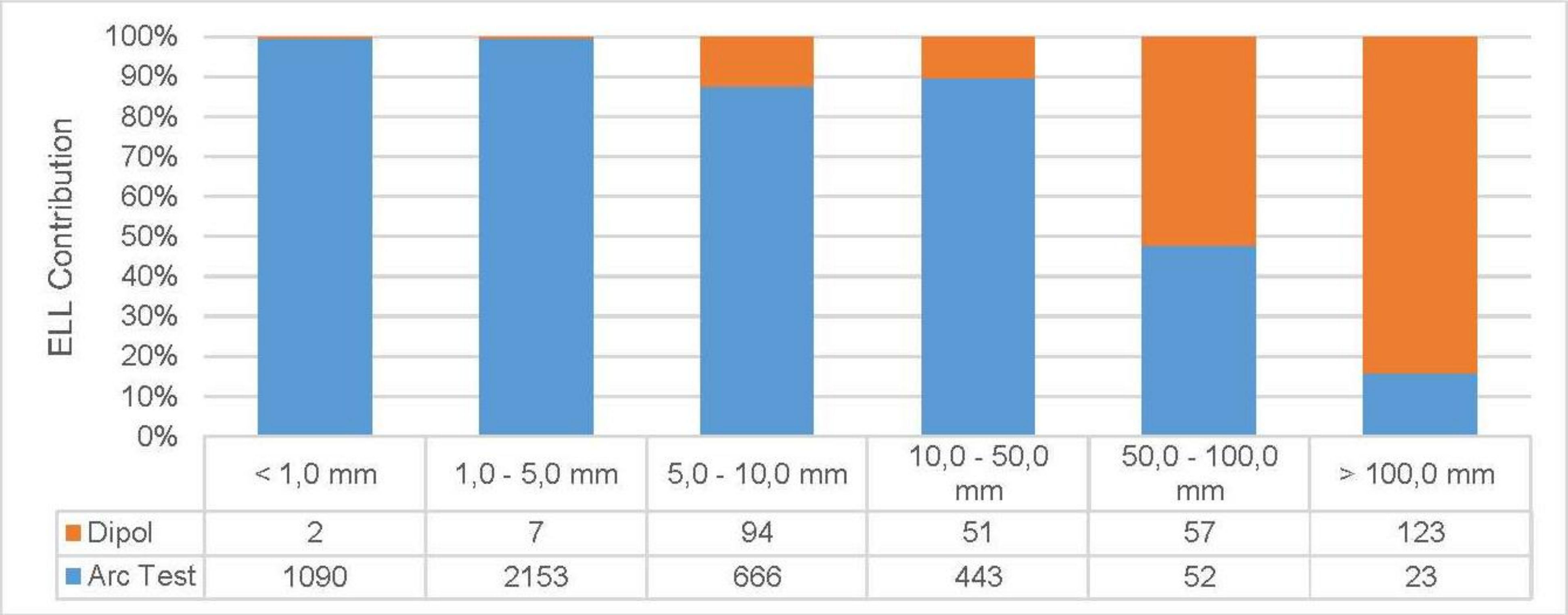
Breakdown of leak types on exposed HDPE geomembrane
1 mm thick geomembrane - without CQA
31.5 leaks/hectare (313 770 m^2)

Breakdown of leak types on exposed HDPE geomembrane
2 mm thick geomembrane - With CQA
3.2 leaks/hectare (362 460 m^2)

Figure 4. Breakdown of Leak Types (Exposed HDPE Geomembranes).

Source: Forget et. al. (2005). “Lessons Learned from 10 Year so Leak Detection Surveys on Geomembranes”, Proceedings of the Sardinia Conference.

Leak Size as a Function of ELL Method

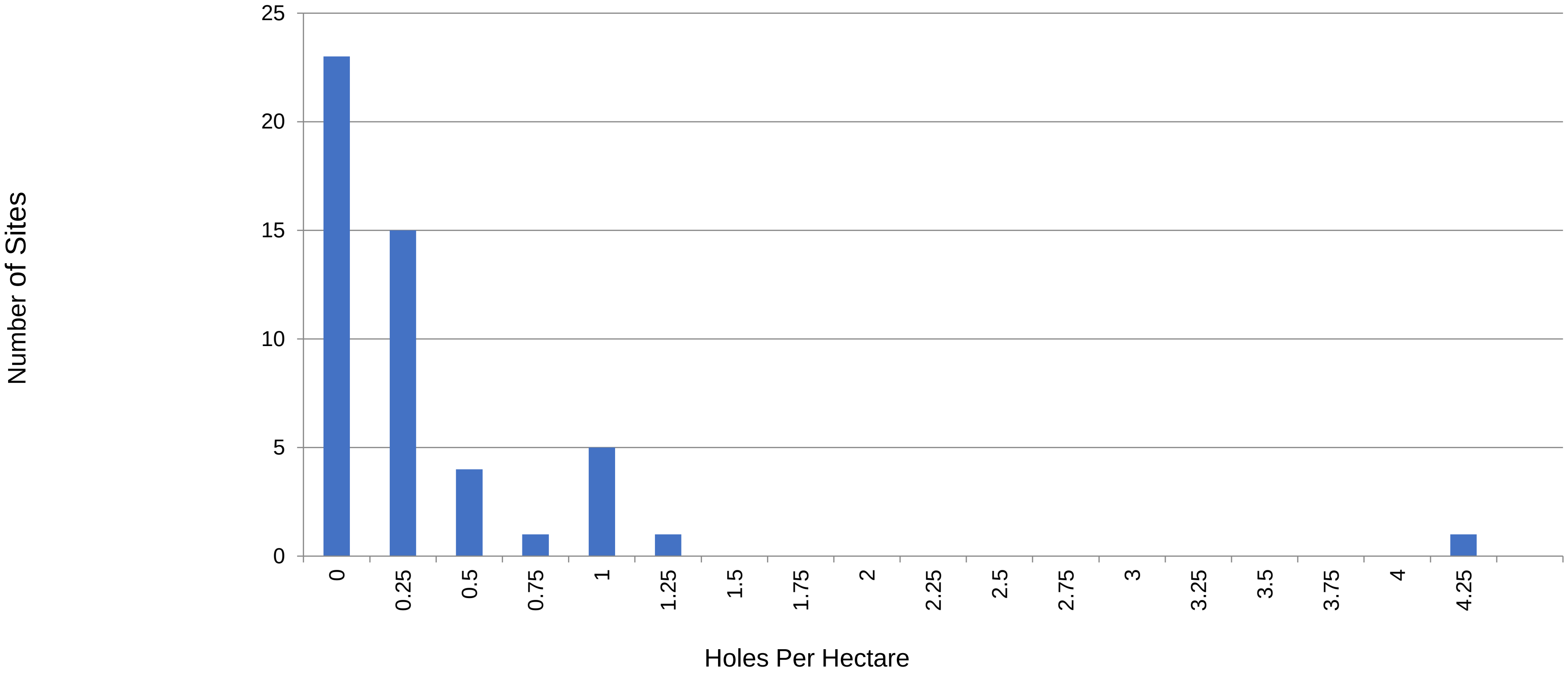


	< 1,0 mm	1,0 - 5,0 mm	5,0 - 10,0 mm	10,0 - 50,0 mm	50,0 - 100,0 mm	> 100,0 mm
🟧 Dipol	2	7	94	51	57	123
🟦 Arc Test	1090	2153	666	443	52	23

Figure 4: ELL Contribution to the whole quantity of leaks / holes detected. Size of leaks vs type of ELL method. Total sample size 6,820,020m^2 surveyed area.

Source: Nosko and Crowther. (2015) “Can the Holy Grail of the Geosynthetics Industry “Zero Leakage” be Achieved by Arc Testing?” Geosynthetics 2015 Conference Proceedings, February 15-18, Portland, Oregon.

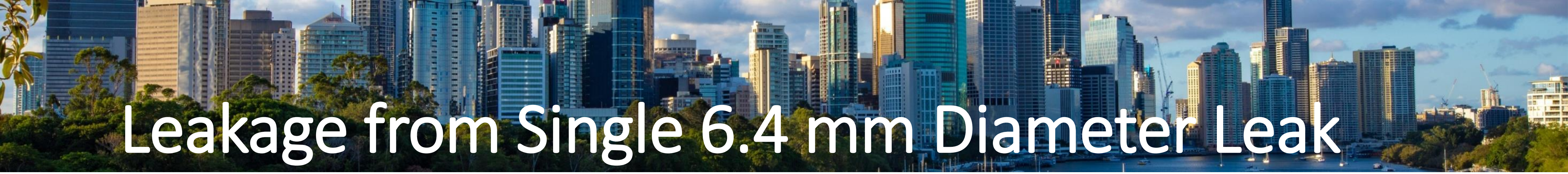
Leak Frequency Histogram



Source: Gilson-Beck (2019). “Controlling leakage through installed geomembranes using electrical leak location”, Geotextiles and Geomembranes 47, 697-710.

Leakage Equations

- Bernoulli equation: $Q = 0.6 * a * \sqrt{2gh}$
  - Free flow below geomembrane
- Giroud equation: $\frac{Q}{A} = n \cdot 0.976\, C_{qo} \cdot [1 + 0.1 \cdot (h/t_s)^{0.95}] \cdot d^{0.2} \cdot h^{0.9} \cdot k_s^{0.74}$
  - Geomembrane underlain by low permeability layer
  - In intimate contact
- Rowe equation: $Q = 2L[k_b b + (k_a \theta D)^{0.5}] * h_d / D$
  - Geomembrane underlain by low permeability layer
  - Geomembrane not in intimate contact with underlying layer (leak on wrinkle)



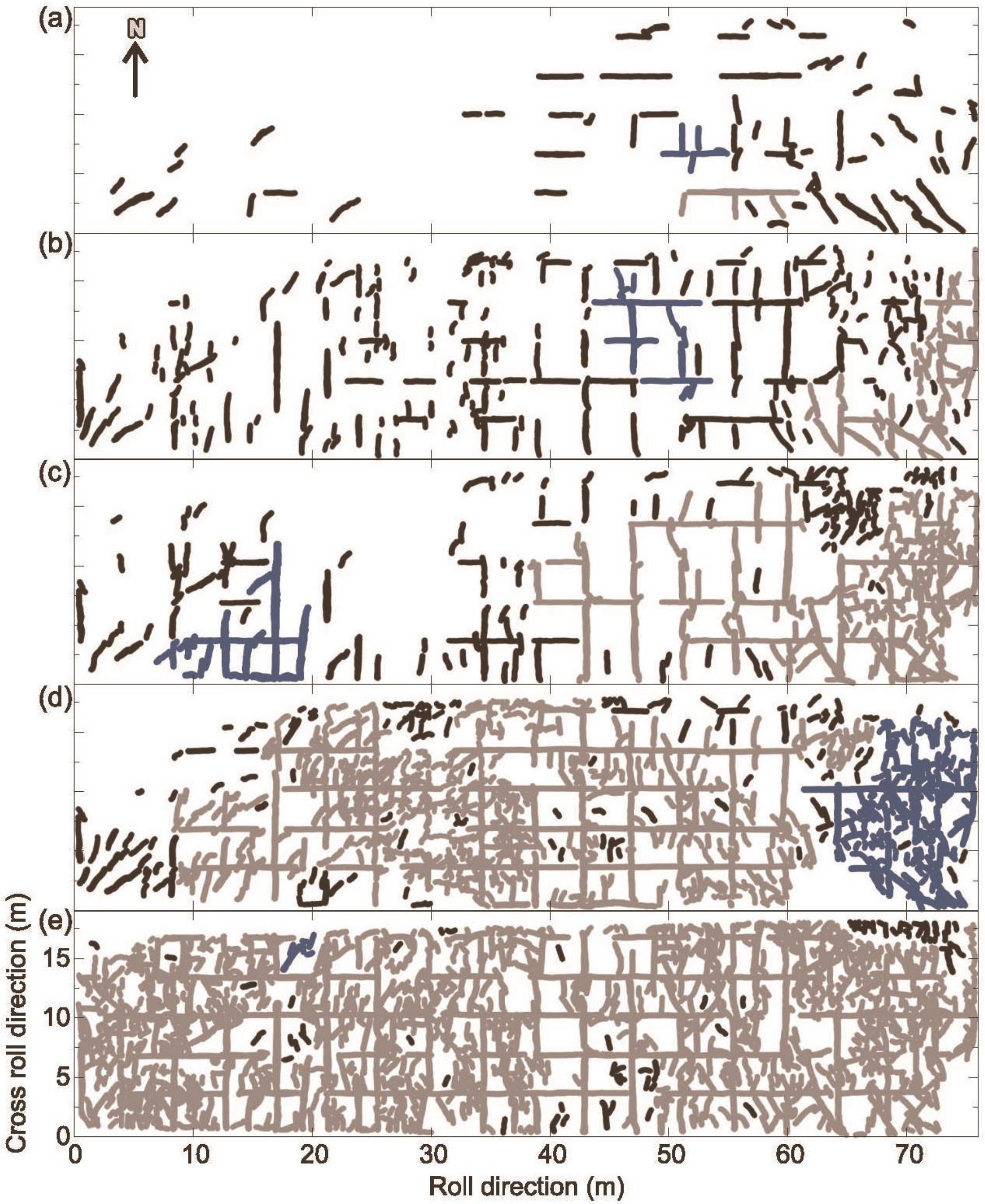
Leakage from Single 6.4 mm Diameter Leak

Hydraulic Head of 0.3048 m (landfill bottom liner)	
Equation	**Leakage (L/day)**
Bernoulli	4,015
Giroud (Good Contact)	0.08
Giroud (Poor Contact)	0.45
Rowe (1,000 m wrinkle)	45

Source: Beck (2012). “How Much Does my Landfill Leak?”, Waste Advantage Magazine, December Issue.

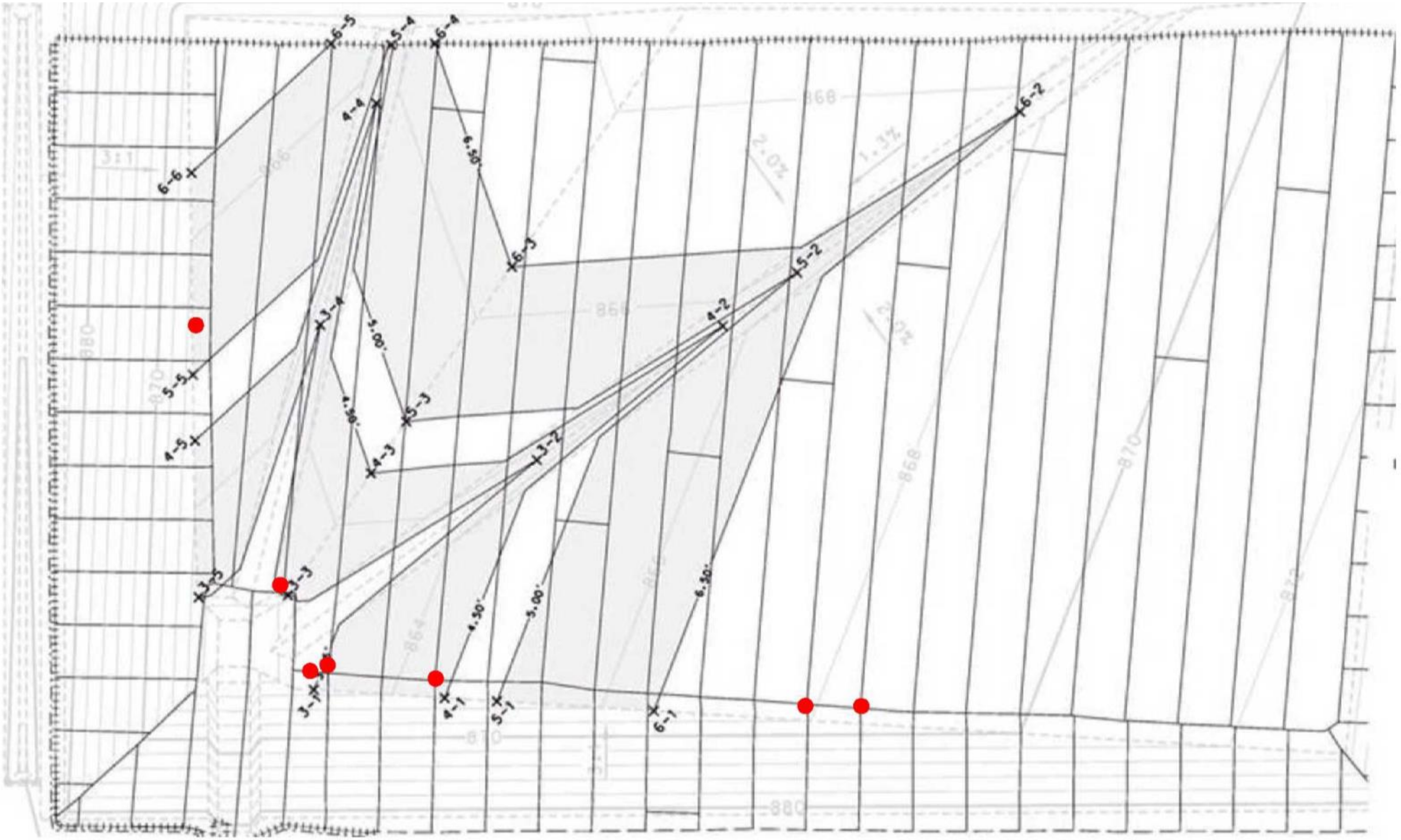
Prevalence of Wrinkles

- Wrinkle extent vs. Time of Day
- Up to 20-30% of area can contain wrinkles
- Wrinkles do not disappear when covered; they are encapsulated
- ELL methods have difficulty locating leaks on wrinkles (need contact through leak)



Source: Rowe, et al. (2012). "Field Study of wrinkles in a geomembrane at a composite liner test site". Canadian Geotechnical Journal.

Case Study : 47 lphd Landfill Cell

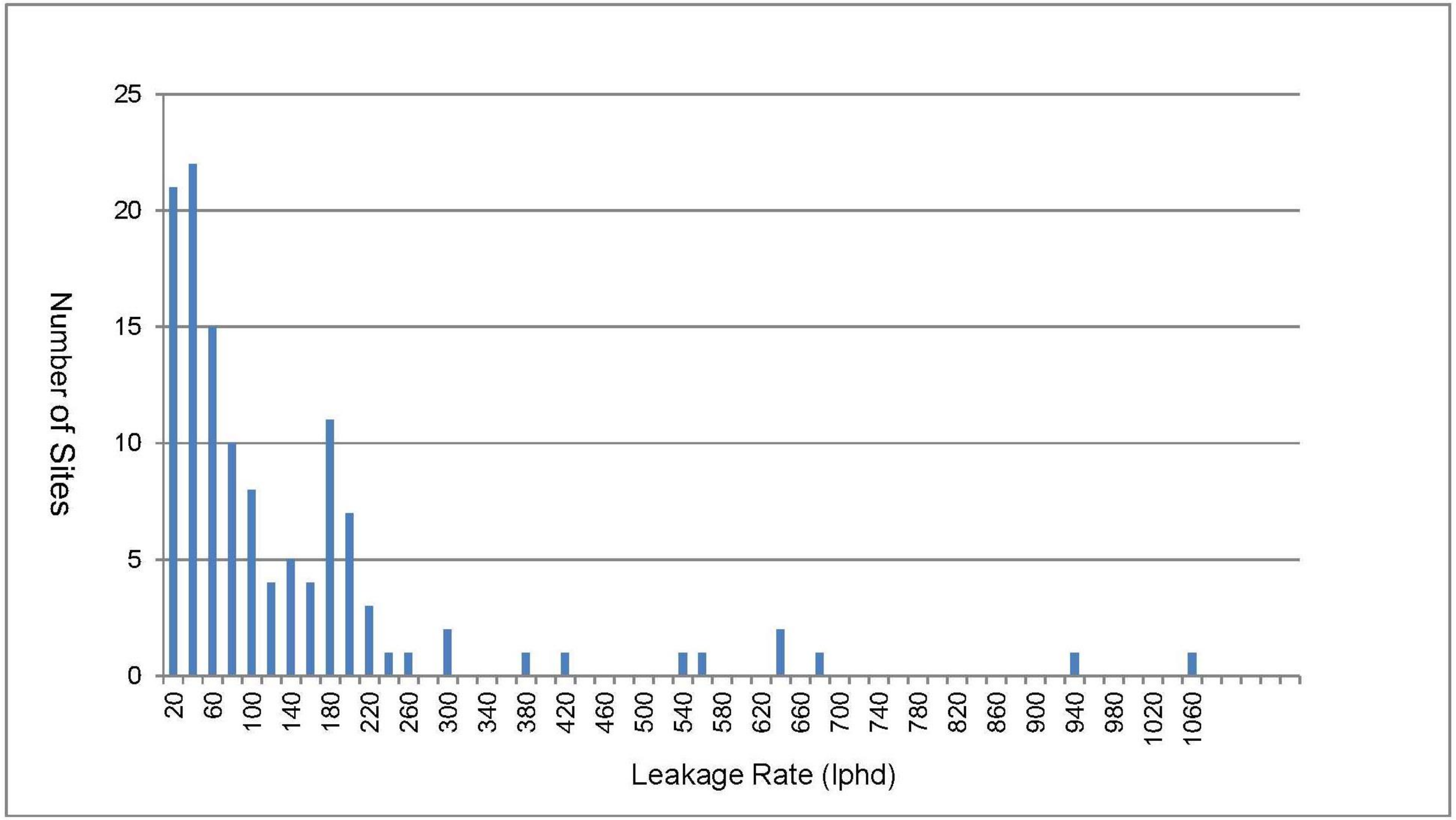


Source: Beck, Abigail (2014). “Designing to Minimize Geomembrane Leakage”. Geosynthetics Magazine, August Issue.

Case Study : 47 lphd Landfill Cell

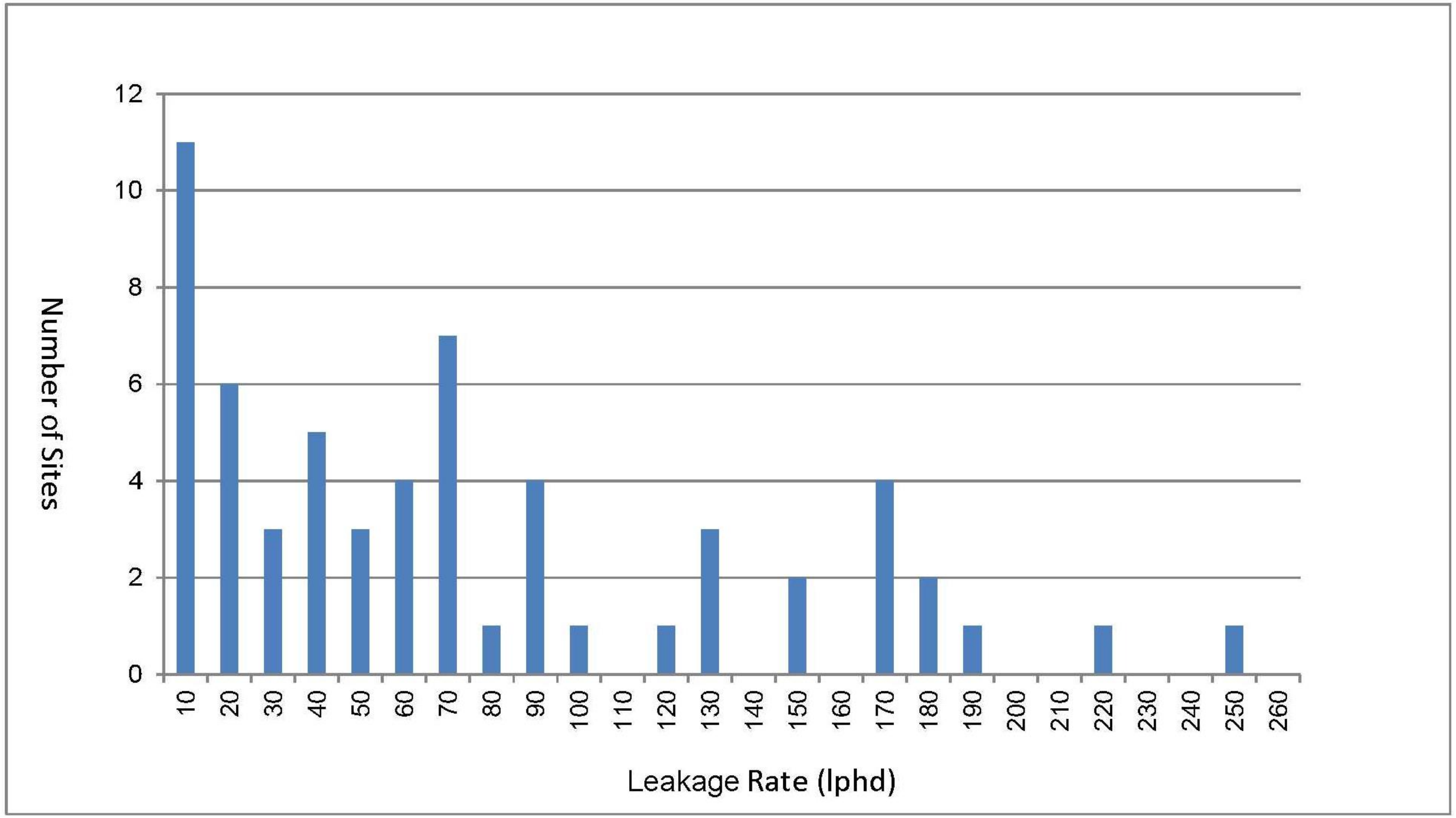
Source: Beck, Abigail (2014). “Designing to Minimize Geomembrane Leakage”. Geosynthetics Magazine, August Issue.

Landfill Leakage – No ELL Applied



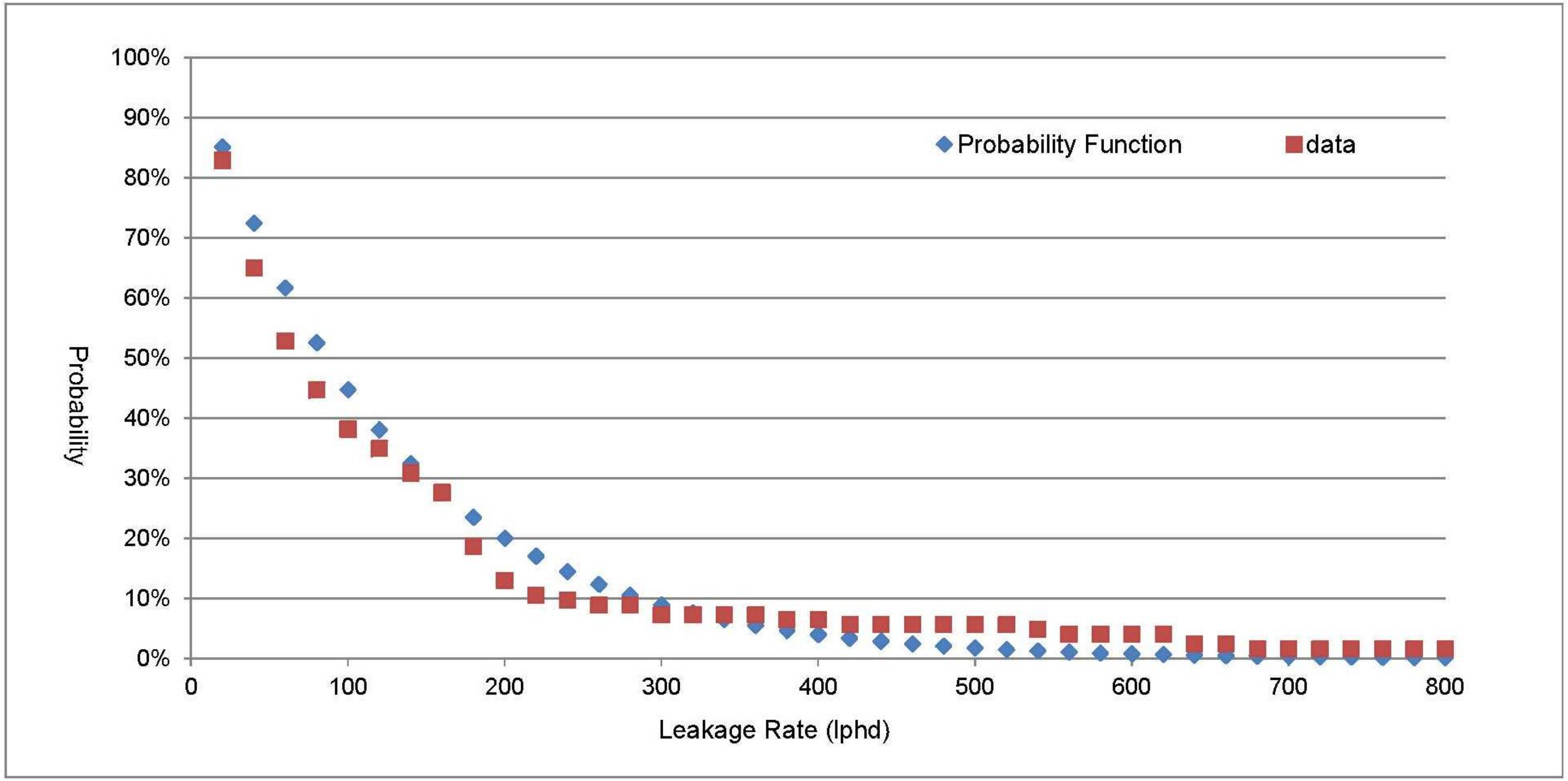
Source: Beck, Abigail (2015). "Available Technologies to Approach Zero Leaks". Geosynthetics 2015 Conference Proceedings.

Landfill Leakage – Dipole Method Applied



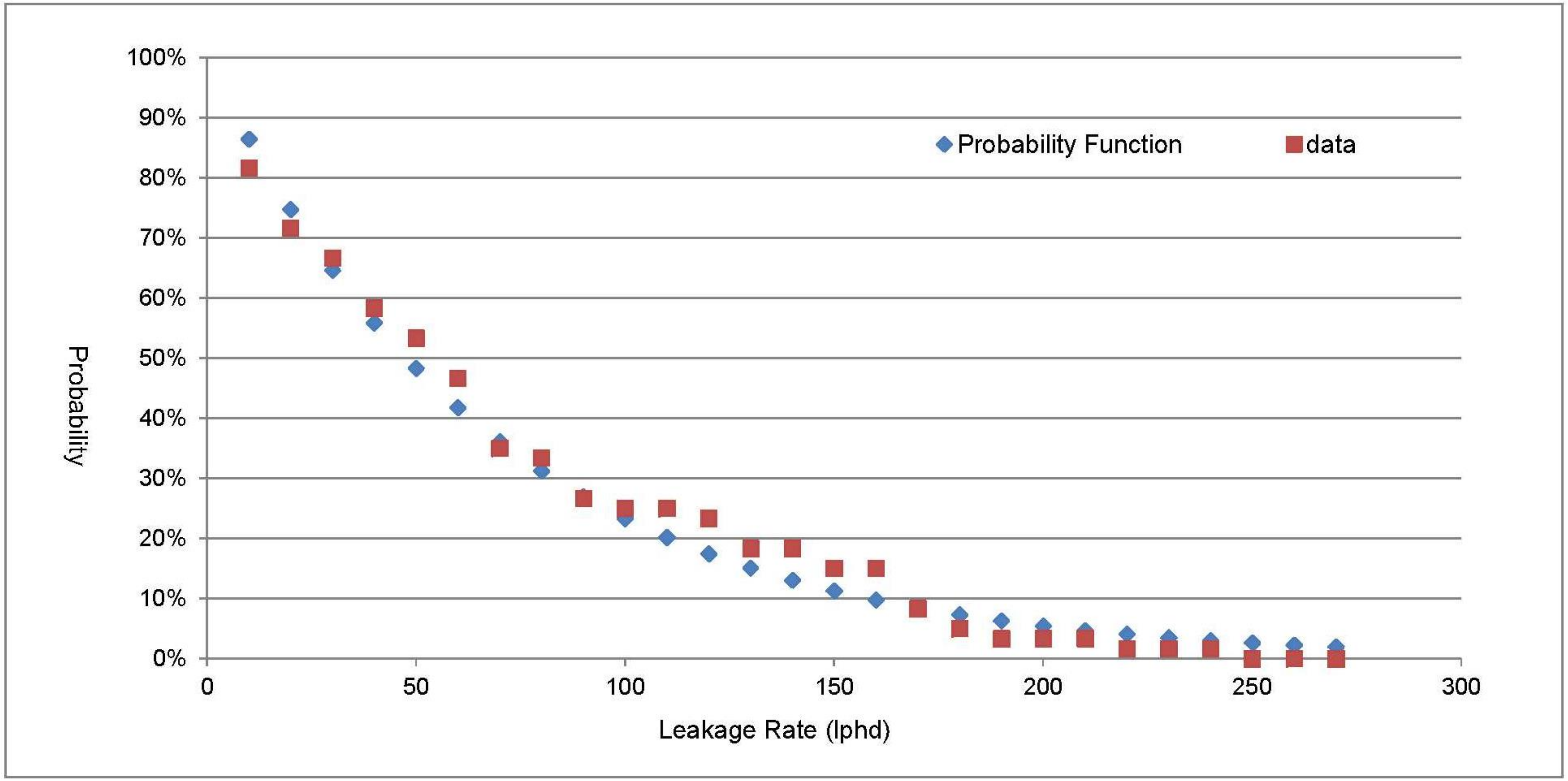
Source: Beck, Abigail (2015). “Available Technologies to Approach Zero Leaks”. Geosynthetics 2015 Conference Proceedings.

Probability Function – No ELL Applied



Source: Beck, Abigail (2015). “Available Technologies to Approach Zero Leaks”. Geosynthetics 2015 Conference Proceedings.

Probability Function – Dipole Method Applied



Source: Beck, Abigail (2015). “Available Technologies to Approach Zero Leaks”. Geosynthetics 2015 Conference Proceedings.

Leakage Equations

- $Y(x) = \exp[(-1/\text{mean}) \cdot x]$
  - Where:
    - **mean** = average leakage value for data set
    - x = target leakage rate (ALR)
    - Y(x) = probability of EXCEEDING target leakage rate
- Calculate expected leakage rate (**mean**) based on:
  - ELL technologies applied (what kinds of leaks might remain?)
  - Potential for “poor contact” between liner and subgrade

Source: Beck, Abigail (2012). “A statistical Approach to Minimizing Landfill Leakage”. SWANA Washington D.C. Conference Proceedings.

Designing for a Leakage Rate – Landfill Example

- Assumptions:
  - Leaks possible in all locations with equal probability
  - 4.9 leaks per ha
  - **ELL will not detect leaks on wrinkles**
  - Percentage of wrinkled area (17% typical GM, 7% white GM)
  - Wrinkle geometry (0.31 m wide, 190 m long)
  - GCL hydraulic conductivity and GM/GCL interface transmissivity (5.0 x 10-11 m/s, 2.0 x 10-10 m2/s)
  - Hydraulic head of 0.3 m

Source: Beck, Abigail (2015). "Available Technologies to Approach Zero Leaks". Geosynthetics 2015 Conference Proceedings.

Designing for a Leakage Rate –Example

Applied Technology	Probability of Exceeding 187 lphd	Probability of Exceeding 47 lphd
ELL Applied after cover material placement only*	6.6%	50.7%
ELL Applied both before and after cover material placement	0.02%	11.7%
ELL Applied both before and after cover material placement, plus white geomembrane	8.9 x 10^{-10}%	0.55%

*Leakage mean from actual leakage statistics shown in earlier slides

Source: Beck, Abigail (2015). "Available Technologies to Approach Zero Leaks". Geosynthetics 2015 Conference Proceedings.

Conclusions and Recommendations

- Designing to minimize leakage is both an art and a science
- The best tool for minimizing leakage is the application of Electrical Leak Location methods
    - Learn methodologies, capabilities and limitations
    - Carefully consider and specify method(s)
- Aim for zero (or minimal) leakage for project specifications
- When designing for an ALR, use conservative assumptions and equations to estimate theoretical leakage and use probabilistic analysis to check for a sufficiently low probability of failure

Questions?

TRI ENVIRONMENTAL

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Master Class #1

Liquid and Gas Depressurisation in Storages

Speaker: Fred Gassner (WSP Golder)

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Why and When is depressurisation a consideration?

- Unconfined conditions – Ponds, covers
- Improved performance of lining system – composite effect
- Buoyancy consideration
- Dimensional stability
- Protection of subgrade materials

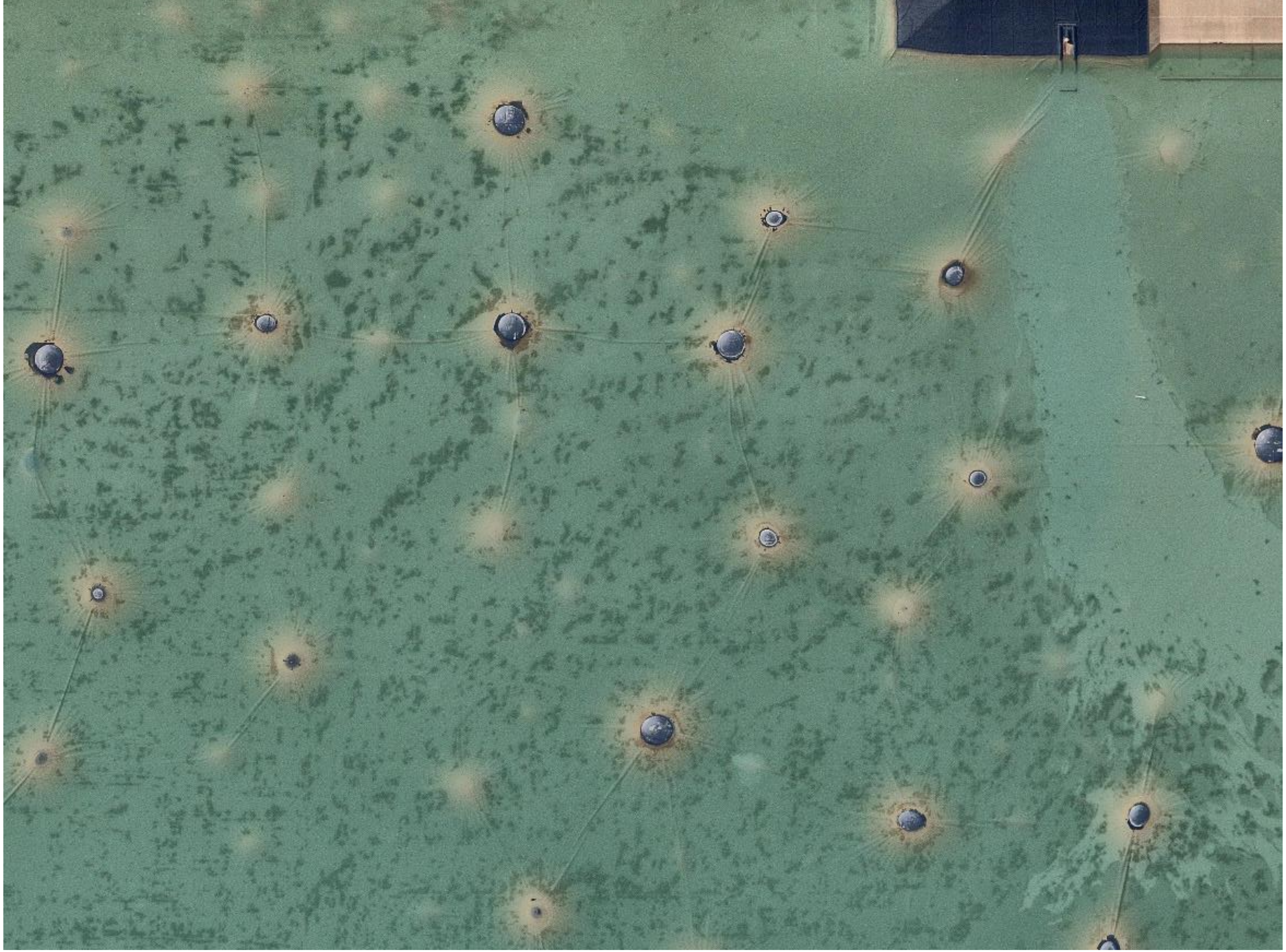
Low confinement conditions – Ponds, covers

- ➢ Pressure below liner is higher than above – can be water or gas pressure
    - Landfill caps – gas and leachate
    - Pond liners – ground gas and groundwater
    - Rain jacket covers - gas
- ➢ Buoyancy – Polyethylene and Polypropylene are lighter than water
    - ➢ Trapped water below liner results in buoyancy

Considerations:

- Weight of liner minor effect
- Overlying water load confines liner only if no leaks or area below liner is lower pressure
- Trapped air combined with liquid buoyancy = potentially high stresses on liner
- Deformed liner keeps growing until balance of forces.
- Below liner seepage rate = leakage rate through defects
- Initial fill – displaces trapped air - wrinkles

Gas: generally diffuse source from under liner

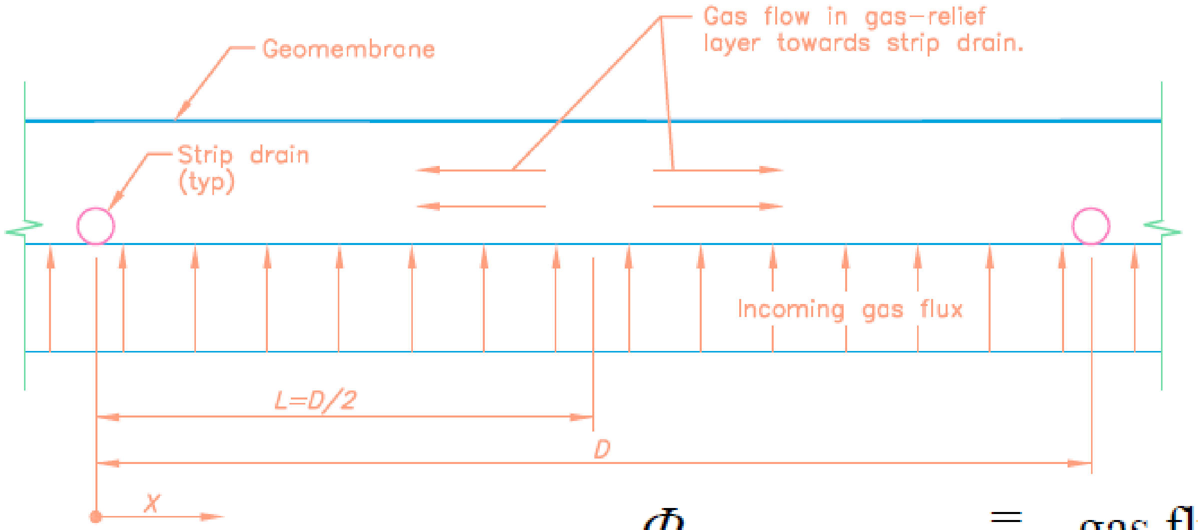


Uplift conditions

- Cap gas pressure > weight of soil/cover
- Uplift conditions = veneer stability on liner underside
- Uneven pressure – strips

Thiel, R.S.1998. “Design Methodology for a Gas Pressure Relief Layer Below a Geomembrane Landfill Cover to Improve Slope Stability.” *Geosynthetics International*, vol. 5, no. 6, pp. 589–617

Gas Depressurisation



$$u_{max} = \frac{\Phi_g \gamma_g}{\Psi_g}\left(\frac{D^2}{8}\right)$$

$\Psi_g = k_g \cdot t$ (gas transmissivity of the gas relief layer)

Φ_g = gas flux from landfill surface ($m^3/s/m^2$)

Ψ_g = gas transmissivity of soil or geosynthetic ($m^3/s/m$)

u_{max} = maximum gas pore pressure (Pa) triangular distribution

γ_g = unit weight of gas (N/m^3)

Gas Depressurisation – cont.

$$\Psi_g = k_g \cdot t \quad \text{(gas transmissivity of the gas relief layer)}$$

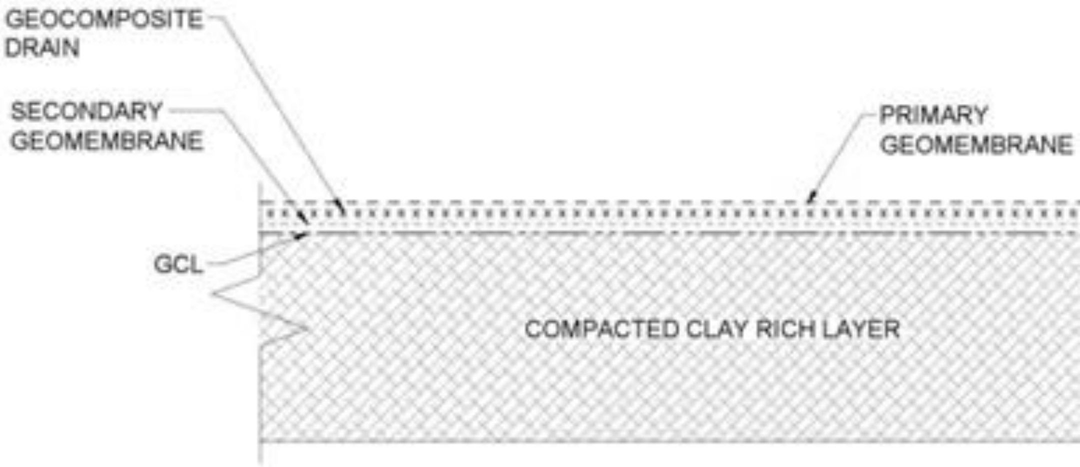
Permeability of relief layer:

- Saturation dependent – transmissivity vary by up to 40%
- Air k is approx. 1/10 of water *k*
- Effect of confining load reduces k_g and *t* of geosynthetics
- Natural materials in covers are usually variable, so variable *k*
- Landfill gas is saturated – condensate drop out from change in temperature/pressure

Note, gas pressure is usually below liner, so movement likely to damage liner

Liner Performance wrt liquid

- Pressure below liner = pressure above liner, reduced seepage benefit of liner
- Drainage below liner – atmospheric conditions
- Drains below liner can promote uplift conditions – wind
- Wrinkle effects vs minimal wrinkles – liner material specific
- Lateral permeability of depressurisation system
  - Wrinkles vs minimal wrinkles
  - Strips vs continuous drainage layer



Effects at toe – floor change in grade and flow capacity

Deflated large bubble / hippo

Buoyancy and Stability

- ➢ Uplifted liners move – relocated shape , stresses, crinkles
- ➢ Hippos can be huge
- ➢ Below liner items may also float/move when uplift occurs, e.g. geocomposite drains and polyethylene pipes (density less than water).

Buoyancy conditions

- 2mm HDPE = 1.9 kg/m^2
- 4.8 mm BGM = 5.8 kg/m^2
- GCL = 4 to 5 kg/m^2
- 6 kg/m^2 = 6 mm water head

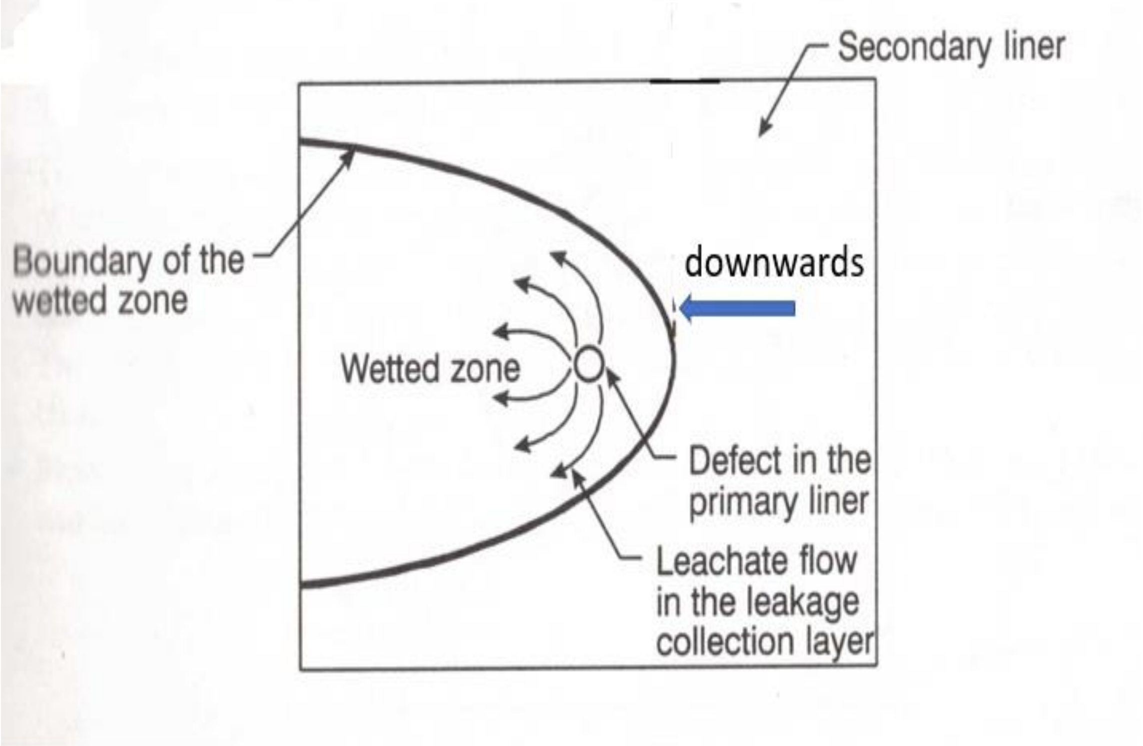
Buoyancy = unconfined, free to float, reposition within water

Permanent ballast reduces freedom

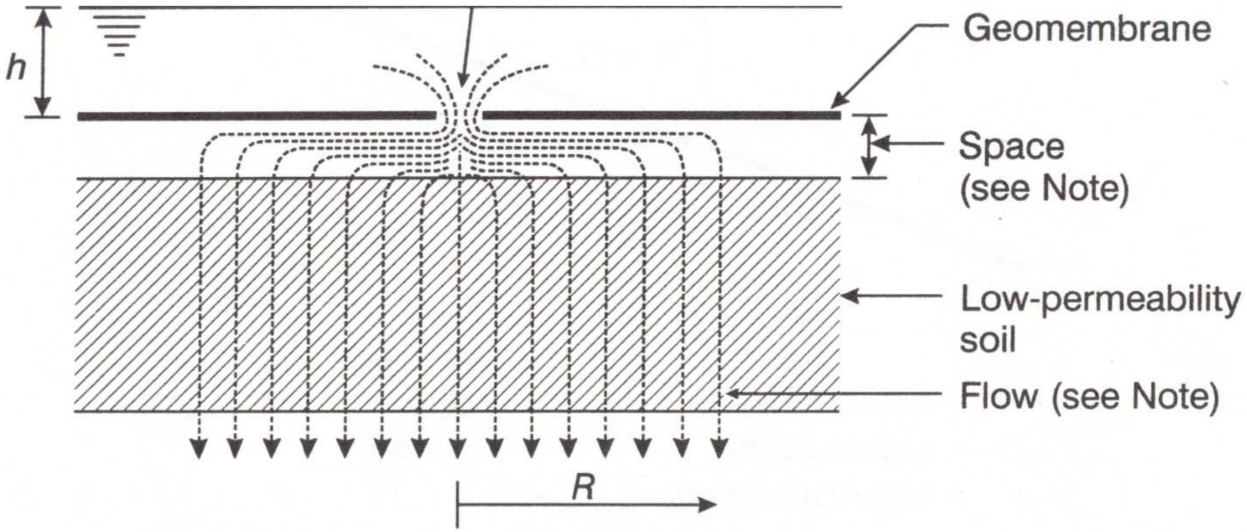
Toe ballast = important

$$Q = 0.6\, a \sqrt{2 g h_{prim}}$$

Liquid: Defect driven flow rate – Point source
High head & gentle grade – near circular wetted zone



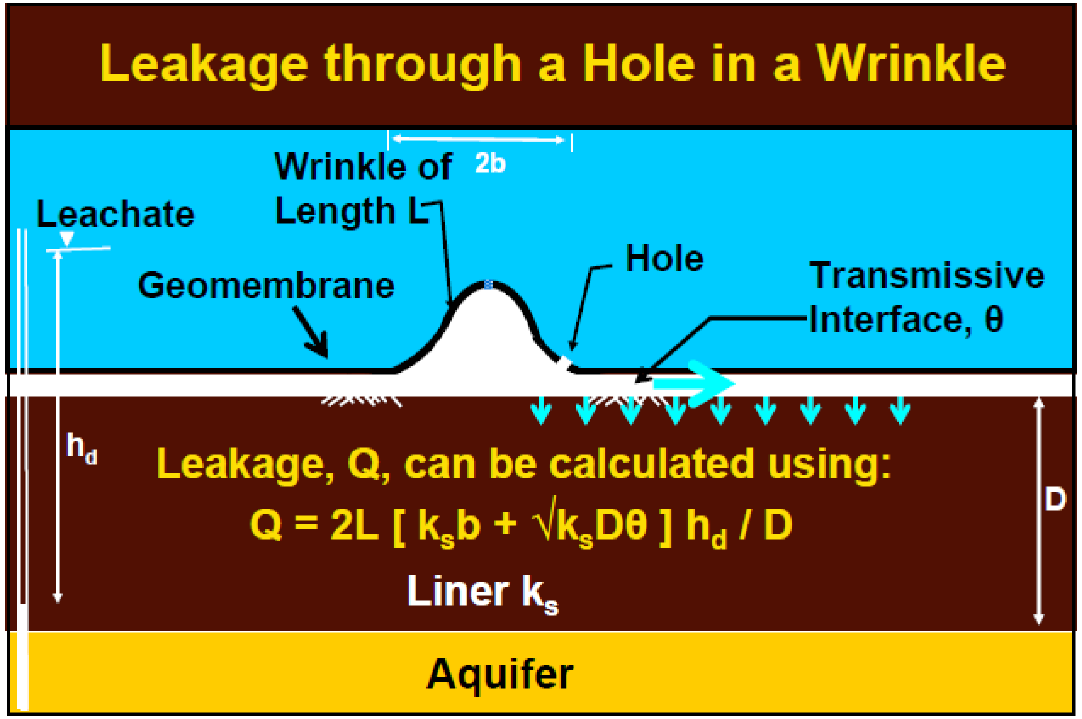
Source: JP Giroud GI Vol 4 No 3&4, 1997



Space = wrinkle, geonet, etc
Flow (seepage) = defect flow rate = equilibrium

Considerations:

- Drainage layer capacity: full flow condition = pressure on secondary liner = pond stored depth (through defects)
- Slope of pond floor – changes in head
- Wrinkles = drainage conduits
- Pressure below geomembrane reduces composite effects



Leakage through a Hole in a Wrinkle

Leakage, Q, can be calculated using:

$$Q = 2L\ [\ k_s b + \sqrt{k_s D\theta}\ ]\ h_d / D$$

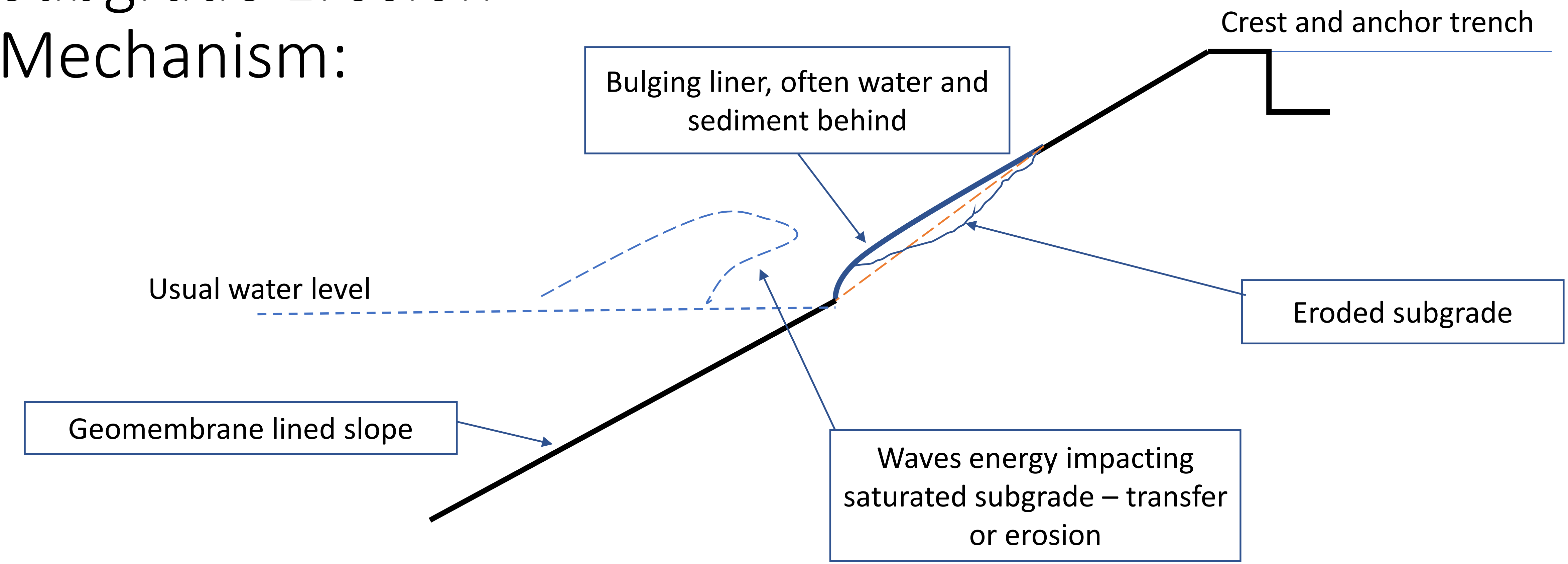
Liner k_s

Ref: Prof K Rowe. – Queens University, numerous publications

Subgrade

- Erosion of subgrade – wave energy transfer to trapped liquid
- Bridging of liner over erosion gullies or bulges
- Expose deeper subgrade materials
- Bulge effect of liner at water liner – no confinement

Subgrade Erosion Mechanism:



Crest and anchor trench

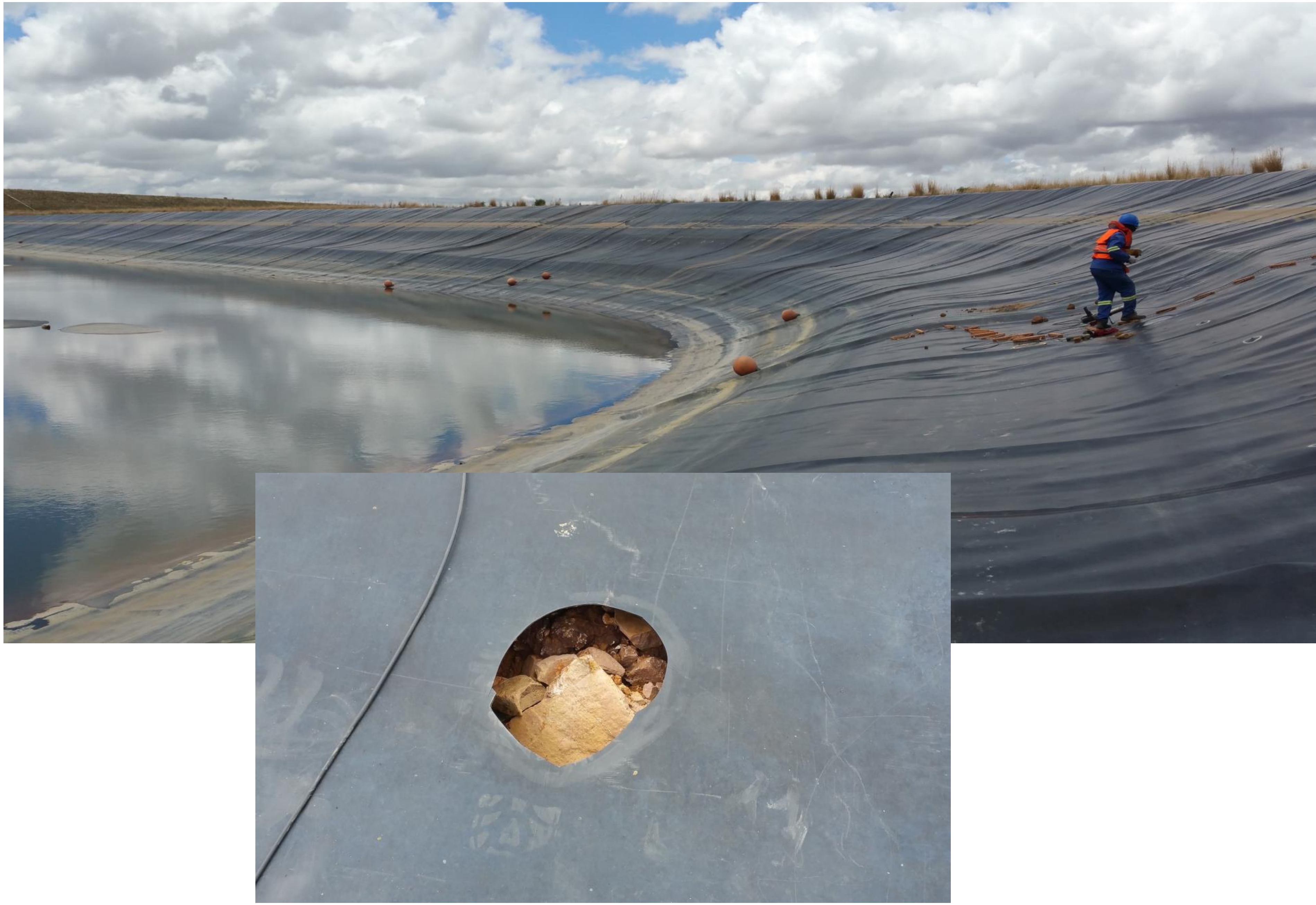
Bulging liner, often water and sediment behind

Usual water level

Eroded subgrade

Geomembrane lined slope

Waves energy impacting saturated subgrade – transfer or erosion



Erosion risk reduction measures

- Design system to remove trapped water below liner
- Early intervention – monitoring during operation
- Consider the effect of variable water level
- Avoid high silt or dispersive clay content slope subgrade

Critical Considerations When Designing for the Containment of PFAS and Other Emerging Contaminants Using Geosynthetics

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1. The Contaminant/s
2. The Proposed Site
3. The Regulatory Requirements
4. The Geosynthetic Components
5. The Performance Assessments

1 The Contaminant/s

- Source/Type/Concentration/Media? PFAS? PPCP's? VOCs? Pesticides? Phlalates? Standardised soil, water and sediment analyses are required to qualify and quantify the scope of the problem.
- Are they likely to change or degrade into other forms over time? eg. precursors = TOP Assay
- What are the current and/or potential pathways into the environment?
- What are the fate and transport mechanisms? Can they volatilise?
- What is the leachability (in soils) and how mobile are they?
- Do one or more of them present an unacceptable human health or environmental risk at the current levels?
- Will certain activities on site add substances to the soil which may raise the background levels?

Image Credit: Río Tinto River, Spain DOI: 10.13140/RG.2.2.28160.64009

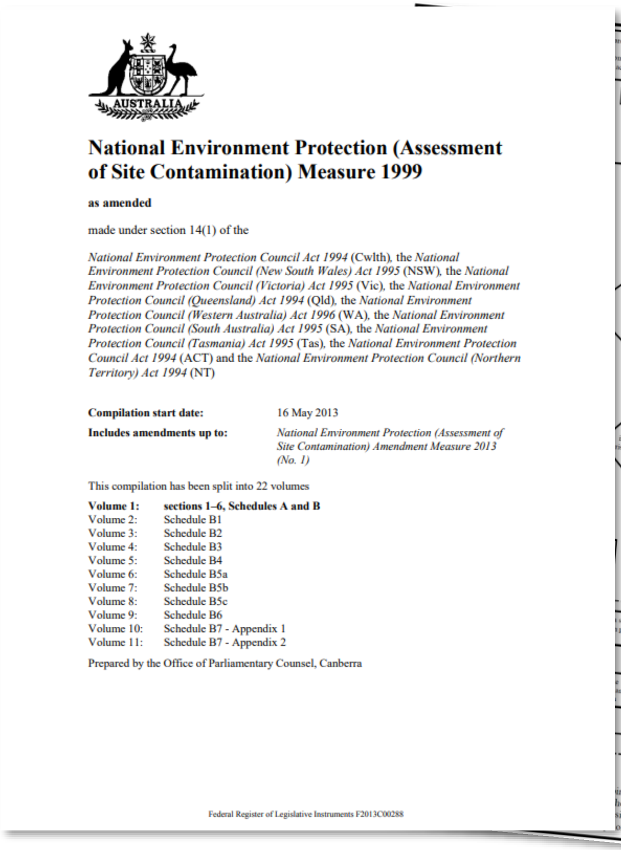
2 The Proposed Site

- What are the geotechnical and geochemical aspects of the site and surrounding area eg. Rock/soil types, groundwater quality?
- What are the hydrological and hydrogeological aspects of the site and surrounding area eg. where's the water table? Plume potential?
- In the event of a liner failure, what is the likelihood of contaminant release and transport?
- Is the site in a metropolitan or regional area? Residential / Commercial / Industrial / Recreational?
- Is the surrounding ecosystem particularly sensitive to the contaminants eg. aquatic life?
- What are the seasonal climatic conditions for the site? Rainfall? Heat? Wind?
- What are the different types of fauna around the site? Is there a chance they may damage the lining system eg. kangaroos?

Image Credit: Peter Glenane/HiVis Pictures

3 The Regulatory Requirements

- Are there any existing or evolving local/state/federal/international regulation or guidance limits on each of the contaminant/s?



AUSTRALIA

National Environment Protection (Assessment of Site Contamination) Measure 1999

as amended

made under section 14(1) of the

National Environment Protection Council Act 1994 (Cwlth), the *National Environment Protection Council (New South Wales) Act 1995* (NSW), the *National Environment Protection Council (Victoria) Act 1995* (Vic), the *National Environment Protection Council (Queensland) Act 1994* (Qld), the *National Environment Protection Council (Western Australia) Act 1996* (WA), the *National Environment Protection Council (South Australia) Act 1995* (SA), the *National Environment Protection Council (Tasmania) Act 1995* (Tas), the *National Environment Protection Council Act 1994* (ACT) and the *National Environment Protection Council (Northern Territory) Act 1994* (NT)

Compilation start date: 16 May 2013

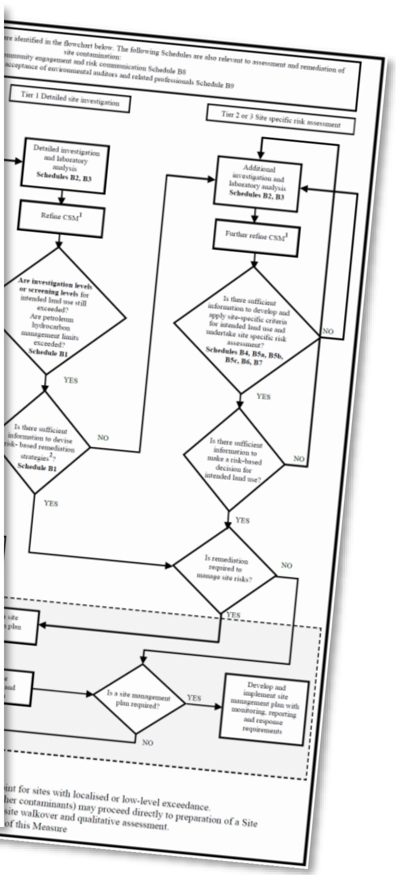
Includes amendments up to: *National Environment Protection (Assessment of Site Contamination) Amendment Measure 2013 (No. 1)*

This compilation has been split into 22 volumes

Volume 1: sections 1–6, Schedules A and B
Volume 2: Schedule B1
Volume 3: Schedule B2
Volume 4: Schedule B3
Volume 5: Schedule B4
Volume 6: Schedule B5a
Volume 7: Schedule B5b
Volume 8: Schedule B5c
Volume 9: Schedule B6
Volume 10: Schedule B7 - Appendix 1
Volume 11: Schedule B7 - Appendix 2

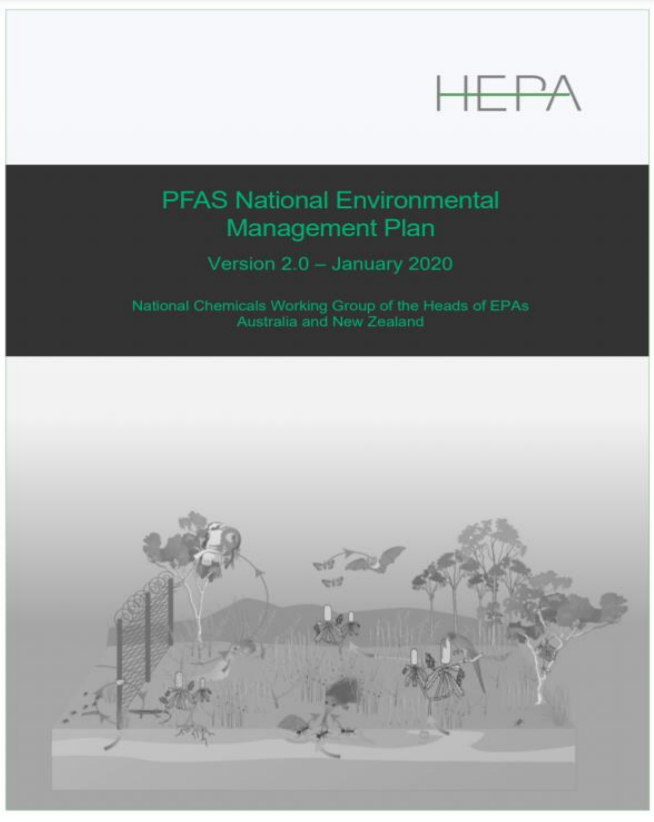
Prepared by the Office of Parliamentary Counsel, Canberra

Federal Register of Legislative Instruments F2013C00288



re identified in the flowchart below. The following Schedules are also relevant to assessment and remediation of site contamination:
ommunity engagement and risk communication Schedule B8
acceptance of environmental auditors and related professionals Schedule B9

int for sites with localised or low-level exceedance.
her contaminants) may proceed directly to preparation of a Site
site walkover and qualitative assessment.
of this Measure

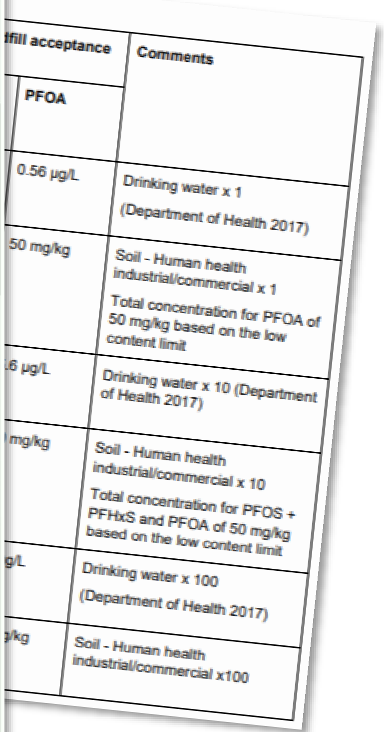


HEPA

PFAS National Environmental Management Plan

Version 2.0 – January 2020

National Chemicals Working Group of the Heads of EPAs Australia and New Zealand



fill acceptance	Comments
PFOA	
0.56 µg/L	Drinking water x 1 (Department of Health 2017)
50 mg/kg	Soil - Human health industrial/commercial x 1 Total concentration for PFOA of 50 mg/kg based on the low content limit
6 µg/L	Drinking water x 10 (Department of Health 2017)
mg/kg	Soil - Human health industrial/commercial x 10 Total concentration for PFOS + PFHxS and PFOA of 50 mg/kg based on the low content limit
g/L	Drinking water x 100 (Department of Health 2017)
g/kg	Soil - Human health industrial/commercial x100

Image Credit: mocah.org

The Geosynthetic Components

- What is the expected design life of the system?
- What is the damage potential of the geosynthetics? Geotechnical? Installation?
- Are the geosynthetic polymers compatible with both the site's geochemistry and the soil/liquid to be contained? Temperature? pH?
- Will the overall design work as a system to inhibit the transport of the contaminants over the design life?
- How will the performance of the geosynthetic materials change over time in contact with the contaminated materials? Mechanical? Shear? Hydraulic? Creep? SCR? Durability?
- Does the design include the current best practice geosynthetic materials?
- Have the proposed geosynthetic components been physically assessed separately and/or together for performance using actual site materials?
- Have the leakage rates of the components been appropriately modeled in line with the expected loads and hydraulic head potential?
- Double lining? Leachate Collection/Detection? Protection? MQC/CQA Program?

Image Credit: Geofabrics Australasia Pty Ltd

The Performance Assessments

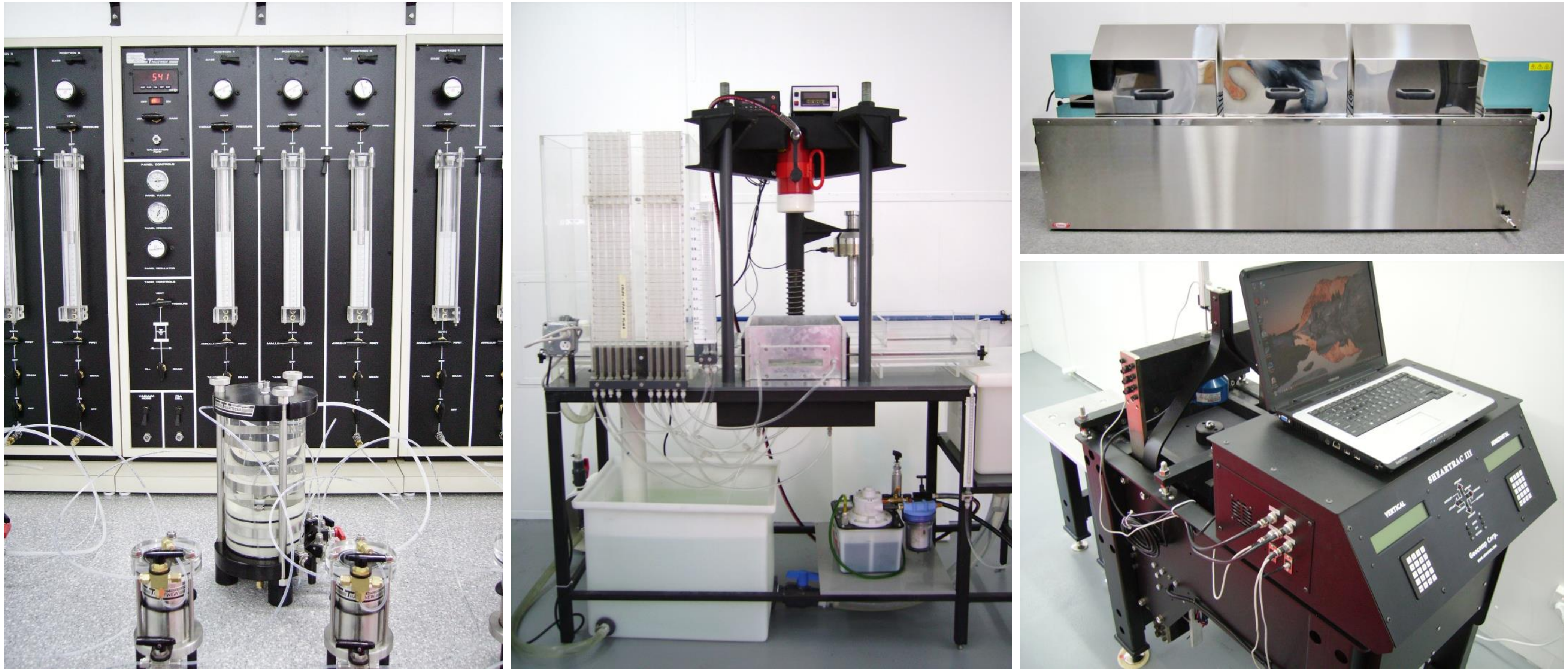
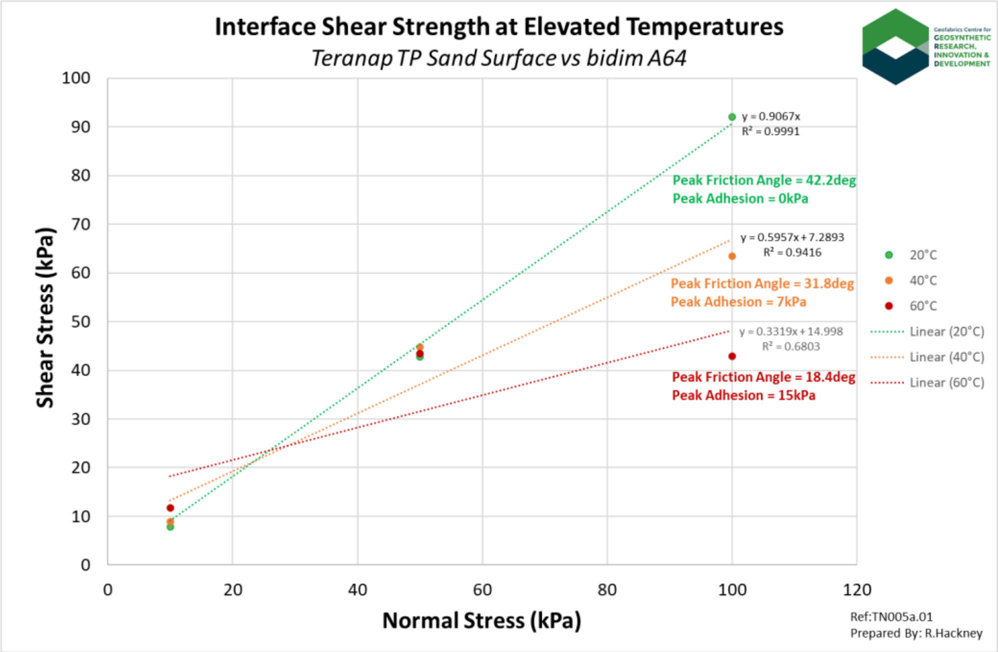


Image Credit: GRID laboratory equipment, Geofabrics

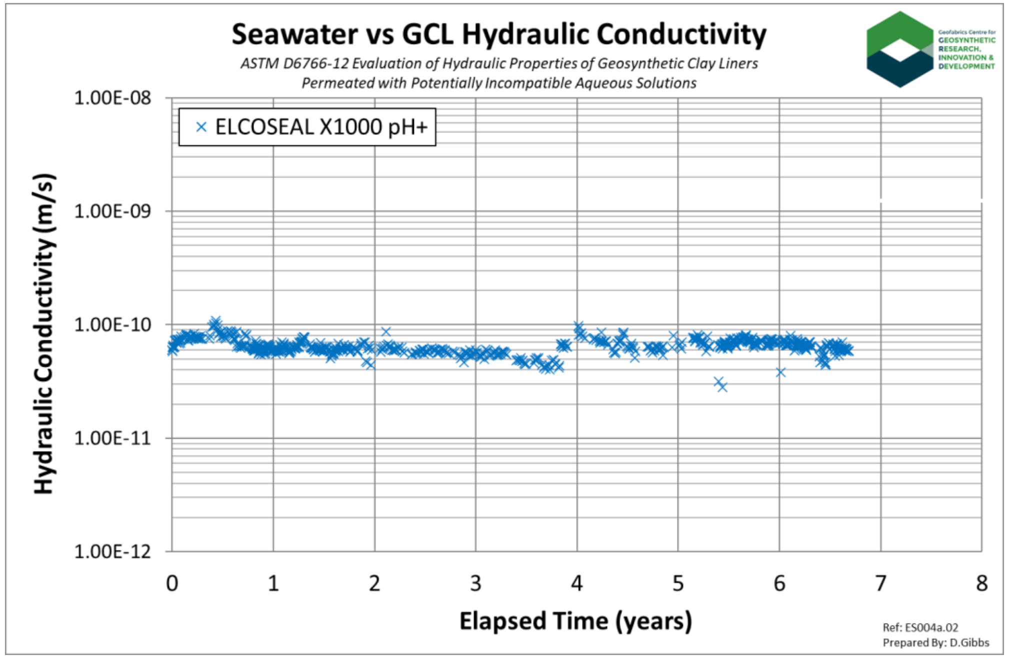
5 The Performance Assessments

Elevated Temperature



Ref:TN005a.01
Prepared By: R.Hackney

Long-Term Testing



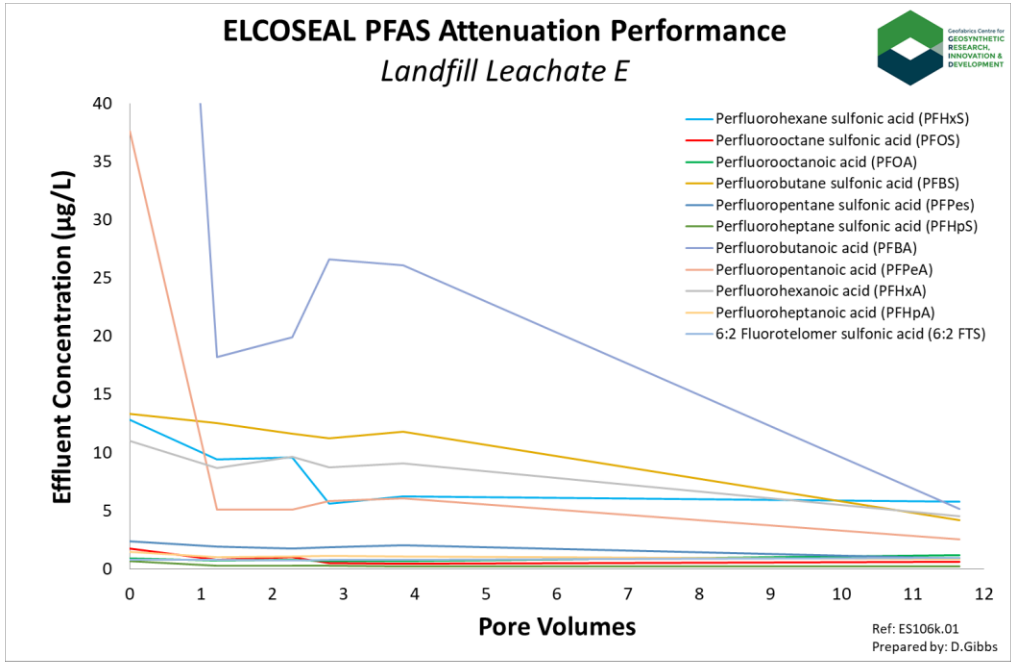
Ref: ES004a.02
Prepared By: D.Gibbs

Image Credit: Hydraulic Conductivity cells, Geofabrics

5

The Performance Assessments

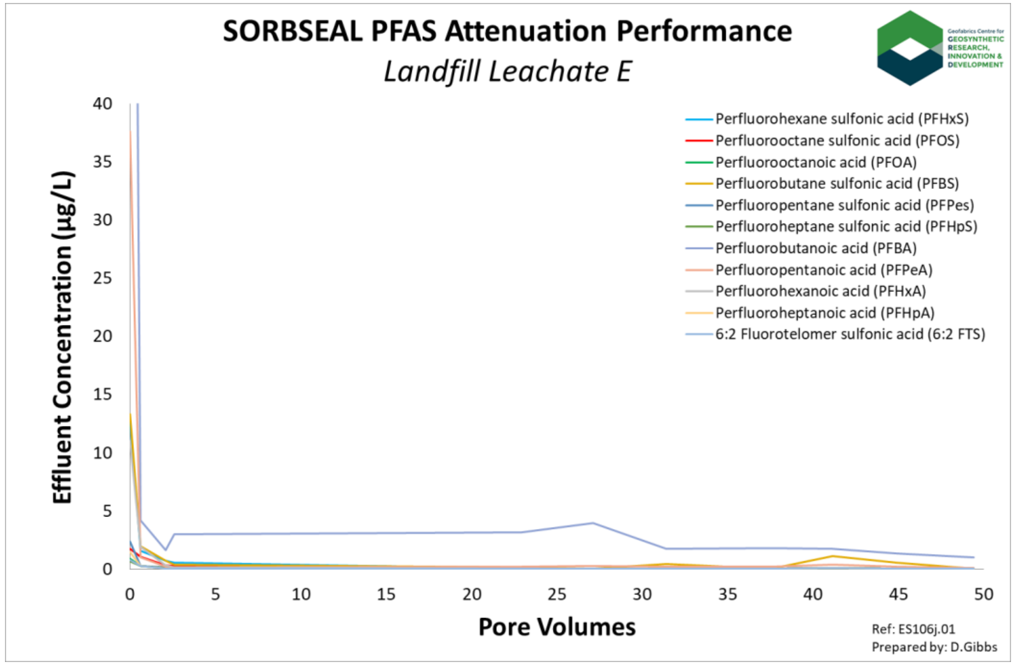
SORBSEAL®



ELCOSEAL PFAS Attenuation Performance

Landfill Leachate E

Ref: ES106k.01
Prepared by: D.Gibbs



SORBSEAL PFAS Attenuation Performance

Landfill Leachate E

Ref: ES106j.01
Prepared by: D.Gibbs

Image Credit: Hydraulic Conductivity cells, Geofabrics

Summary

A robust geosynthetic lining design should include a range of critical considerations including, inter alia:

- ✓ Contaminant assessment (e.g. type/s, concentration, transport mechanisms etc),
- ✓ Desktop assessments (e.g. modelling, lit reviews, case studies, geosynthetic material datasheets etc),
- ✓ Site assessments (e.g. enviro, geotech and hydro reports etc),
- ✓ Regulatory review (e.g. NEPM, NEMP etc),
- ✓ Geosynthetic material performance assessments using design inputs, proposed geosynthetics and site-specific materials (e.g. long-term interaction and durability analyses, site trials etc)

ACigs GEOANZ Master Class #1
Innovations in Multi- Component GCL applications in Contaminated Land Remediation

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GRI-GCL3

https://geosynthetic-institute.org/grispecs/gcl3.pdf

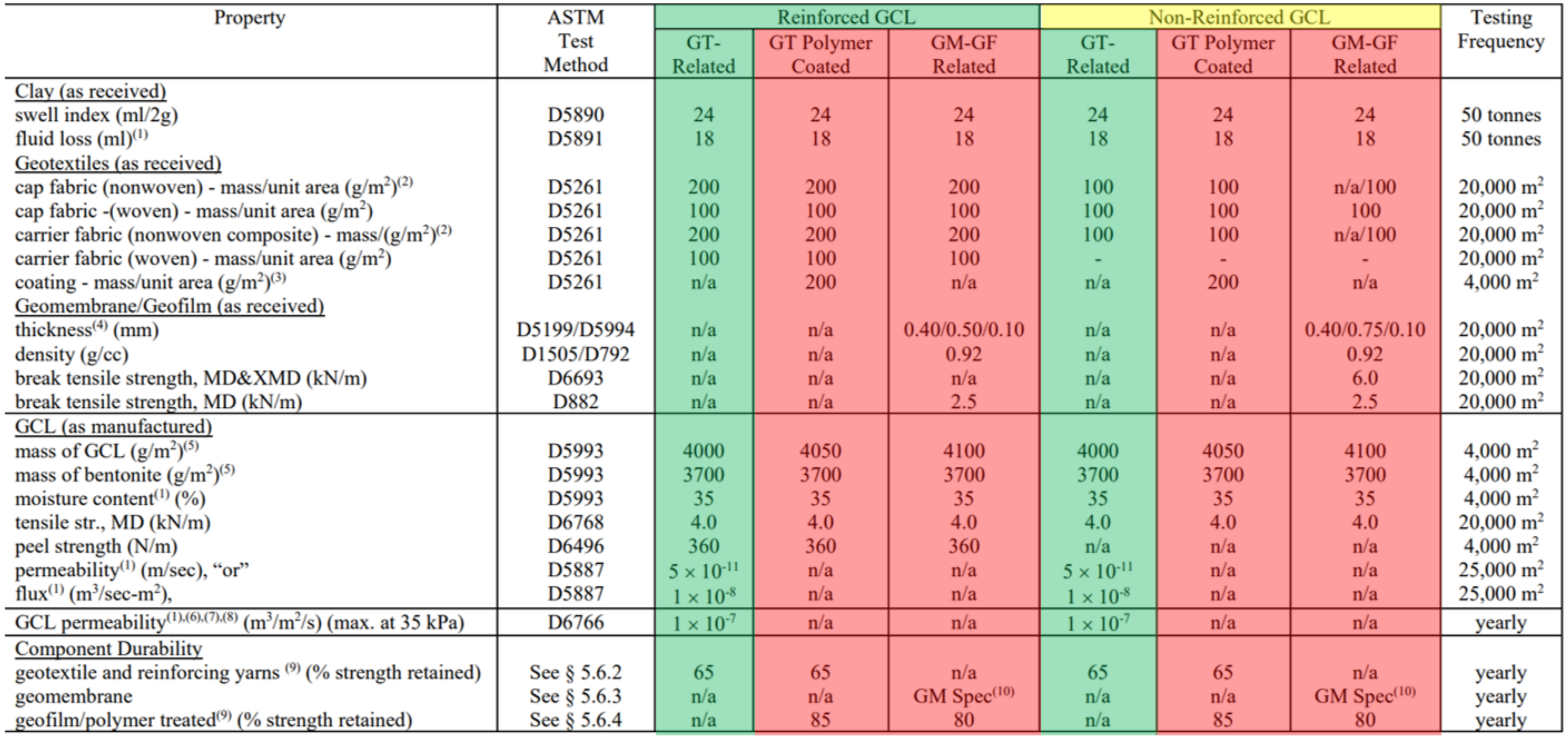
Generic GCL specification

Geosynthetic Institute
475 Kedron Avenue
Folsom, PA 19033, U. S. A.
Tel: (610) 522 - 8440
Fax: (610) 522 - 8441

GRI-GCL3 Spec - S.I. (Metric) Units

Multi-component GCL

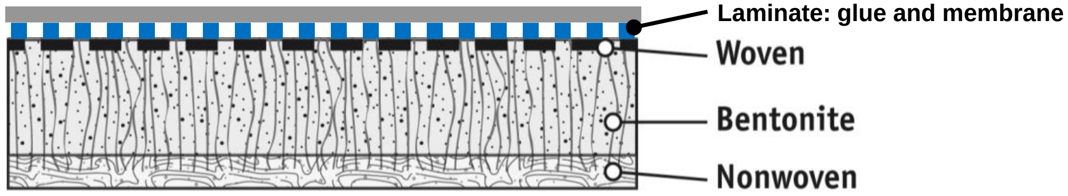
Table 1(a) – Specification for Geosynthetic Clay Liners (GCLs)



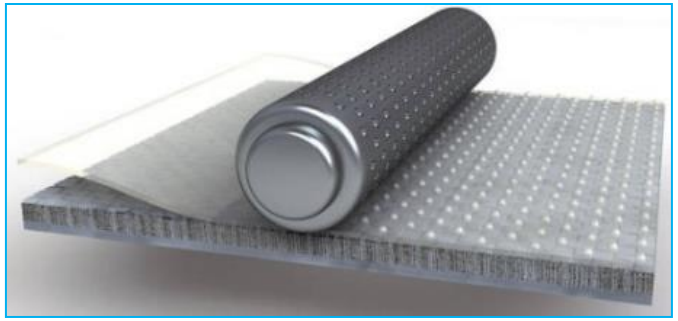
Property	ASTM Test Method	Reinforced GCL			Non-Reinforced GCL			Testing Frequency
		GT-Related	GT Polymer Coated	GM-GF Related	GT-Related	GT Polymer Coated	GM-GF Related	
<u>Clay (as received)</u>								
swell index (ml/2g)	D5890	24	24	24	24	24	24	50 tonnes
fluid loss (ml)$^{(1)}$	D5891	18	18	18	18	18	18	50 tonnes
<u>Geotextiles (as received)</u>								
cap fabric (nonwoven) - mass/unit area (g/m^2)$^{(2)}$	D5261	200	200	200	100	100	n/a/100	20,000 m^2
cap fabric -(woven) - mass/unit area (g/m^2)	D5261	100	100	100	100	100	100	20,000 m^2
carrier fabric (nonwoven composite) - mass/(g/m^2)$^{(2)}$	D5261	200	200	200	100	100	n/a/100	20,000 m^2
carrier fabric (woven) - mass/unit area (g/m^2)	D5261	100	100	100	-	-	-	20,000 m^2
coating - mass/unit area (g/m^2)$^{(3)}$	D5261	n/a	200	n/a	n/a	200	n/a	4,000 m^2
<u>Geomembrane/Geofilm (as received)</u>								
thickness$^{(4)}$ (mm)	D5199/D5994	n/a	n/a	0.40/0.50/0.10	n/a	n/a	0.40/0.75/0.10	20,000 m^2
density (g/cc)	D1505/D792	n/a	n/a	0.92	n/a	n/a	0.92	20,000 m^2
break tensile strength, MD&XMD (kN/m)	D6693	n/a	n/a	n/a	n/a	n/a	6.0	20,000 m^2
break tensile strength, MD (kN/m)	D882	n/a	n/a	2.5	n/a	n/a	2.5	20,000 m^2
<u>GCL (as manufactured)</u>								
mass of GCL (g/m^2)$^{(5)}$	D5993	4000	4050	4100	4000	4050	4100	4,000 m^2
mass of bentonite (g/m^2)$^{(5)}$	D5993	3700	3700	3700	3700	3700	3700	4,000 m^2
moisture content$^{(1)}$ (%)	D5993	35	35	35	35	35	35	4,000 m^2
tensile str., MD (kN/m)	D6768	4.0	4.0	4.0	4.0	4.0	4.0	20,000 m^2
peel strength (N/m)	D6496	360	360	360	n/a	n/a	n/a	4,000 m^2
permeability$^{(1)}$ (m/sec), “or”	D5887	5×10^{-11}	n/a	n/a	5×10^{-11}	n/a	n/a	25,000 m^2
flux$^{(1)}$ (m^3/sec-m^2),	D5887	1×10^{-8}	n/a	n/a	1×10^{-8}	n/a	n/a	25,000 m^2
GCL permeability$^{(1),(6),(7),(8)}$ (m^3/m^2/s) (max. at 35 kPa)	D6766	1×10^{-7}	n/a	n/a	1×10^{-7}	n/a	n/a	yearly
<u>Component Durability</u>								
geotextile and reinforcing yarns $^{(9)}$ (% strength retained)	See § 5.6.2	65	65	n/a	65	65	n/a	yearly
geomembrane	See § 5.6.3	n/a	n/a	GM Spec$^{(10)}$	n/a	n/a	GM Spec$^{(10)}$	yearly
geofilm/polymer treated$^{(9)}$ (% strength retained)	See § 5.6.4	n/a	85	80	n/a	85	80	yearly

Multi-component GCL, n - GCL with an attached film, coating, or membrane decreasing the hydraulic conductivity or protecting the clay core or both

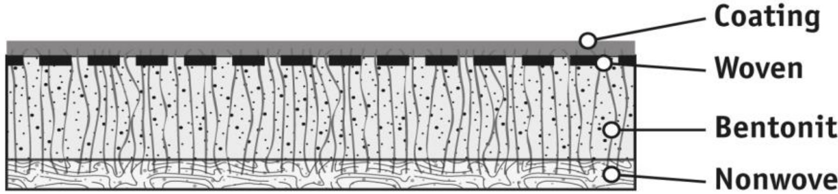
laminated GCL, n—GCL product with at least one film or membrane layer superimposed and bonded to the GCL by an adhesive (e.g. glue) usually under heat and pressure



Likely only short-term bonding as adhesive hardly sticks long-term to e.g. PE laminate



coated GCL, n - GCL product with at least one layer of a synthetic substance applied to the GCL as a fluid and allowed to solidify



Permanent bonding due to fibre reinforcment of GCL bonded into the coating material

Brownfield Development and Contaminated Land, and Australian perspective

- **2012 Urban Brownfields – Australian perspective paper, University of Melbourne**
- …….Brownfield development is key to achieving cities economic and development goals, in particular to addressing social welfare and sustainability concerns.
- **Docklands in Melbourne, Darling harbour in Sydney, Newport Quays in Adelaide, Southbank in Brisbane**
- Looking at experiences in China and UK (60% of all new development is on brownfield sites" recognises the " …Challenge for direct comparison and transference of urban regeneration knowledge"

Multi component GCL and standard GCL in Australian contaminated land sites

- Camellia Remediation project for Parramatta Light railway – textured Multi component GCL used against “cocktail highly toxic chemicals”
- Sydney light rail Chromium contamination capping works for Phase 1 construction
- Port Bonython secondary containment for Mitsubishi.

MGCL – Reinforced GLCs with Geotextile polymer coating product advances for Contaminated Land

- **Enhanced root penetration prevention** – Barrier to high moisture Bentonite, reduces cover soil thickness
- **Increased resistance to desiccation** – allow for soil thickens reduction – in accepted by environmental regulatory authorities in UK / UAE
- **Ionic exchange** – proven barrier to natural bentonite chemical reactions and aggressive contaminates, supports Bentonite field holding water capacity
- **Instant gas barrier** – prior to full hydration of Bentonite and natural dehydration cycles.
- **Retains self healing properties** – as with standard reinforced GCLS

MGCL – Reinforced GLCs with Geotextile polymer coating application advances for Contaminated Land

- Project site specific cost reduction of soil cover import / export.
- Paris Agreement - climate change and CO2 reduction on construction project requirements
- Phase 1 remediation – post MGCL installation steel driven hollow piling penetration possible with self healing properties retained

SIGHTHILL REMEDIATION CAP 2016 - 2020

SITE INTRODUCTION

- £250 million Sighthill Regeneration Programme 2014 - 2020
- 650 housing / social housing units. Schools, churches, park spaces, community facilities and health centres.
- Hydrocarbon and Galligu Waste.
- industrial process using Sodium Chloride, Vital for Paper, Textile, Glass and Soap Industries
- by products include Hydrochloric acid gas, sulphur based insoluble waste and hydrogen sulphide – toxic gas “rotten egg” smell

DESIGN CRITERIA

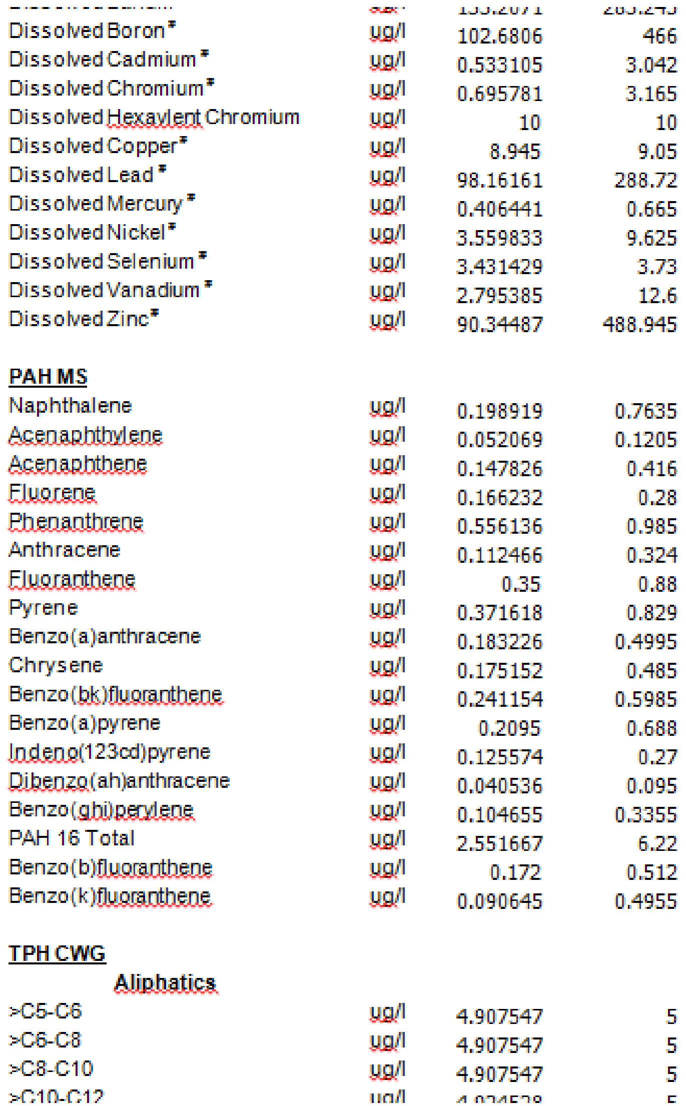
- Remediation strategy for contaminated land to comply with BS 10175:2001 contamination code of practice and meet CO2 project reduction targets
- Membrane to tie and connect to site boundary slurry walls
- Membrane to prevent fresh water ingress to stop leachate creation whilst being an instant and permeant gas barrier
- Membrane to be chemically compatible with contaminates, meet 50 year design life and CE Mark Durability requirements
- Membrane to be self healing to allow post construction piling
- Long term gas monitoring of piling penetrations

CHEMICAL ANALYSIS

Based on Galligu Chemical analysis Chemical combability undertaken on natural sodium bentonite and polymer based coating

500 gram protection geotextile placed above Multi component GCL to allow “cushion” protection

Multi component GCL installed with polymer coating face down on subgrade / galligu waste.



Dissolved Boron*	ug/l	102.6806	466
Dissolved Cadmium*	ug/l	0.533105	3.042
Dissolved Chromium*	ug/l	0.695781	3.165
Dissolved Hexavlent Chromium	ug/l	10	10
Dissolved Copper*	ug/l	8.945	9.05
Dissolved Lead*	ug/l	98.16161	288.72
Dissolved Mercury*	ug/l	0.406441	0.665
Dissolved Nickel*	ug/l	3.559833	9.625
Dissolved Selenium*	ug/l	3.431429	3.73
Dissolved Vanadium*	ug/l	2.795385	12.6
Dissolved Zinc*	ug/l	90.34487	488.945
PAH MS			
Naphthalene	ug/l	0.198919	0.7635
Acenaphthylene	ug/l	0.052069	0.1205
Acenaphthene	ug/l	0.147826	0.416
Fluorene	ug/l	0.166232	0.28
Phenanthrene	ug/l	0.556136	0.985
Anthracene	ug/l	0.112466	0.324
Fluoranthene	ug/l	0.35	0.88
Pyrene	ug/l	0.371618	0.829
Benzo(a)anthracene	ug/l	0.183226	0.4995
Chrysene	ug/l	0.175152	0.485
Benzo(bk)fluoranthene	ug/l	0.241154	0.5985
Benzo(a)pyrene	ug/l	0.2095	0.688
Indeno(123cd)pyrene	ug/l	0.125574	0.27
Dibenzo(ah)anthracene	ug/l	0.040536	0.095
Benzo(ghi)perylene	ug/l	0.104655	0.3355
PAH 16 Total	ug/l	2.551667	6.22
Benzo(b)fluoranthene	ug/l	0.172	0.512
Benzo(k)fluoranthene	ug/l	0.090645	0.4955
TPH CWG			
Aliphatics			
>C5-C6	ug/l	4.907547	5
>C6-C8	ug/l	4.907547	5
>C8-C10	ug/l	4.907547	5

Multi Component GCL with 500 gram geotextile installation

Multi Component GCL with 500 gram geotextile installation

POST INSTALLATION PILE TESTING

- 45 no boreholes - 50 m grid network across the site – 24 months of monitoring data
- Pre piling gas monitoring for base line data
- Client, Engineer, Contractor and Architect present on site during excavation for visual inspection of 9 BH two months after installation
- Method statement for exposure to inspect integrity of imitate content agreed by all parties.

POST INSTALLATION PILE TESTING

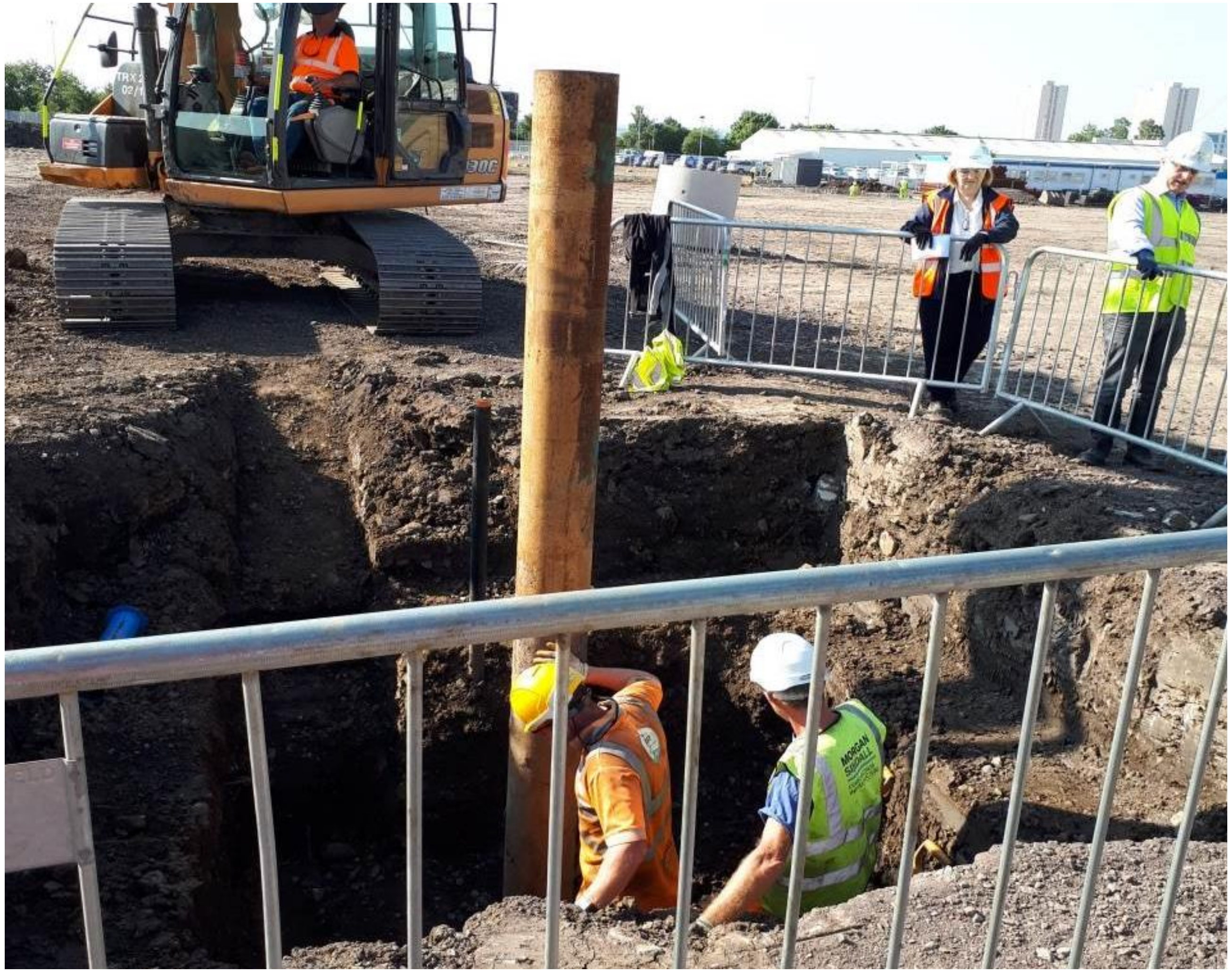
Gas monitoring data showed initial peak in gas monitoring followed by quick return to minimal reading for 7 out of 8 BH.

BH with high gas readings engineer determined to be other factors

Exposure of BH showed mix of "intimate contact min 6 mm gap" .

Self healing around penetration approved

Pile penetration acceptance certified by Glasgow Council, SEPA and NHBC January 2020



POST INSTALLATION PILE TESTING

Thank you for your time,

Any questions

Geosynthetic Barriers for PFAS containment: current options, historical precedents and new materials

GEOANZ #1 ADVANCES IN GEOSYNTHETICS
7–9 JUNE 2022 | BRISBANE CONVENTION & EXHIBITION CENTRE

Geosynthetic Barriers for PFAS containment: current options, historical precedents and new materials

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Business Manager
HUESKER Australia

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E-Mail: gus@HUESKER.com.au

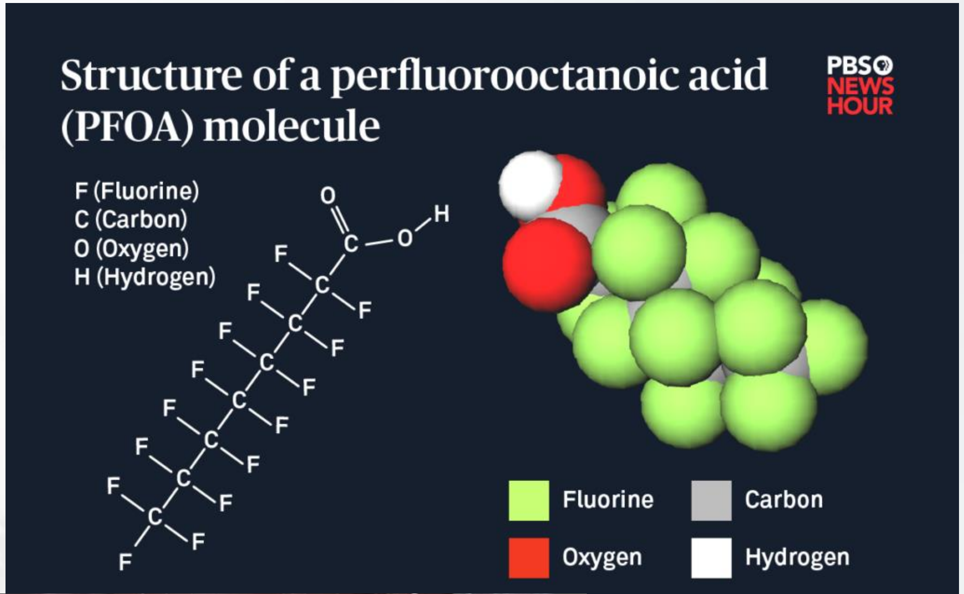
GEOANZ #1 ADVANCES IN GEOSYNTHETICS
7–9 JUNE 2022 | BRISBANE CONVENTION & EXHIBITION CENTRE

Modern Contaminants - PFAS

- *These substances have surfactant properties due to their hydrophilic functional end groups and hydrophobic fluorinated tail*

- *Many consumer products contain PFAS… protective coatings to textiles, papers, and packaging and to enhance the performance of various consumer products*

(So3M Company 1999)

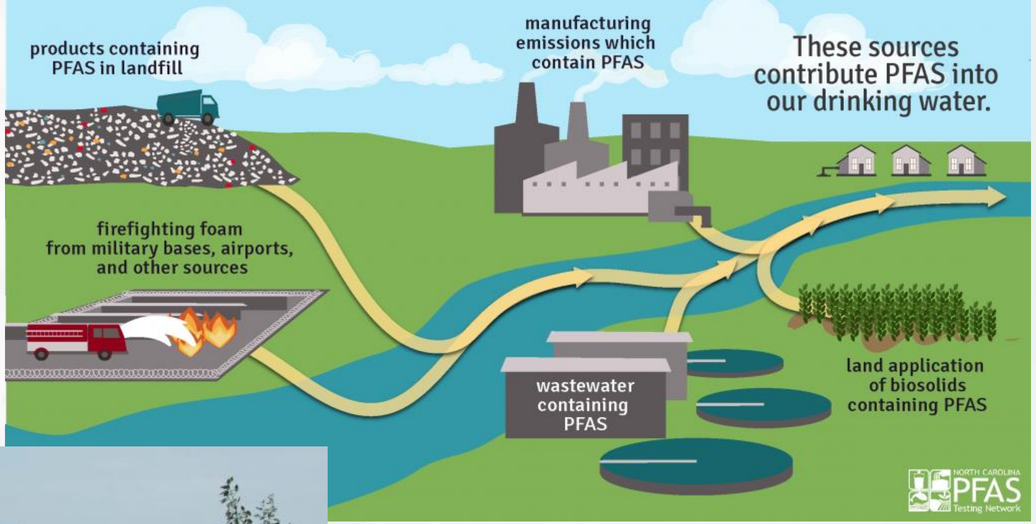


PFOA molecule (Source: PSBorg)

Tunnel construction site (Source: Herald Sun)

Modern Contaminants - PFAS

- Bioaccumulation – harmful threat
- Very Mobile molecules
- Costly Treatment Options
- Energy Intensive Remedial Techniques
- Landfills & PFAS



Firefighting foam (Source: ABC news)

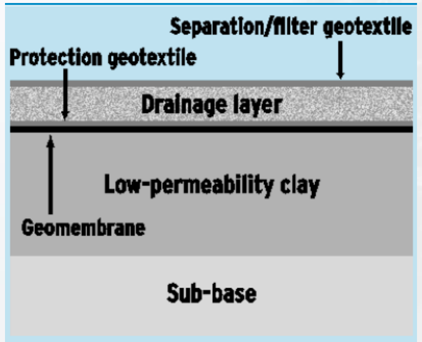
Modern Contaminants - PFAS

GCL

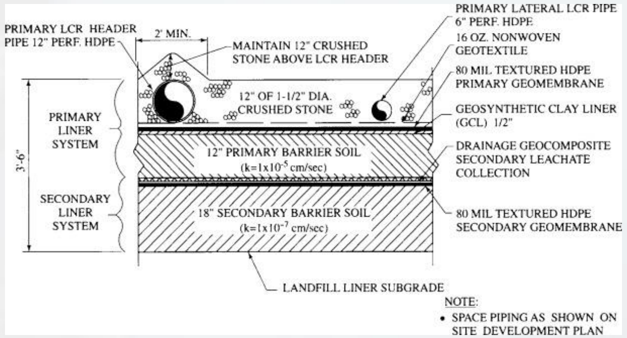
Coated GCL

Geomembrane

Composite liner



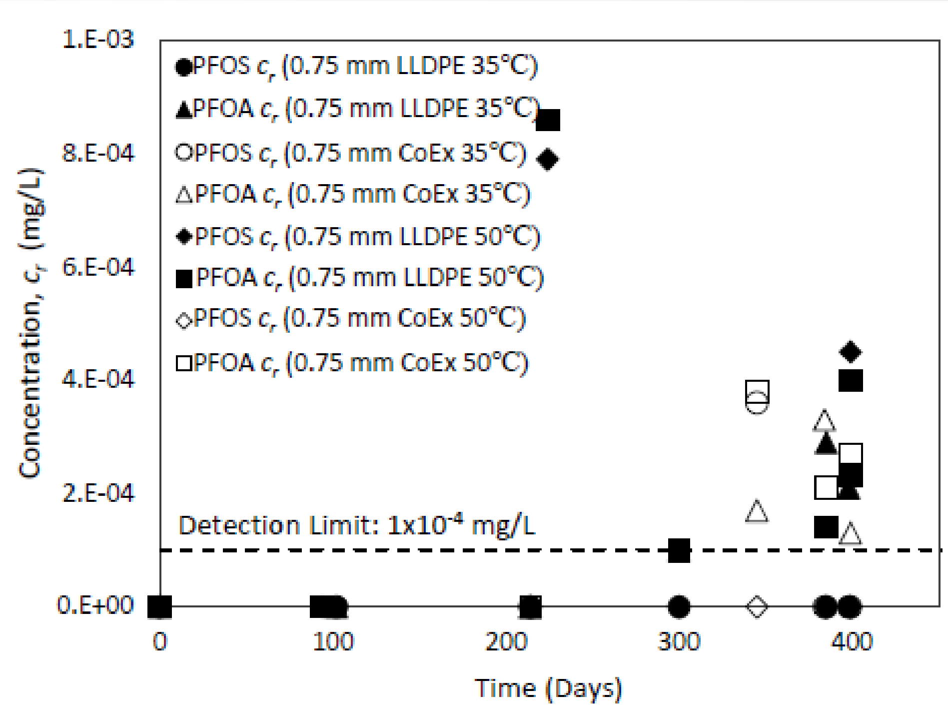
Double Composite liner



Woodard & Curran, Inc., in Industrial Waste Treatment Handbook (Second Edition), 2006

Modern Contaminants - PFAS

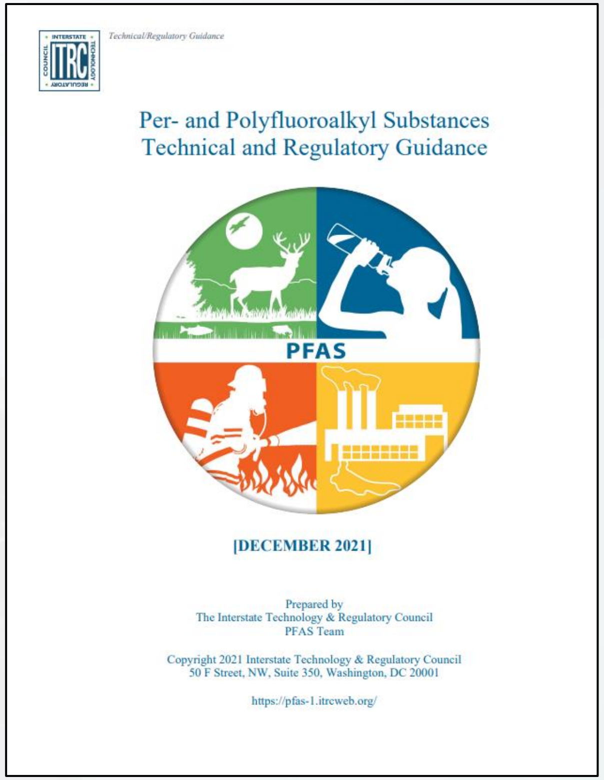
- *“As leachate collects on the base of the landfill, the chemicals can migrate through the landfill liner, via advective and diffusive processes, and contaminate the surrounding environment (Rowe 2015; Rowe et al. 2004).”*
- *“A study of 27 Australian landfills of various ages and stages of closure found PFOA and PFOS present in all 27 landfills* (DiBattista *et al. 2020)*



PFOA and PFOS Diffusion through LLDPE and LLDPE Coextruded with EVOH at 22 ℃, 1 35 ℃, and 50 ℃, Di Battista et. al. 2020)

PFAS – Main Treatment Technologies

- Field-Implemented Liquids Treatment Technologies
  - *PFAS-impacted water is extracted and treated (GAC filters/Reverse osmosis)*
- Field-Implemented Solids Treatment Technologies
  - *Sorption and Stabilization*
  - *Excavation and Disposal*
- Incineration
- Limited Applications and Developing Technologies



Technical/Regulatory Guidance

Per- and Polyfluoroalkyl Substances
Technical and Regulatory Guidance

[DECEMBER 2021]

Prepared by
The Interstate Technology & Regulatory Council
PFAS Team

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50 F Street, NW, Suite 350, Washington, DC 20001

https://pfas-1.itrcweb.org/

Interstate Technology & Regulatory Council (ITRC) 2020 – Technical and Regulatory Guidance Document and Fact sheets PFAS-1

PFAS Regulations – Current guidelines

US EPA – Groundwater limits for PFAS

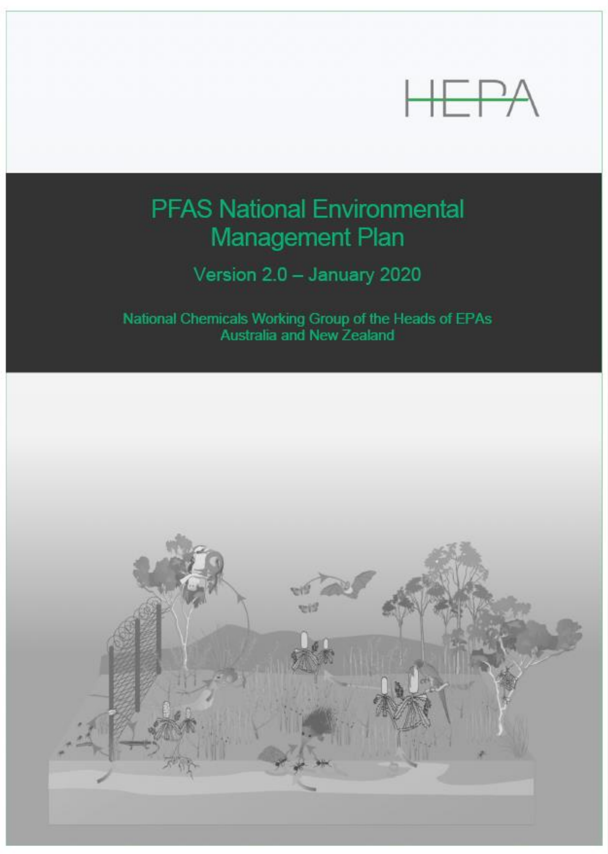
70 ppt (parts per trillion)

4 minutes in 31,710 years

Australia NEMP – Limits for freshwater marine environment

230 ppt (parts per trillion)

35m on the distance between Earth and Sun

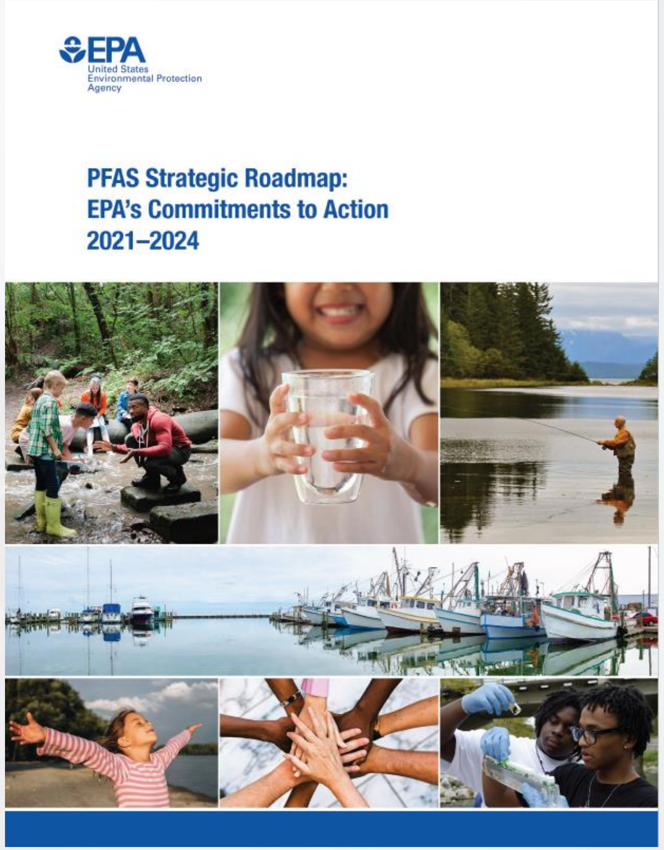


HEPA

PFAS National Environmental Management Plan

Version 2.0 – January 2020

National Chemicals Working Group of the Heads of EPAs
Australia and New Zealand



EPA
United States
Environmental Protection
Agency

PFAS Strategic Roadmap:
EPA's Commitments to Action
2021–2024

October 18, 2021

Passive Remediation with Geocomposites

High performance for short and long chain PFAS

Special high-performance textiles and the selective ion exchange resin ensure the highest pollutant absorption capacity for a wide range of applications.

Alternative solution for long chain PFAS

High-performance textiles and selected activated carbon form a pollutant barrier for selected applications.

Geocomposites Capabilities

High performance for short and long chain PFAS

Effective
Removal of all PFAS congeners with a 99.9% proven effectiveness (tested at concentration range between < 1 - 4000 µg/L).

Strong
Extremely high binding strength ensures that less than 0.1% of the bound PFAS have been released again (desorption). Only this level of performance can guarantee long longevity for the solution.

Efficient
With a proven capacity of up to 7000 µg/g, Tektoseal Active PFAS has a much higher contaminant binding capacity than many other adsorbents.

Durable
The durability of our materials makes it possible to protect or even reuse contaminated soils in structures over long periods of time while also passively decontaminating the soil happens with the help of natural precipitation.

Fast
A very fast sorption rate of fewer than 3 minutes allows use at comparatively high leachate flow rates.

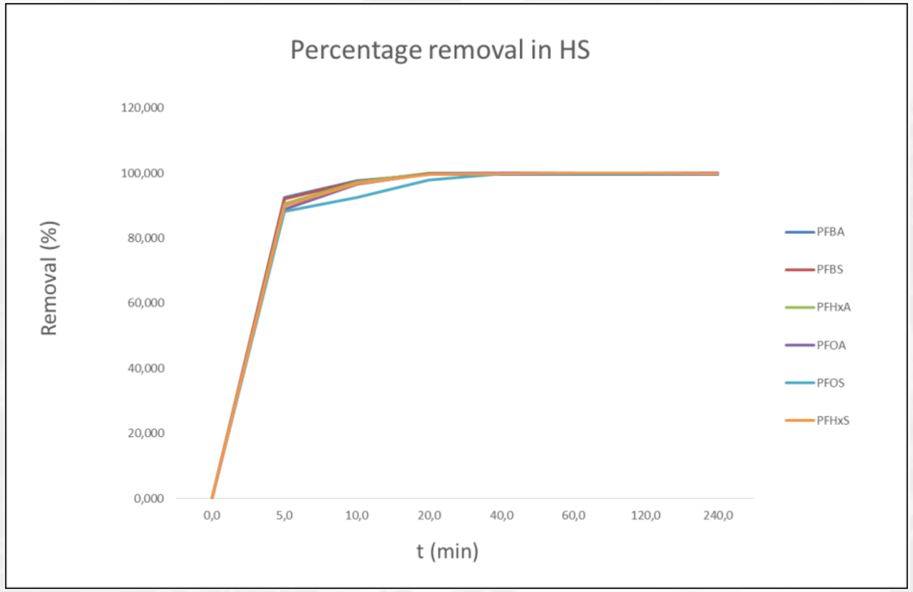
Safe
Our active geocomposite has been proven to be ideal for landfill leachate applications with mixed contaminants.

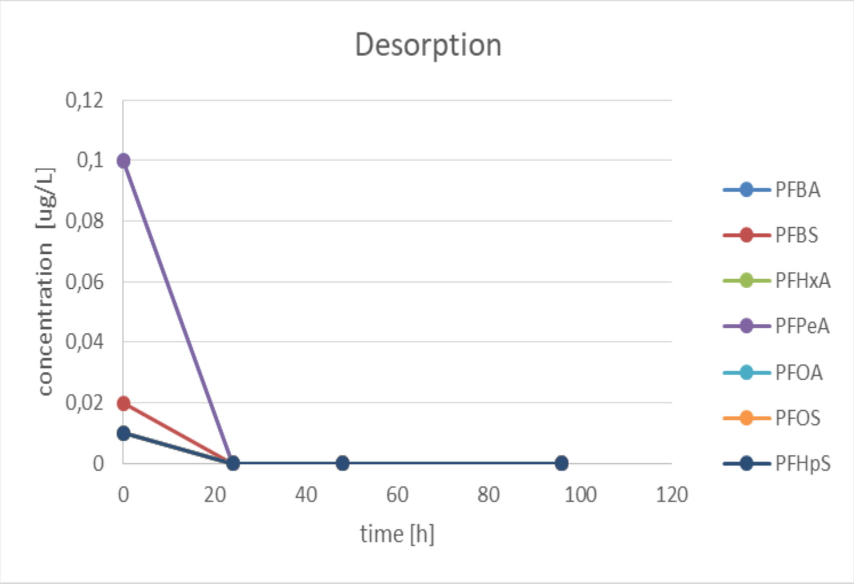
Geocomposites Capabilities

- Strong selective Resin with a loading capacity up to 70 times higher than activated carbon
- Very fast sorption kinetics and strong binding that excludes desorption

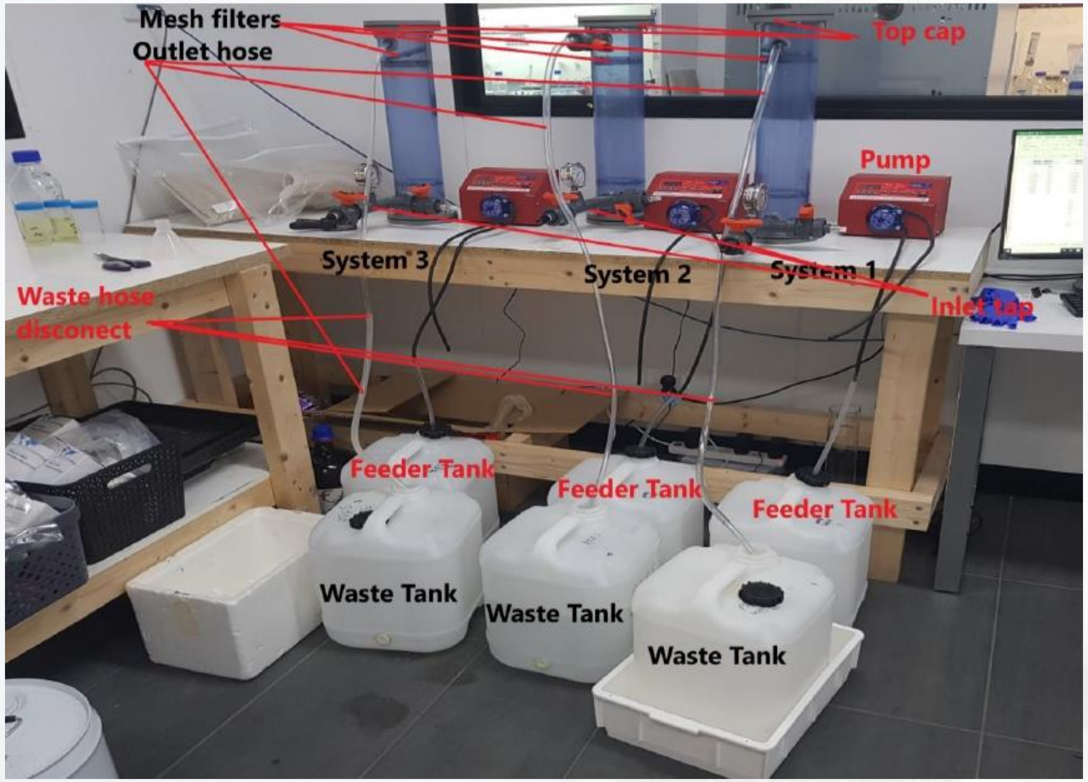
Tektoseal Active **PFAS**

Modified Resin to remove long- and short chain PFAS





Bench tests – MR Geocomposite



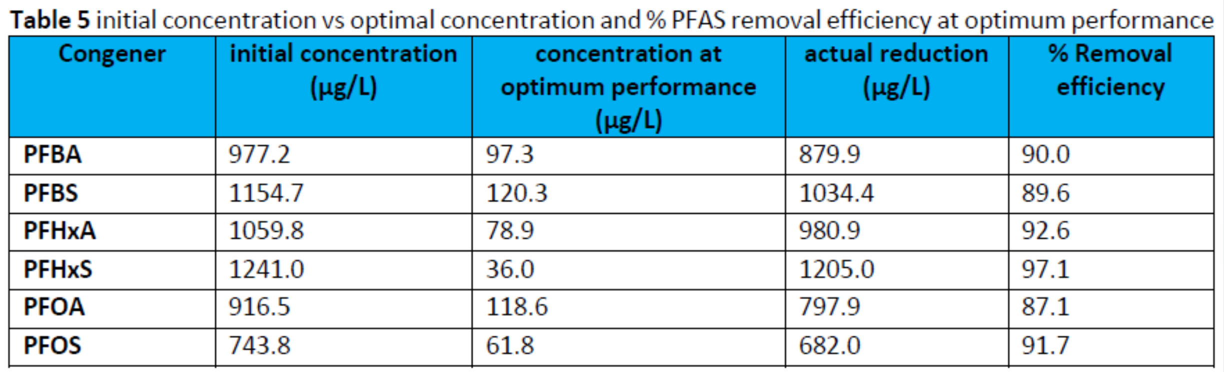
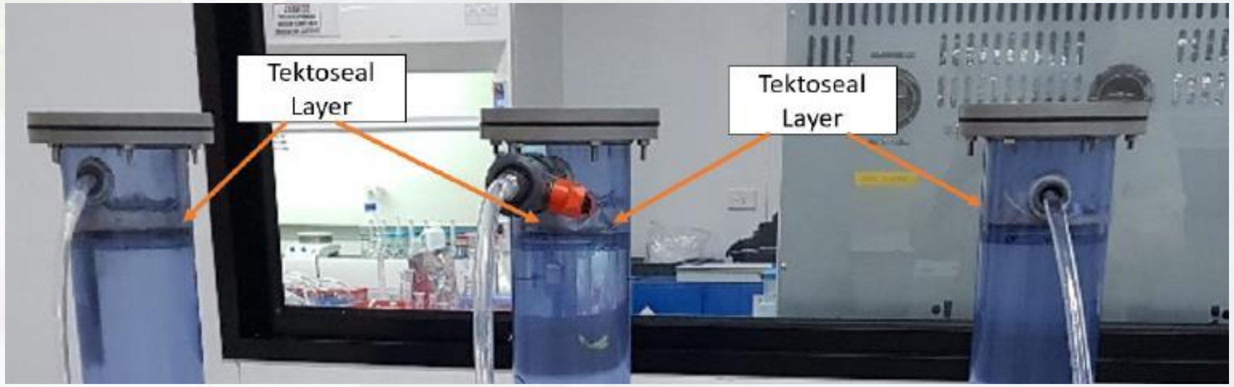


Table 5 initial concentration vs optimal concentration and % PFAS removal efficiency at optimum performance

Congener	initial concentration (μg/L)	concentration at optimum performance (μg/L)	actual reduction (μg/L)	% Removal efficiency
PFBA	977.2	97.3	879.9	90.0
PFBS	1154.7	120.3	1034.4	89.6
PFHxA	1059.8	78.9	980.9	92.6
PFHxS	1241.0	36.0	1205.0	97.1
PFOA	916.5	118.6	797.9	87.1
PFOS	743.8	61.8	682.0	91.7

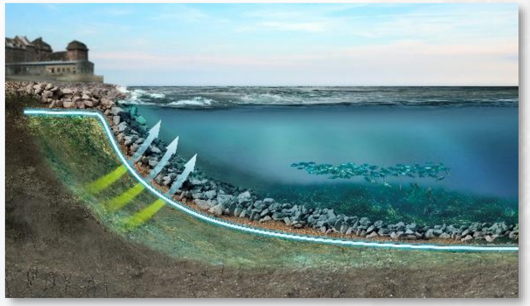


Passive Remediation with Geocomposites - Applications

In-situ securing of contaminated soils

Construction with contaminated soils

Groundwater protection (roads/airports)



Sediment capping

Landfill lining

Barrier material at mobile filling stations

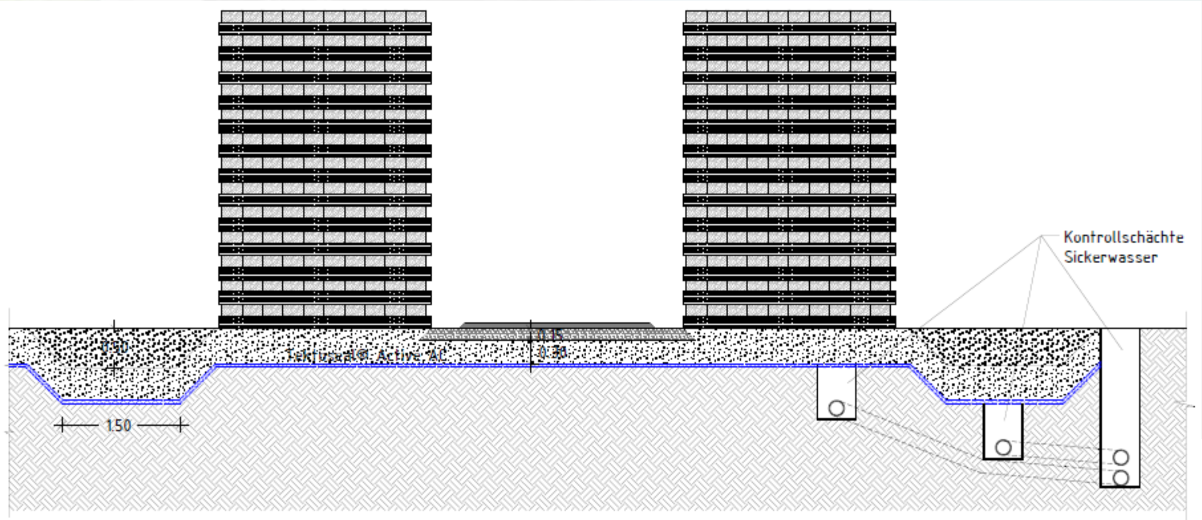
Passive Remediation with Geocomposites

Short term storage of contaminated soils (laydown pads)

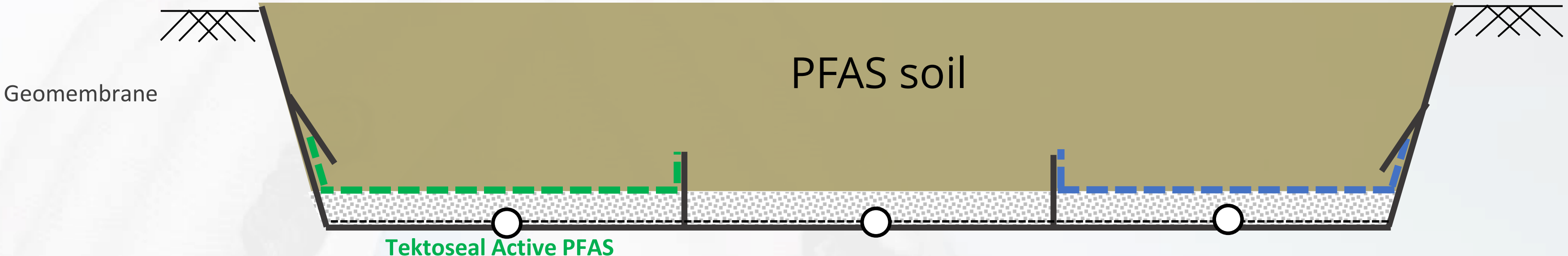
- Medium-term storage (<2years)
- On-site soil storage without active leachate treatment
- Contain contaminants isolated from clean soil
- No surface water management is required

Passive Remediation with Geocomposites

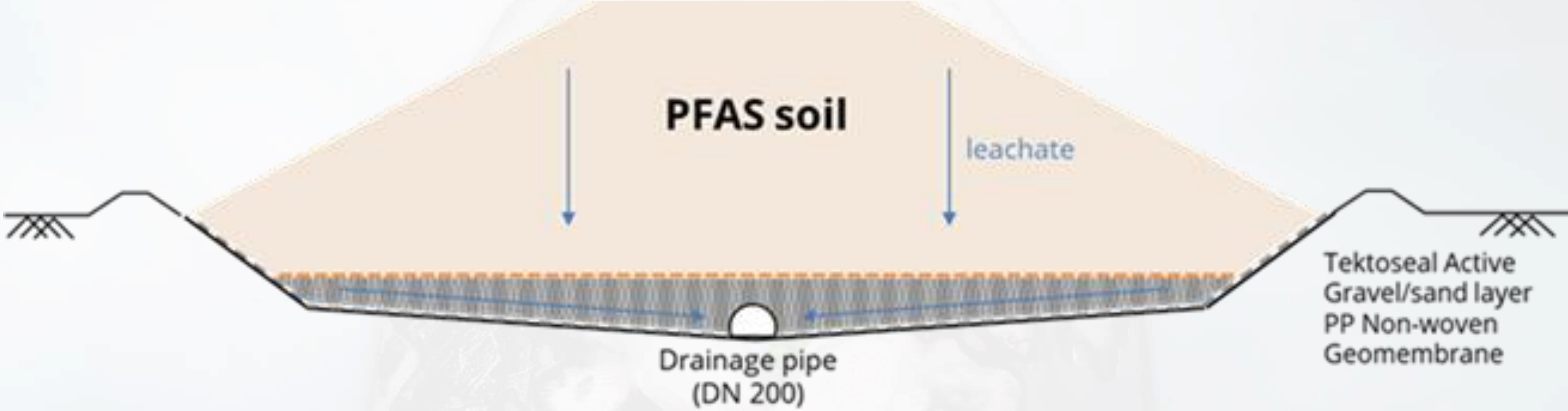
Storage of contaminated materials
(laydown pads)



Passive Remediation with Geocomposites – Installation

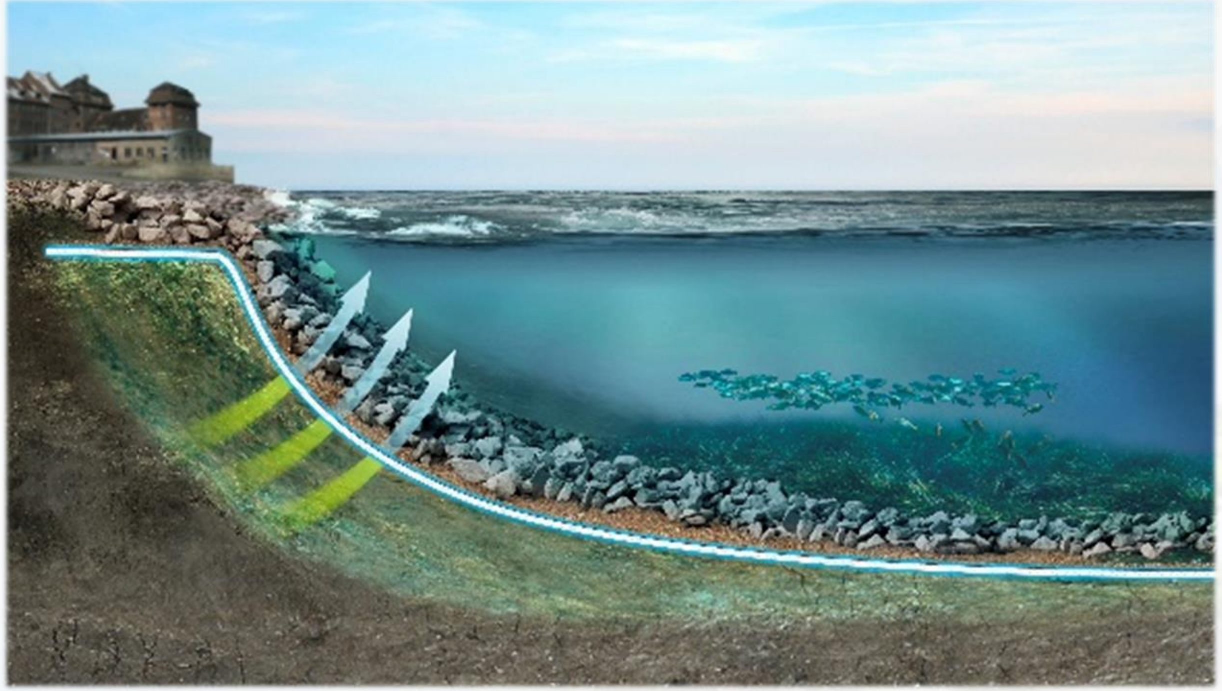


Passive Remediation with Geocomposites



Remediation with natural precipitation

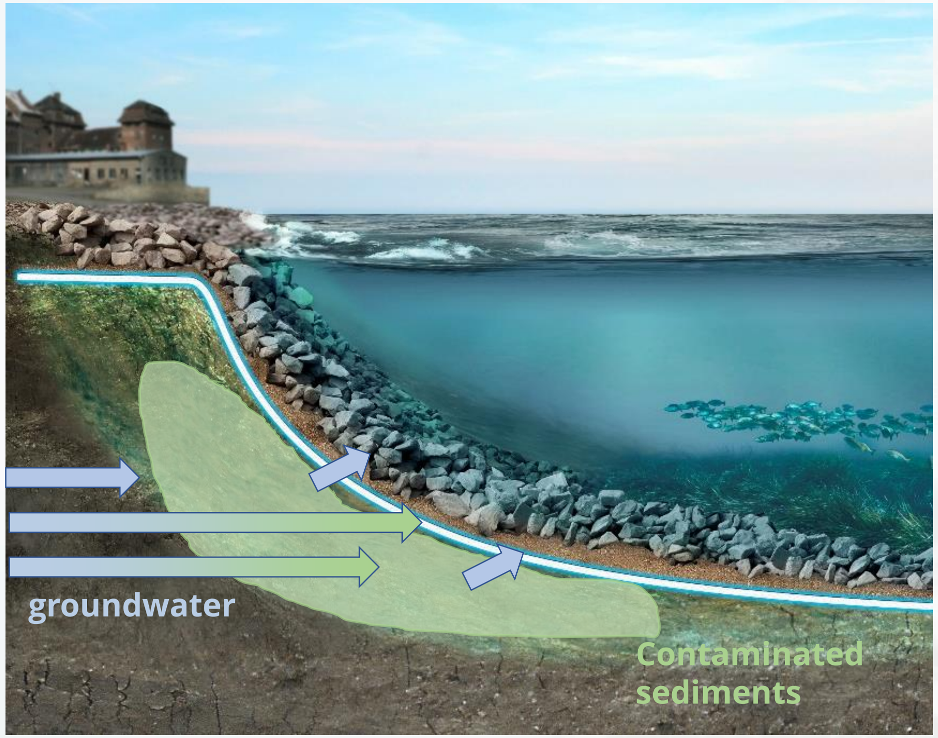
Passive Remediation with Geocomposites



Minimization of PFAS spread, sediment subaqueous capping and short-term barriers

- Subaqueous capping
- Isolation/treatment of contaminants
- Risk Reduction
- Disturbance minimized
- Fast Installation

Passive Remediation with Geocomposites



Passive Remediation with Geocomposites

Permanent closure (capping) of a contaminated spoil

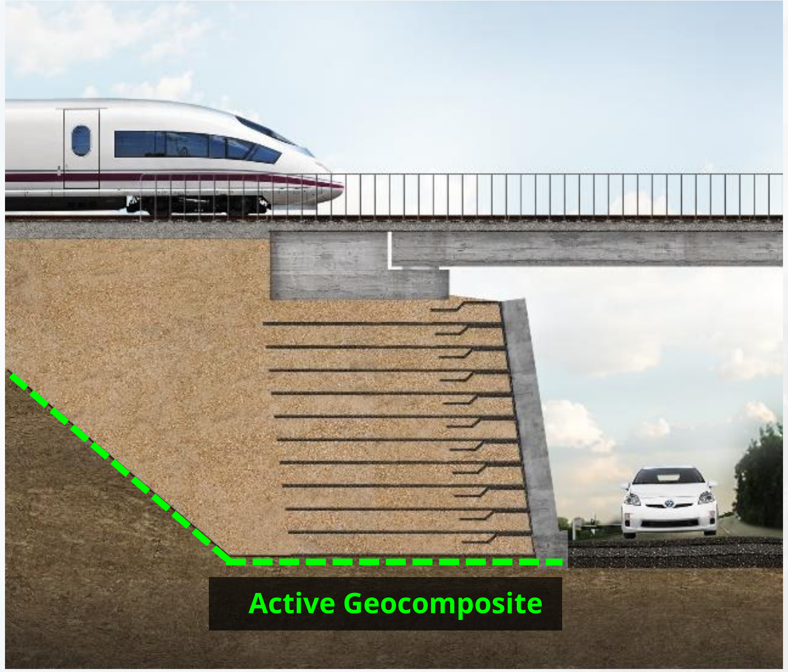
- Geomembrane on top and geocomposite at the bottom (German Standards)
- Long term alternative
- Geocomposite as the second layer of treatment

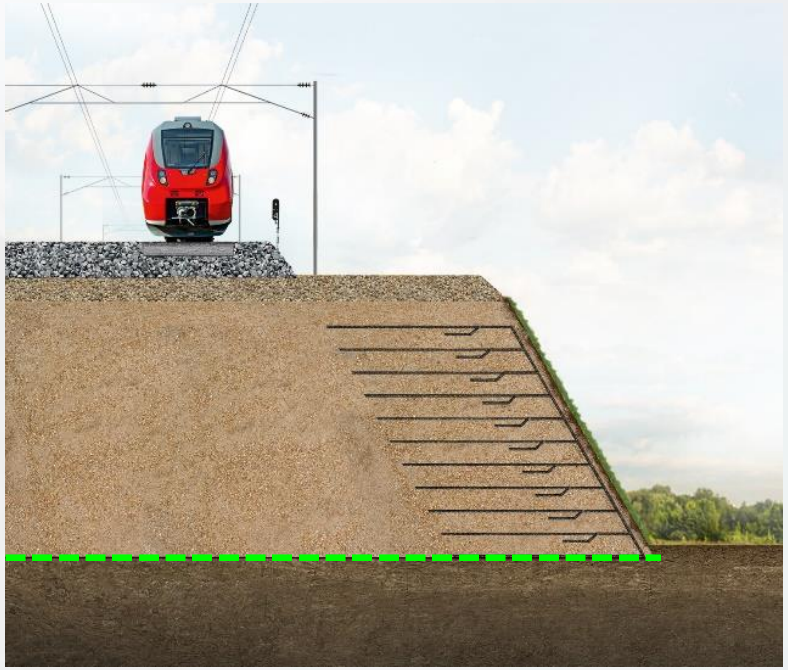
PFAS Containment in Landfills

Permanent storage (base liner and capping) of contaminated materials

- Long-term solution
- Highly contaminated spoils
- Composite liner
- Geocomposite as an additional layer of containment

Passive Remediation with Geocomposites





Sustainable Solutions with Geocomposites

Avoidance of energy-intensive solutions

Conservation and reuse of Natural Resources

Reduction of mass transports

Energy-saving through lightweight materials

Sealing of contaminated sites and landfills

Filtration and remediation of harmful contaminants

Extension of service life

Proven **reduction in CO_2** emissions in up to 89%

Thank you for your attention

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GeoANZ 2022
MASTER CLASS

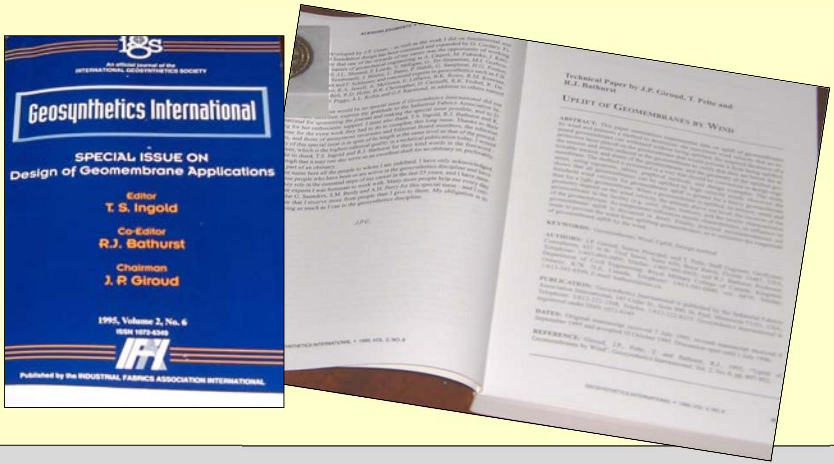
DESIGN CONSIDERATIONS
ABOUT
GEOMEMBRANE UPLIFT BY WIND

By

J.P. GIROUD

2022 June 07

I have been told to assume that
all attendees are familiar
with the method published in 1995.



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SPECIAL ISSUE ON
Design of Geomembrane Applications

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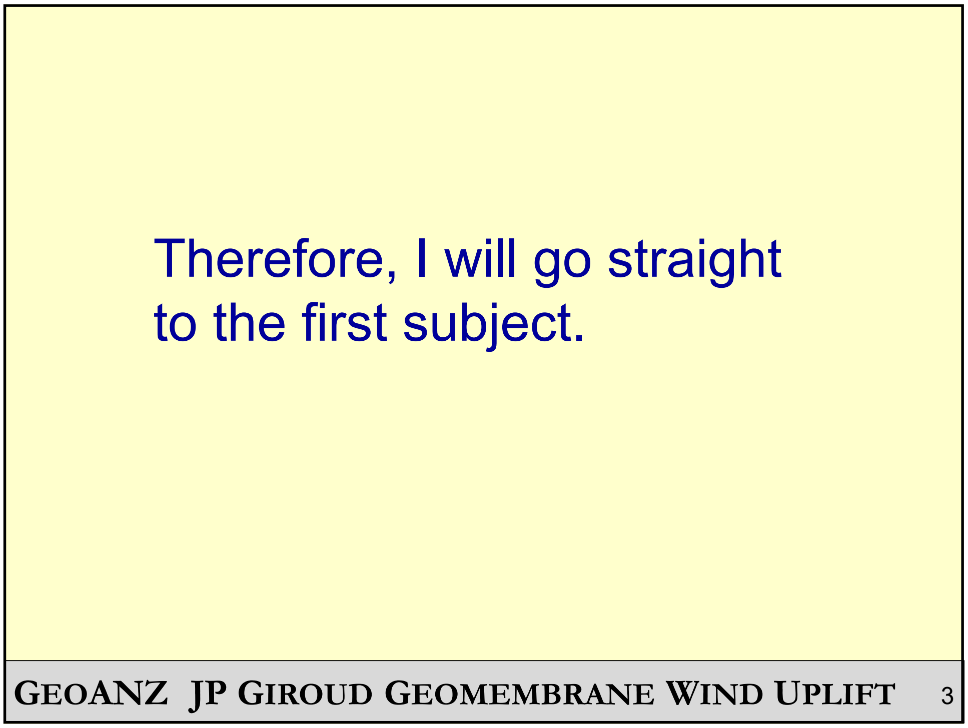
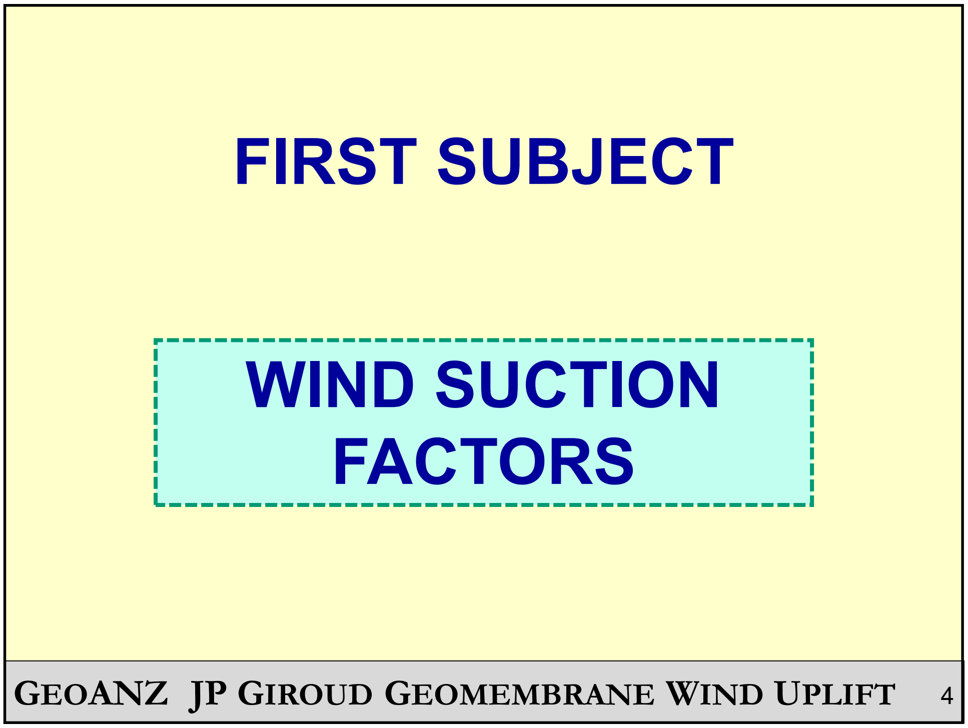
Technical Paper by J.P. Giroud, T. Pelte and R.J. Bathurst

UPLIFT OF GEOMEMBRANES BY WIND

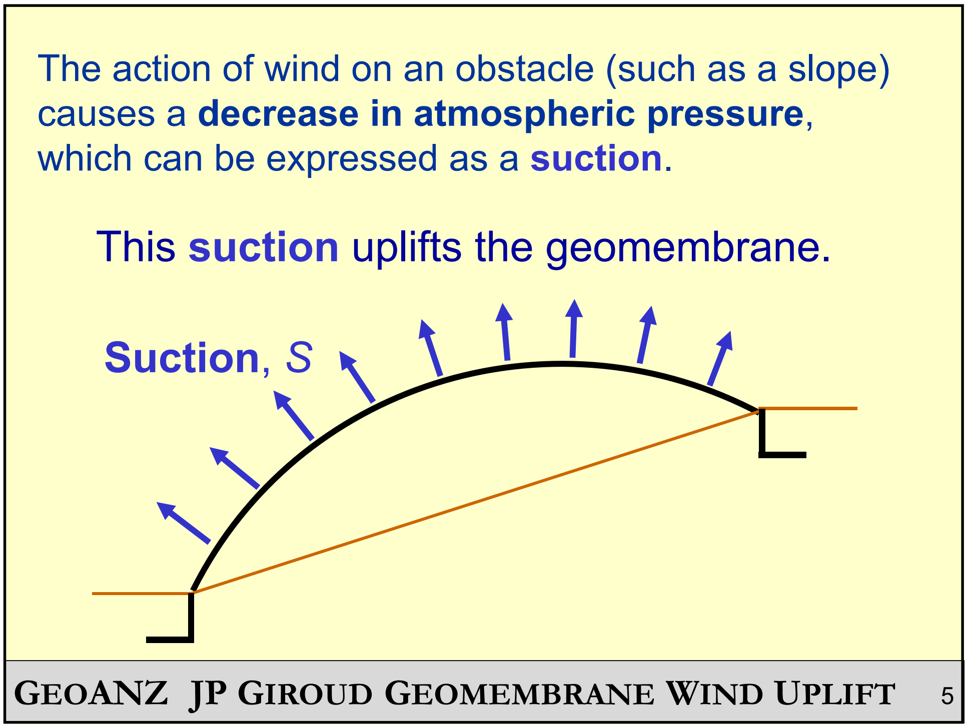


Therefore, I will go straight to the first subject.



FIRST SUBJECT

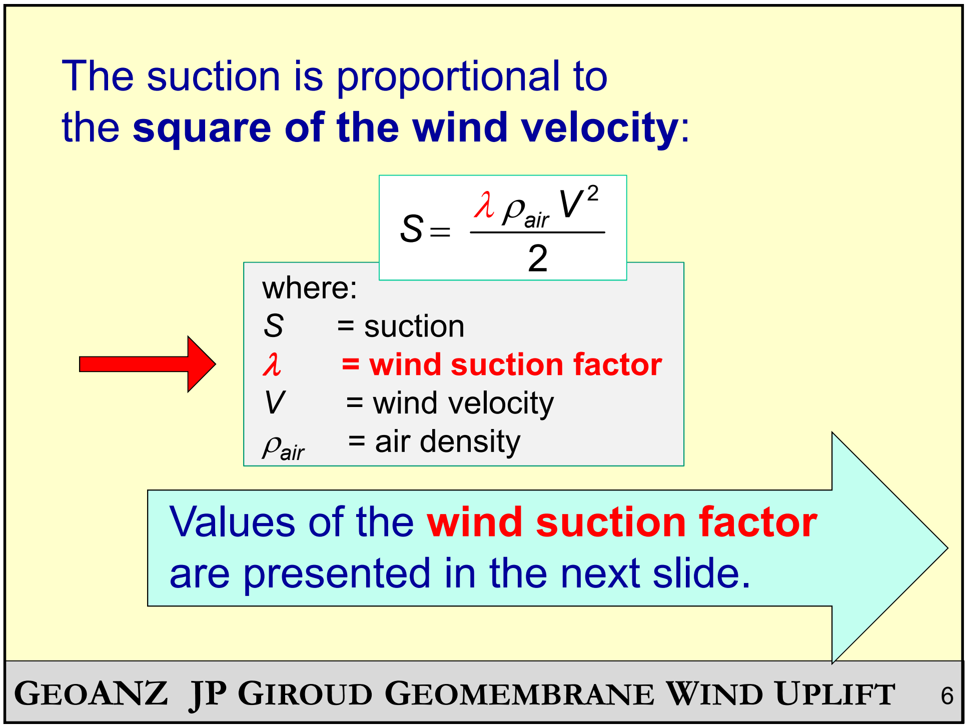
WIND SUCTION FACTORS



The action of wind on an obstacle (such as a slope) causes a **decrease in atmospheric pressure**, which can be expressed as a **suction**.

This **suction** uplifts the geomembrane.

Suction, *S*



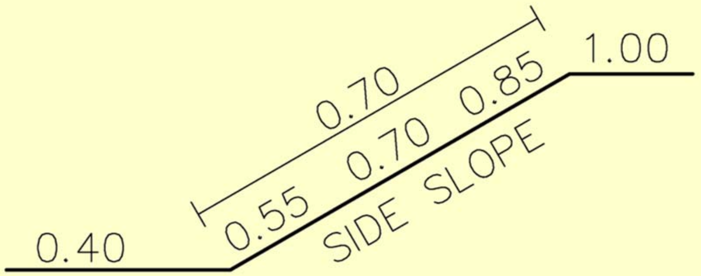
The suction is proportional to the **square of the wind velocity**:

$$S = \frac{\lambda \rho_{air} V^2}{2}$$

where:
S = suction
λ = wind suction factor
V = wind velocity
ρ_{air} = air density

Values of the **wind suction factor** are presented in the next slide.

Here are
the **initially proposed values**
for the wind suction factor.



This was in 1995.

Based on:

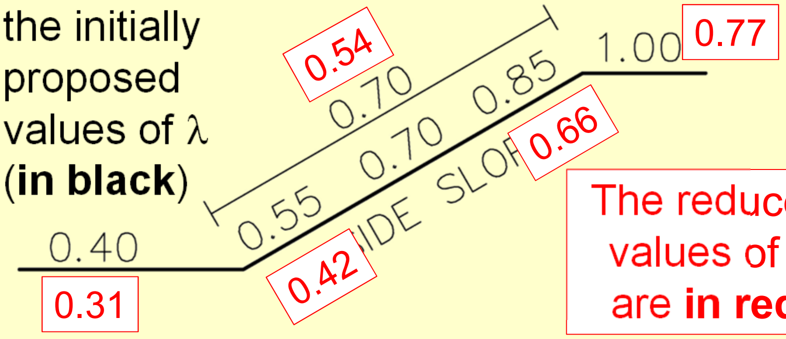
- results of wind tunnel tests,
  and
- observations made
  on actual projects,

reduced values
of the **wind suction factor**, λ,
have been **proposed and used.**

A reduction of 23% was proposed in 2011.

[Perera, Giroud & Roberts 2011]

Here, again, are the initially proposed values of λ (**in black**)



The reduced values of λ are **in red.**

I recommend and I use the reduced factors.

SECOND SUBJECT

INFLUENCE OF GEOMEMBRANE MASS PER UNIT AREA

A typical question is:

Are **heavy** geomembranes
less likely to be uplifted by wind
than **light** geomembranes?

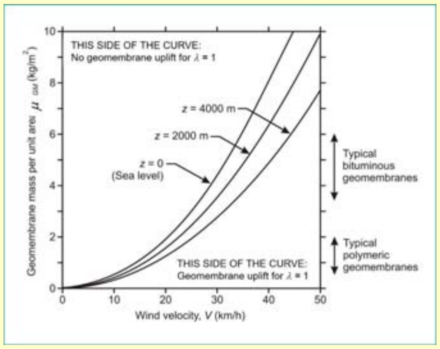
This is a claim made by suppliers
of bituminous geomembranes.

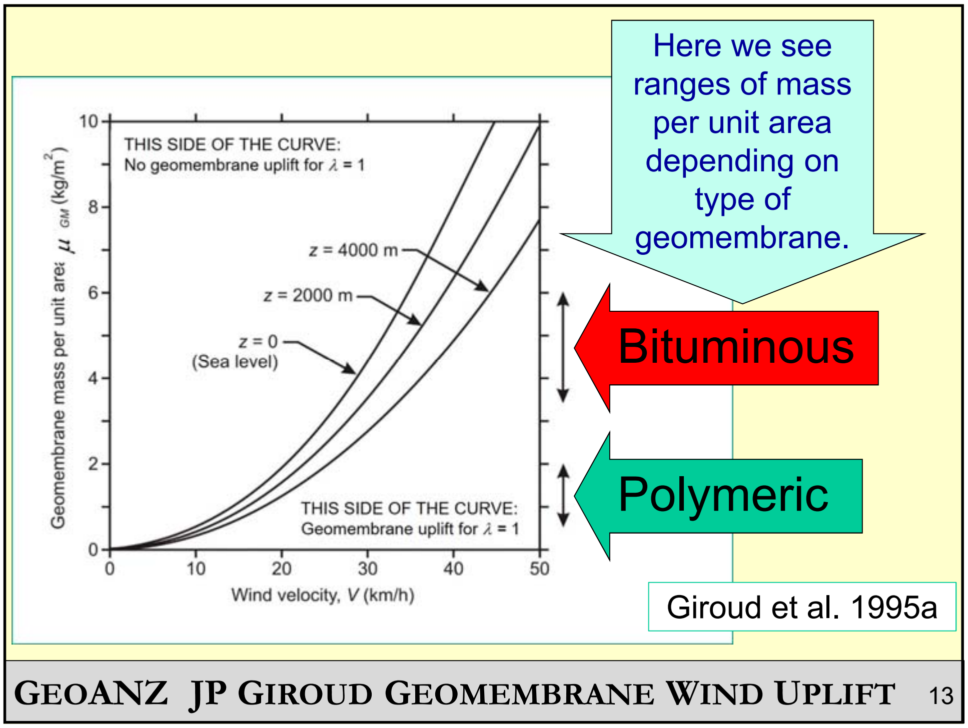
Here are typical values of mass per unit area:

- 2 kg/m^2 for a 2 mm thick **HDPE** geomembrane
- 5 kg/m^2 for a typical **bituminous** geomembrane

Here is a graph of
mass per unit area (on the vertical axis)
as a function of
wind velocity (on the horizontal axis).

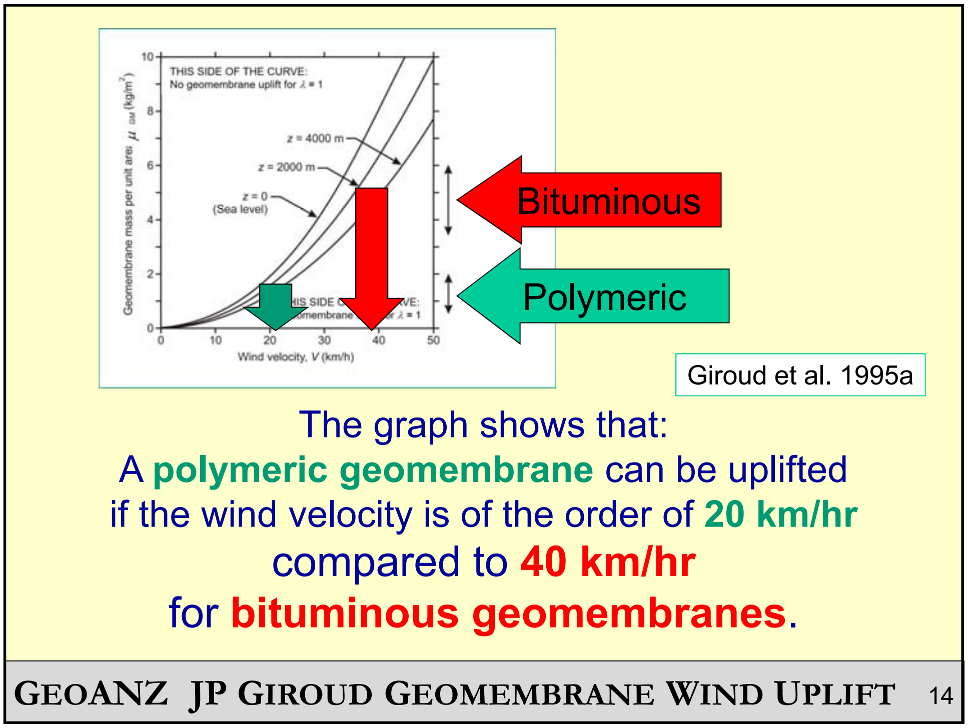
This graph gives the
threshold wind velocity
beyond which
a geomembrane is uplifted
as a function of
its **mass per unit area**.





Here we see ranges of mass per unit area depending on type of geomembrane.

Giroud et al. 1995a



Giroud et al. 1995a

The graph shows that:
A **polymeric geomembrane** can be uplifted
if the wind velocity is of the order of **20 km/hr**
compared to **40 km/hr**
for **bituminous geomembranes**.

Clearly,
heavy geomembranes,
such as bituminous geomembranes,
can be uplifted by wind.

However,
the minimum wind **velocity required**
to uplift **heavier geomembranes**,
such as bituminous geomembranes,
is **significantly higher** than the wind velocity
required to uplift lighter geomembranes,
such as HDPE geomembranes.

The beneficial effect
of the geomembrane **mass per unit area**
is taken into account by using
the **effective suction**.

The **effective suction**
is the **actual suction**
minus the **weight**
of the geomembrane
per unit area.

The effective suction is expressed as follows :

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

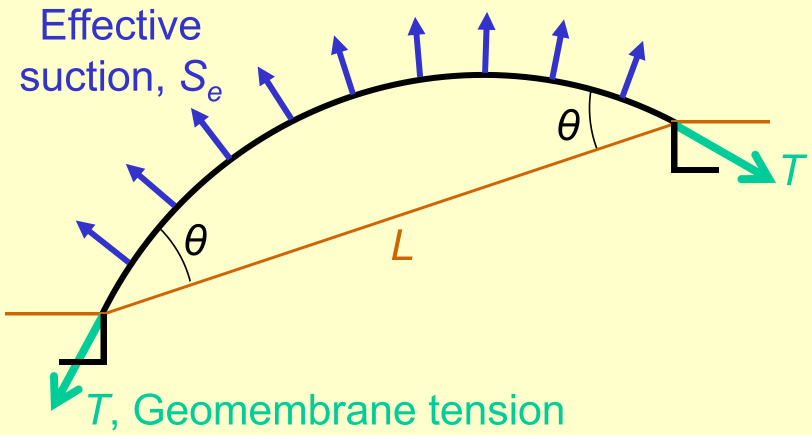
$$S = \frac{\lambda\, \rho_{air}\, V^2}{2}$$

where:
S = suction
S_e = effective suction
μ_{GMB} = geomembrane mass per unit area
g = acceleration due to gravity
β = slope angle
λ = wind suction factor
V = wind velocity
ρ_{air} = air density

THIRD SUBJECT

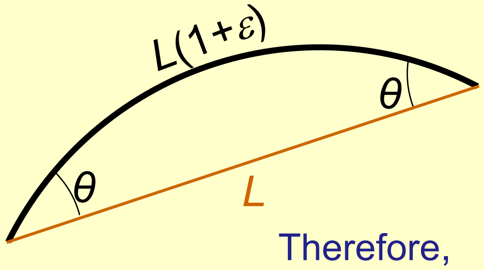
GEOMEMBRANE SELECTION

The **effective suction**, which is applied over the length ***L***, is balanced by the geomembrane **tension *T***, which is acting at an **angle** θ.



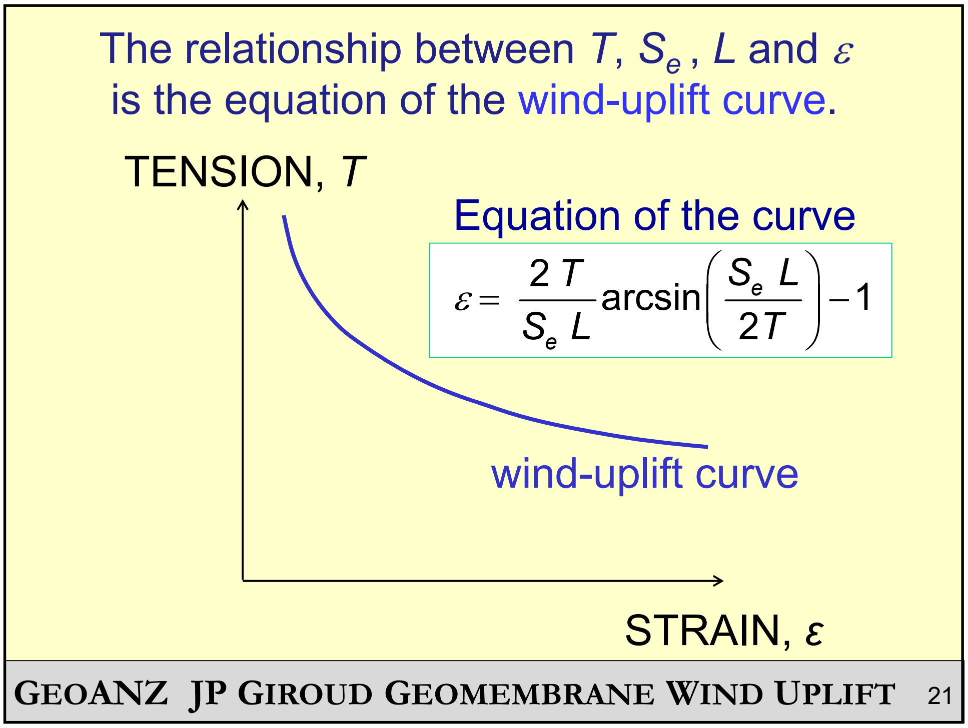
Based on the preceding figure, there is a **relationship between** T, S_e , L and θ.

But the angle, θ, is related to the geomembrane strain, ε, according the following equation:



$$\boxed{1+\varepsilon=\frac{\theta}{\sin\theta}}$$

Therefore, there is a **relationship between** T, S_e , L and ε.

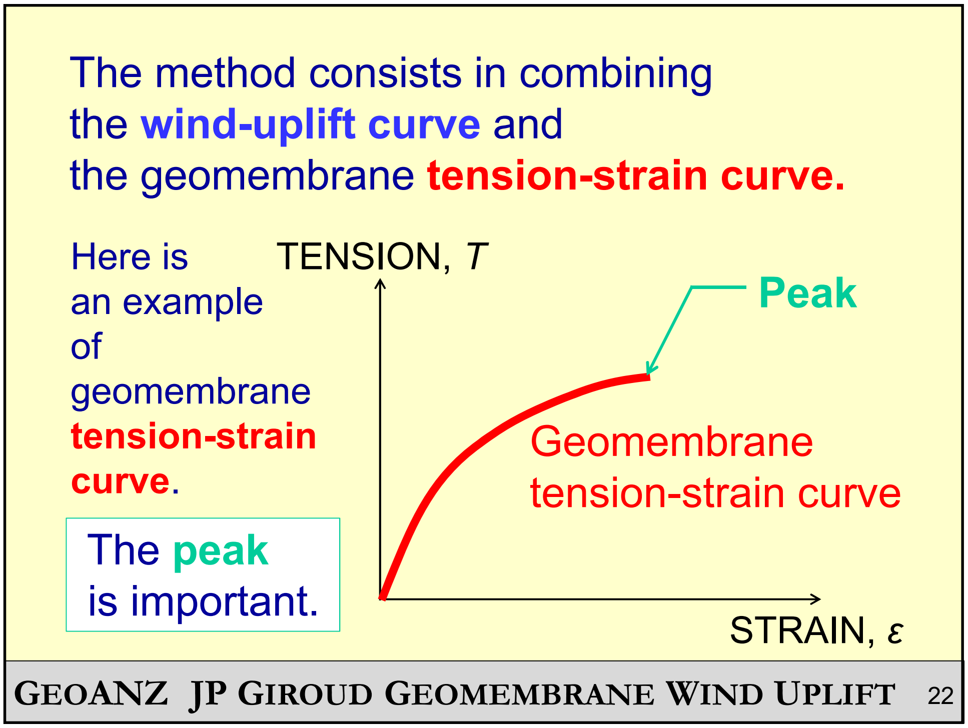


The relationship between T, S_e , L and ε is the equation of the wind-uplift curve.

Equation of the curve

$$\varepsilon = \frac{2\,T}{S_e\,L}\arcsin\left(\frac{S_e\,L}{2T}\right) - 1$$

wind-uplift curve



The method consists in combining
the **wind-uplift curve** and
the geomembrane **tension-strain curve.**

Here is an example of geomembrane **tension-strain curve**.

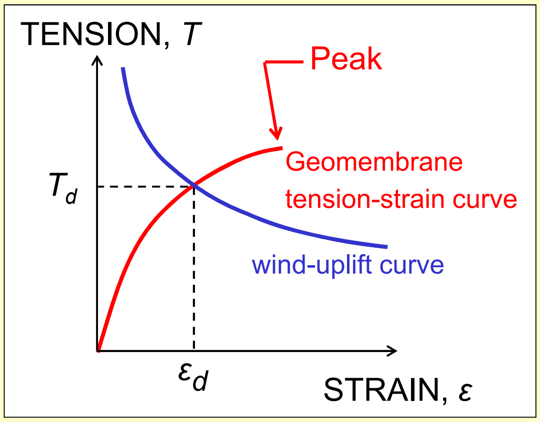
The **peak** is important.

Peak

Geomembrane tension-strain curve

The **selected geomembrane** must have the **peak** of its **tension-strain curve** **above the wind-uplift curve** for the considered slope and wind velocity.

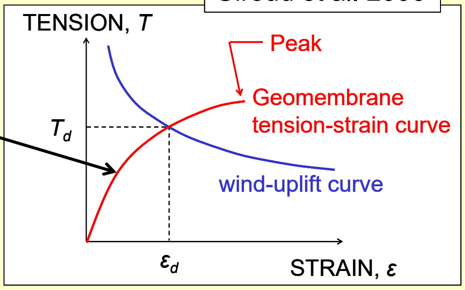
The **intersection** of the two curves gives the tension, T_d , and strain, ε_d , of the **deflected** geomembrane.



This **can be done analytically**,
instead of graphically,
by using an **equation**
for the geomembrane tension-strain curve.

For example, an *N*-order parabola for PE geomembranes

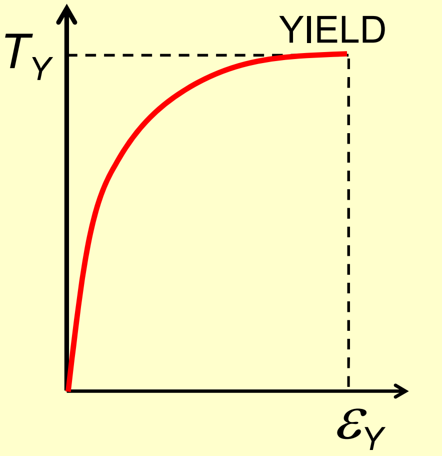
Giroud et al. 2006



This is the equation of an *N*-order parabola

$$\frac{T}{T_Y} = 1 - \left(1 - \frac{\varepsilon}{\varepsilon_Y}\right)^N$$

for the
tension-strain curve
HDPE geomembranes
from the origin
to the yield peak.

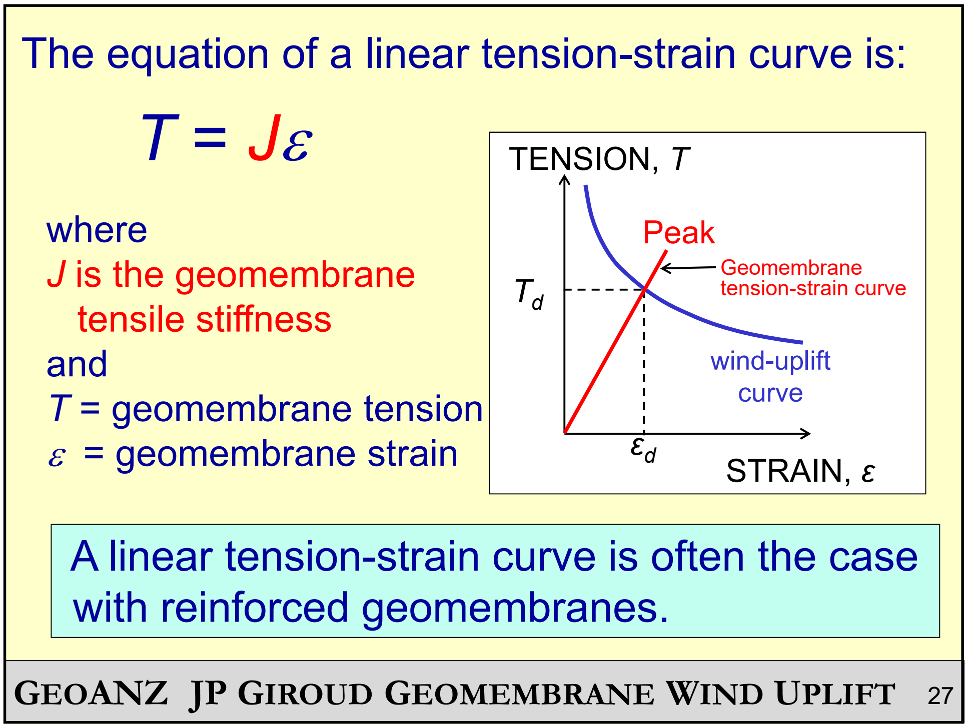


[Giroud 1994, 2005]

with a typical, *N* = 4, exponent

FOURTH SUBJECT

GEOMEMBRANE SELECTION
Case of a linear tension-strain curve

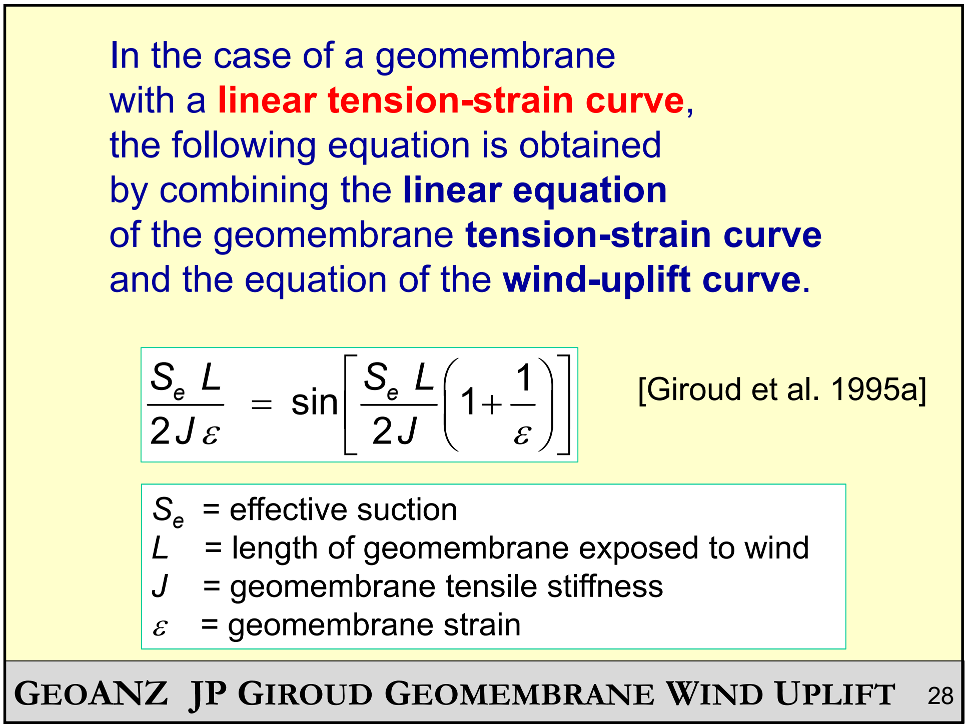


The equation of a linear tension-strain curve is:

$$T = J\varepsilon$$

where
J is the geomembrane tensile stiffness
and
T = geomembrane tension
ε = geomembrane strain

A linear tension-strain curve is often the case with reinforced geomembranes.



In the case of a geomembrane with a **linear tension-strain curve**, the following equation is obtained by combining the **linear equation** of the geomembrane **tension-strain curve** and the equation of the **wind-uplift curve**.

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

[Giroud et al. 1995a]

S_e = effective suction
L = length of geomembrane exposed to wind
J = geomembrane tensile stiffness
ε = geomembrane strain

$$\boxed{\frac{S_e\,L}{2\,J\,\varepsilon} = \sin\left[\frac{S_e\,L}{2\,J}\left(1+\frac{1}{\varepsilon}\right)\right]}$$

The geomembrane strain, ε,
is on **both sides** of the equation.

Therefore, to determine
the geomembrane strain, ε,
the equation must be solved by **iterations**,
which is time consuming,
even with computer programs.

However, **iterations can be avoided** because
I have shown that the preceding equation
has the following **quasi-exact** explicit solution:

$$\boxed{\varepsilon_{qe} = \frac{0.3467\left(\dfrac{S_e\,L}{J}\right)^{2/3}}{1-0.3103\left(\dfrac{S_e\,L}{J}\right)^{2/3}}}$$

[Giroud 2009]

The **difference** between the quasi-exact strain, ε_{qe} ,
and the exact strain, ε,
is less than 0.01% of the strain value
for strains lower than 20%, which is the general case.

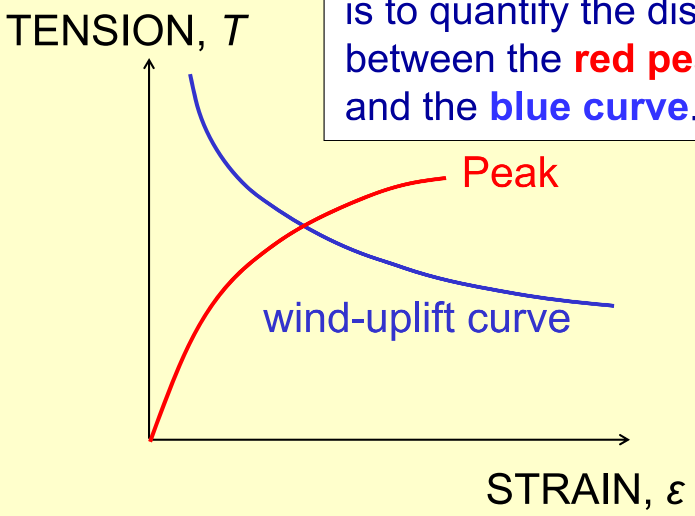
In conclusion,
if the geomembrane
has a **linear tension-strain curve**,
there is an explicit solution
and **iterations can be avoided**.

FIFTH SUBJECT

FACTOR
OF
SAFETY

The purpose of the **factor of safety** is to quantify the **distance** between the **wind uplift curve**
and
the **peak** of
the geomembrane tension-strain curve.

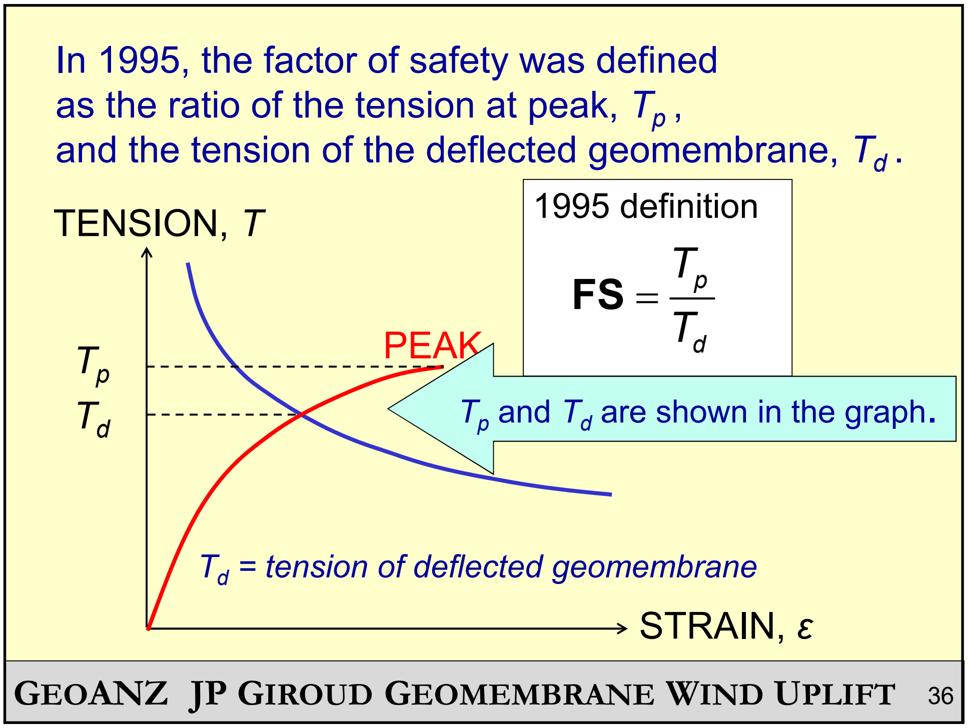
In other words, the purpose of the factor of safety is to quantify the distance between the **red peak** and the **blue curve**.



But there are **several ways to quantify** the distance between the peak of the **geomembrane tension-strain curve** and the **wind uplift curve**.

Let's start with the definition of factor of safety proposed in the original paper in 1995.

This shown on the next slide.



In 1995, the factor of safety was defined as the ratio of the tension at peak, T_p , and the tension of the deflected geomembrane, T_d .

1995 definition

$$\mathbf{FS} = \frac{T_p}{T_d}$$

T_p and T_d are shown in the graph.

T_d = *tension of deflected geomembrane*

The 1995 factor of safety seems to make sense.

However, as shown in following slides, other approaches are more rational.

Therefore, the 1995 definition of the factor of safety should be considered obsolete.

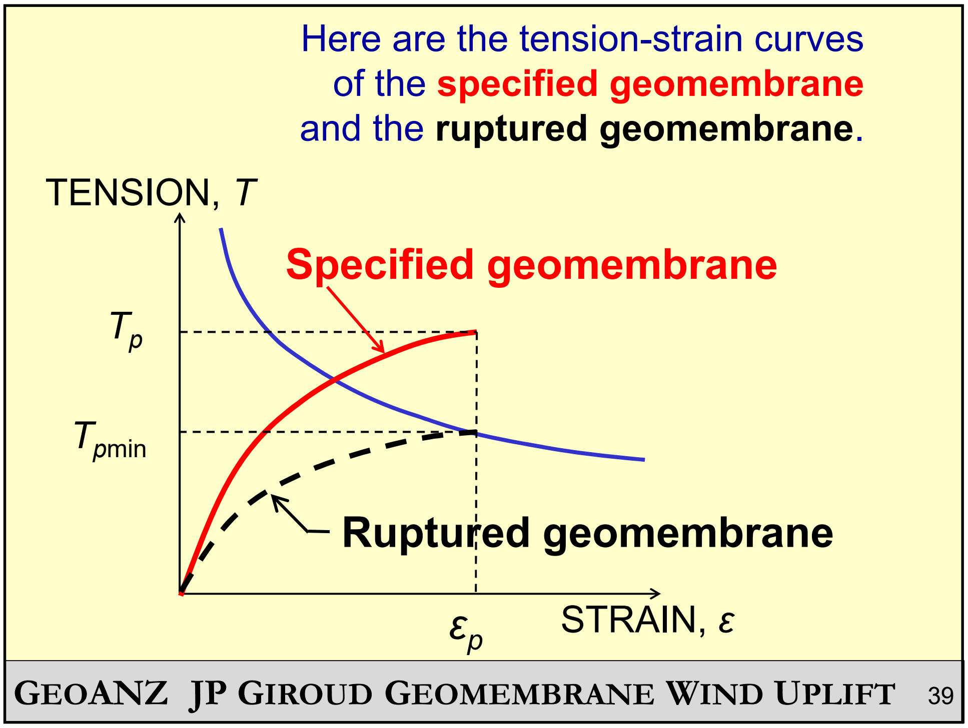
1995 definition

$$\cancel{\mathbf{FS} = \frac{T_p}{T_d}}$$

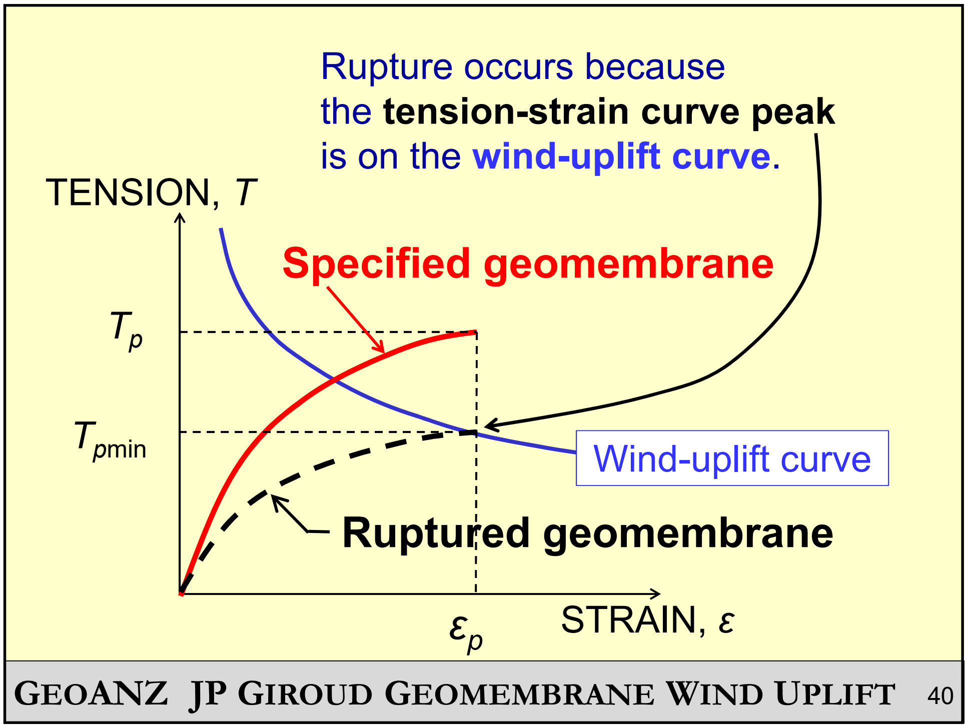
The first rational approach is the following:

The factor of safety quantifies how **far from rupture** is the specified geomembrane compared to a weaker geomembrane that is **just weak enough to be ruptured** by the considered wind.

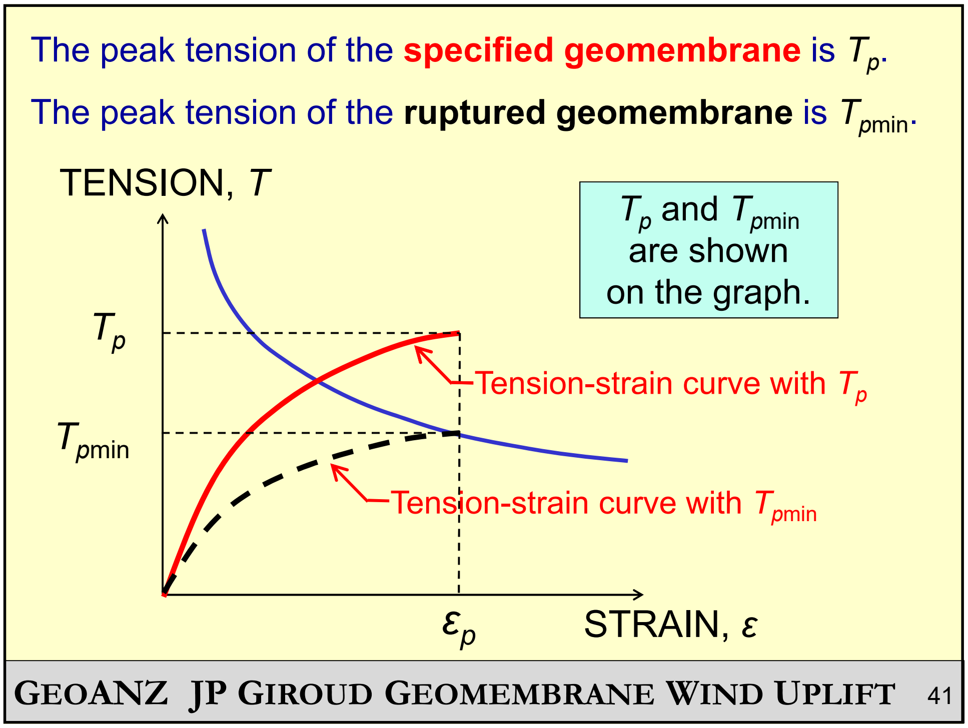
The next slide shows the tension-strain curves of the specified geomembrane and the ruptured geomembrane.



Here are the tension-strain curves of the **specified geomembrane** and the **ruptured geomembrane**.



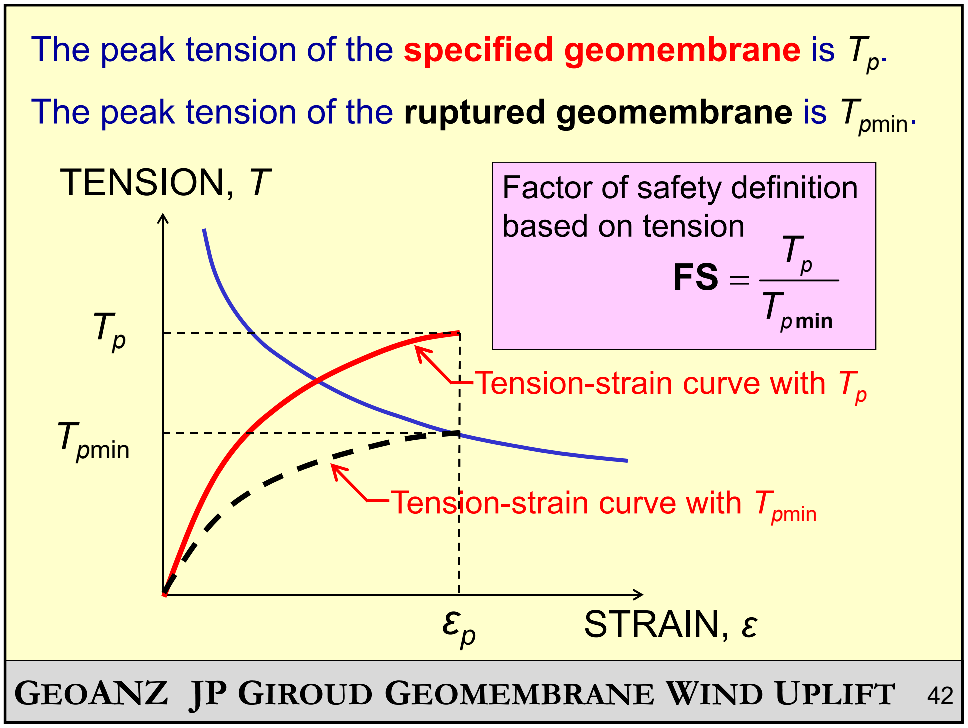
Rupture occurs because the **tension-strain curve peak** is on the **wind-uplift curve**.



The peak tension of the **specified geomembrane** is T_p.

The peak tension of the **ruptured geomembrane** is T_{pmin}.

T_p and T_{pmin} are shown on the graph.



The peak tension of the **specified geomembrane** is T_p.

The peak tension of the **ruptured geomembrane** is T_{pmin}.

Factor of safety definition based on tension

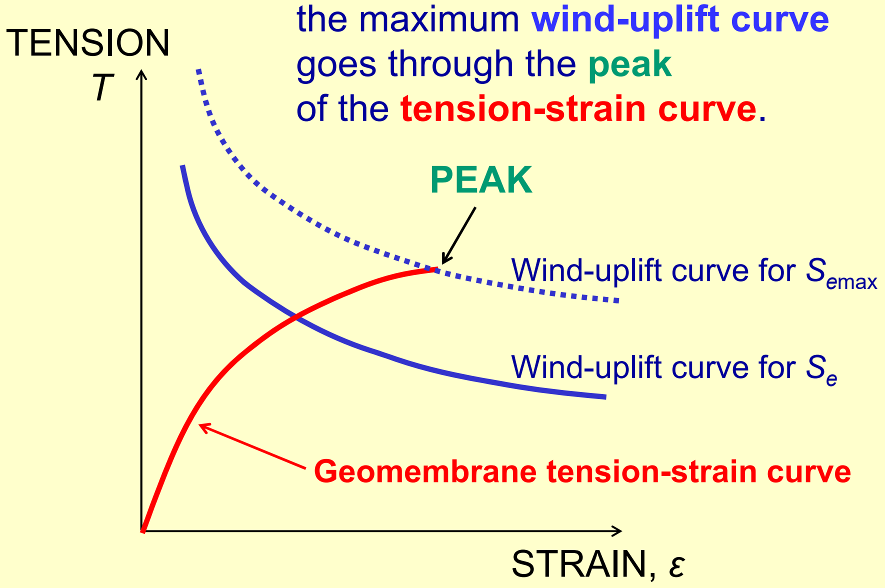
$$\mathbf{FS} = \frac{T_p}{T_{p\,\mathrm{min}}}$$

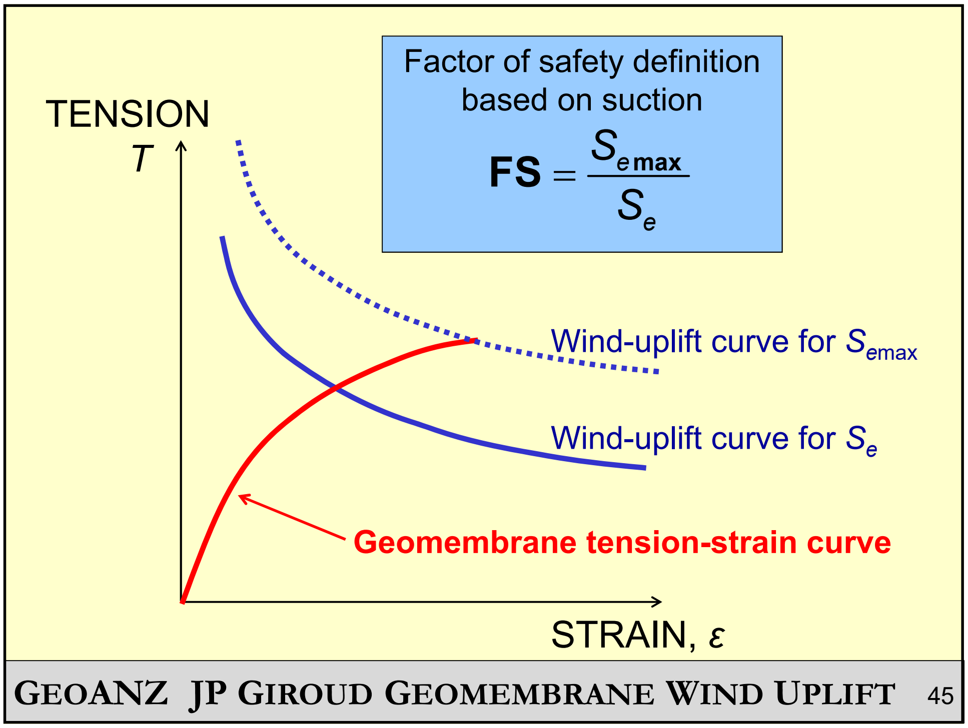
The **second rational approach**
to the factor of safety is the following.

The factor of safety quantifies
how **far from rupture**
the specified geomembrane is
if the wind-generated **suction**
is **greater** than assumed.

Therefore, we use the **wind-uplift curve**
for the effective suction that causes
rupture of the specified geomembrane.

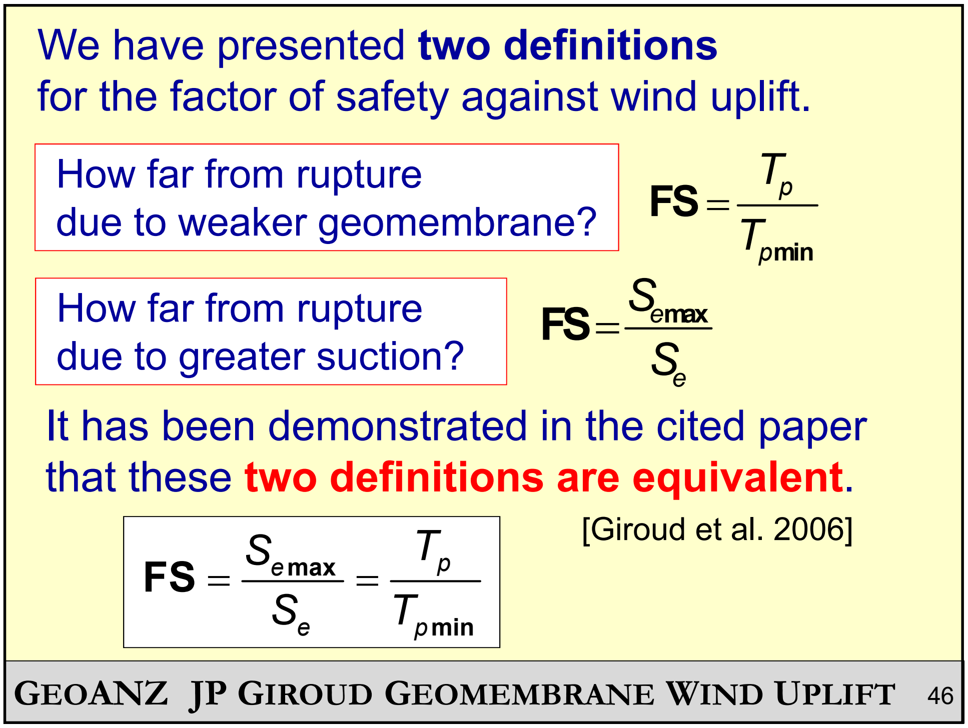
Rupture occurs because
the maximum **wind-uplift curve**
goes through the **peak**
of the **tension-strain curve**.





Factor of safety definition based on suction

$$\mathbf{FS} = \frac{S_{e\,\mathbf{max}}}{S_e}$$



We have presented **two definitions** for the factor of safety against wind uplift.

How far from rupture due to weaker geomembrane?

$$\mathbf{FS} = \frac{T_p}{T_{p\mathbf{min}}}$$

How far from rupture due to greater suction?

$$\mathbf{FS} = \frac{S_{e\mathbf{max}}}{S_e}$$

It has been demonstrated in the cited paper that these **two definitions are equivalent.**

[Giroud et al. 2006]

$$\mathbf{FS} = \frac{S_{e\,\mathbf{max}}}{S_e} = \frac{T_p}{T_{p\,\mathbf{min}}}$$

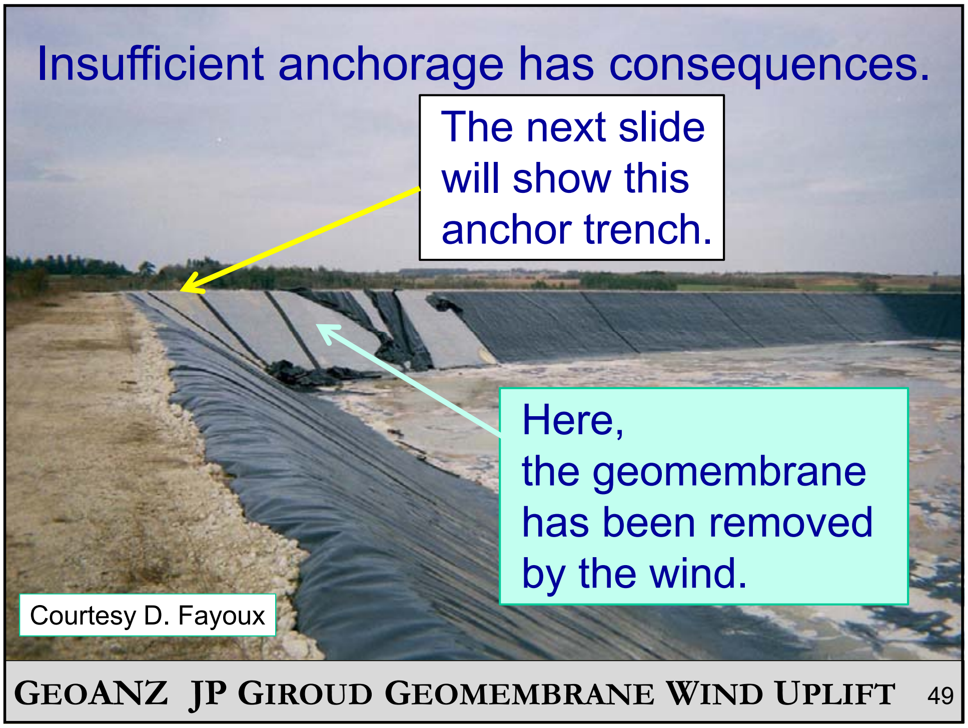
This definition of the **factor of safety**
is consistent with the generally accepted
meaning of factor of safety,
and it is based on **both**
geomembrane **tension** and wind **suction**.

This is a **significant improvement**
compared to the factor of safety
initially defined in 1995.

*In fact, the 1995 factor of safety was **not consistent** with the generally accepted meaning of factor of safety, which consists in evaluating **how far from rupture** the specified geomembrane is.*

SIXTH SUBJECT

ANCHORAGE DESIGN



Insufficient anchorage has consequences.

The next slide will show this anchor trench.

Here,
the geomembrane has been removed by the wind.

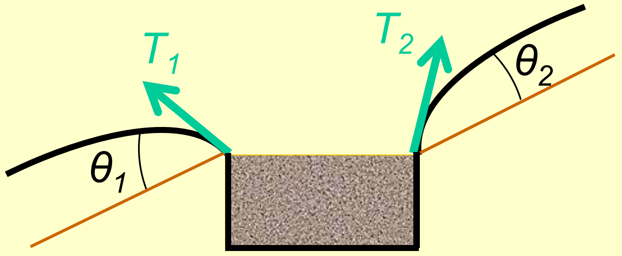
Courtesy D. Fayoux

The anchor trench failed,
the geomembrane was removed,
the geotextile was not removed.

Courtesy D. Fayoux

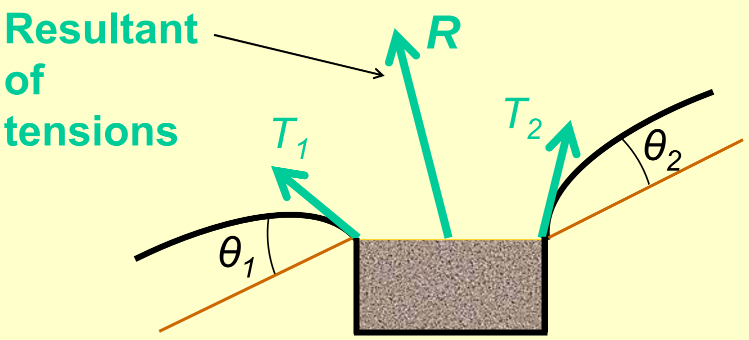
Let’s discuss anchor trench design.

The geomembrane is **under tension**
on each side of the anchor trench.



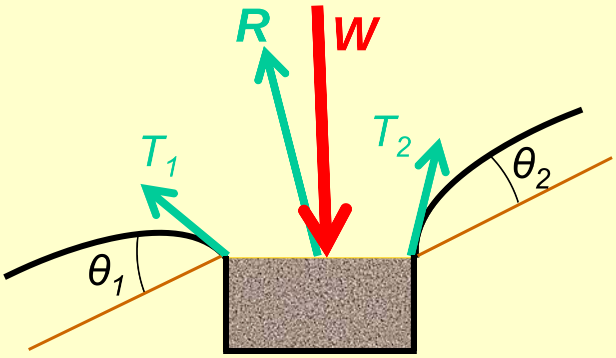
In general, the magnitude and orientation of the tension
are different on the two sides of the anchor trench.

ANCHOR TRENCH DESIGN



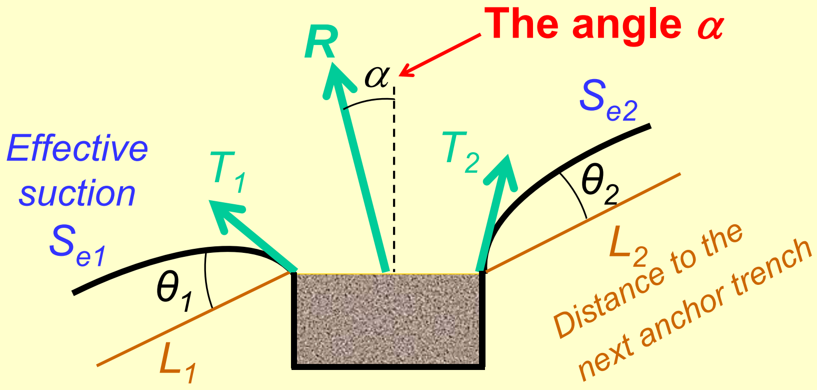
The **resultant of tensions, *R*,**
can cause failure of the anchor trench
by uplifting of the trench backfill.

ANCHOR TRENCH DESIGN



The **weight** of the anchor trench, ***W***,
(and, to some extend, the reactions against the sides of the trench)
must balance the **resultant of tensions**, ***R***.

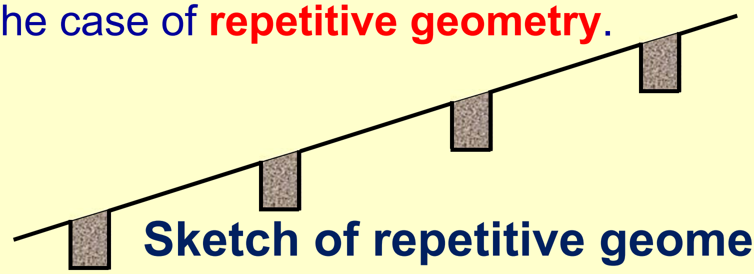
ANCHOR TRENCH DESIGN



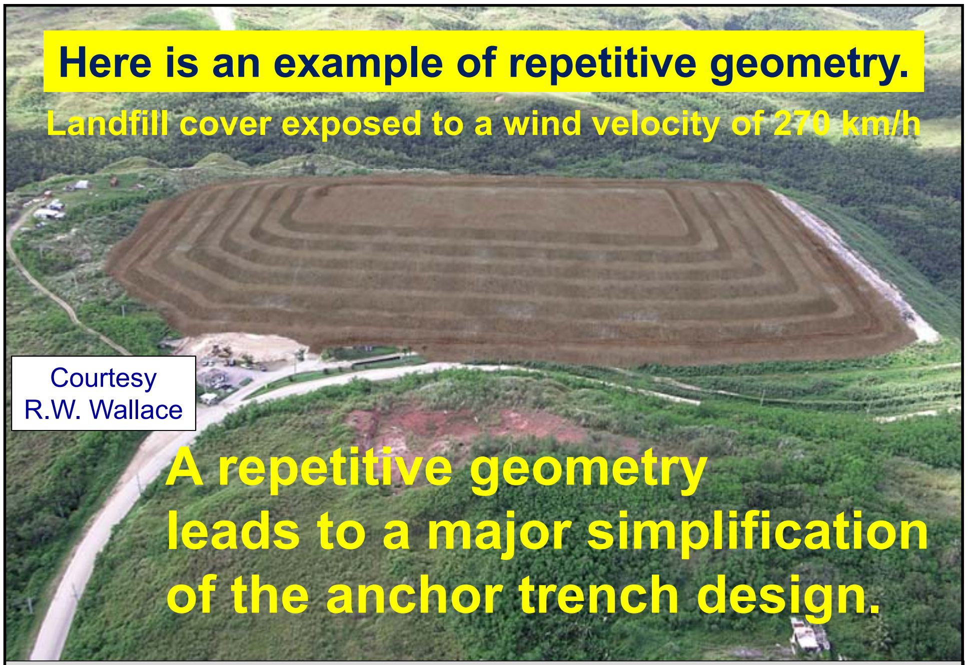
In general, the angle, α, depends on
the parameters on both sides, S_e , L and θ.

Therefore, each anchor trench
on a given slope
must be specifically designed.

However, the **calculations**
can be much simpler
in the case of **repetitive geometry**.



Sketch of repetitive geometry
(not to scale)



Here is an example of repetitive geometry.

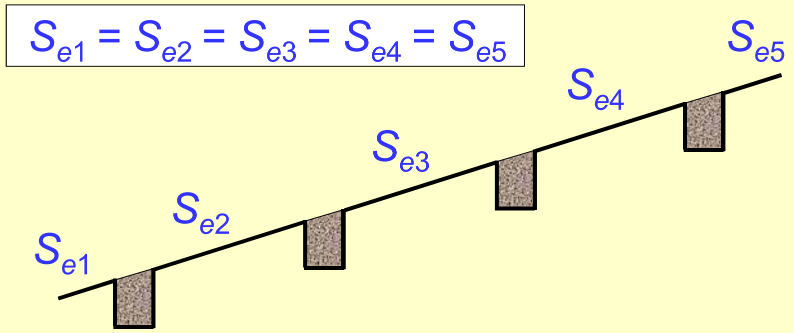
Landfill cover exposed to a wind velocity of 270 km/h

Courtesy
R.W. Wallace

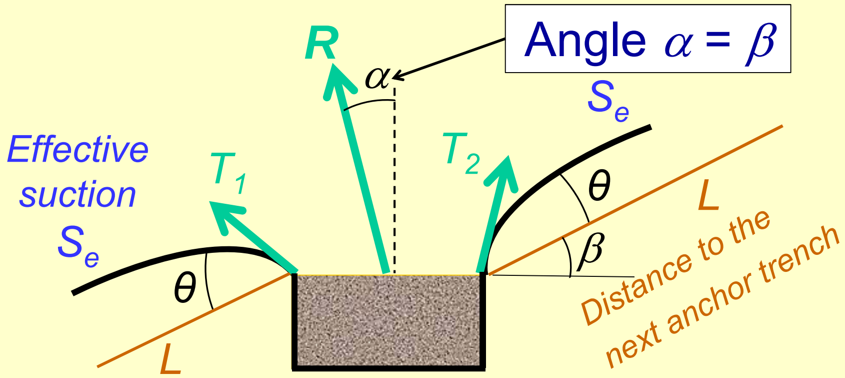
**A repetitive geometry
leads to a major simplification
of the anchor trench design.**

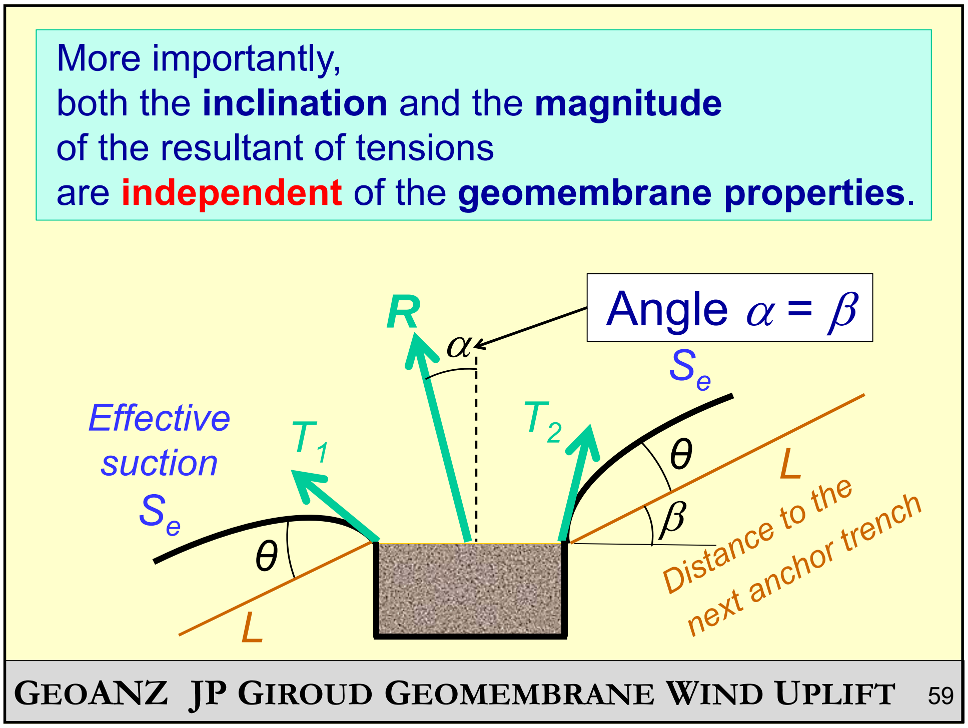
It is important to note that the **simple calculations**, in the case of a repetitive geometry, are possible only if the **same effective suction** is assumed along the entirely considered slope.

$$S_{e1} = S_{e2} = S_{e3} = S_{e4} = S_{e5}$$

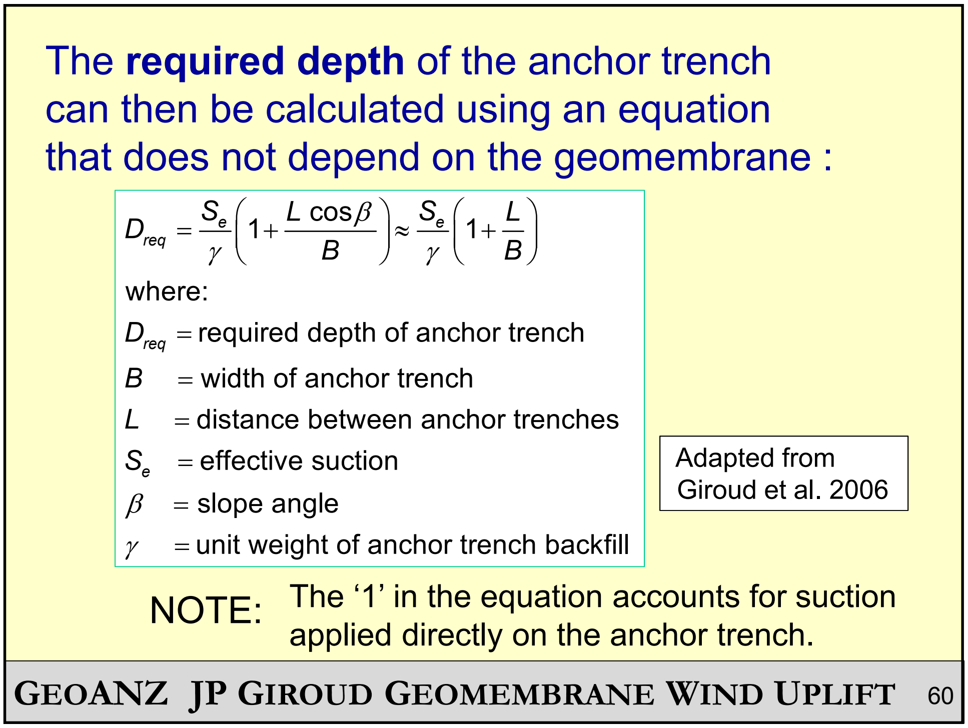


In the case of a **repetitive geometry**, with the **same effective suction** over the entire slope, the **angle α is the same** for all anchor trenches, and it is equal to the slope angle, β.





More importantly,
both the **inclination** and the **magnitude**
of the resultant of tensions
are **independent** of the **geomembrane properties**.



The **required depth** of the anchor trench can then be calculated using an equation that does not depend on the geomembrane :

$$D_{req} = \frac{S_e}{\gamma}\left(1+\frac{L\cos\beta}{B}\right) \approx \frac{S_e}{\gamma}\left(1+\frac{L}{B}\right)$$

where:

D_{req} = required depth of anchor trench
B = width of anchor trench
L = distance between anchor trenches
S_e = effective suction
β = slope angle
γ = unit weight of anchor trench backfill

Adapted from Giroud et al. 2006

NOTE: The ‘1’ in the equation accounts for suction applied directly on the anchor trench.

SEVENTH SUBJECT

OPTIMIZATION OF DISTANCE BETWEEN ANCHOR TRENCHES

The approach described earlier
consisted in calculating
the **geomembrane strain and tension**
for a **given distance**, *L*,
between adjacent anchor trenches.

The approach described here consists in
calculating the **maximum distance**
between anchor trenches
for **given strain and tension**
in the geomembrane.

Optimizing the distance between anchor trenches consists in selecting
the **greatest** possible **distance**
that is **compatible** with
the **allowable strain and tension**
in the geomembrane.

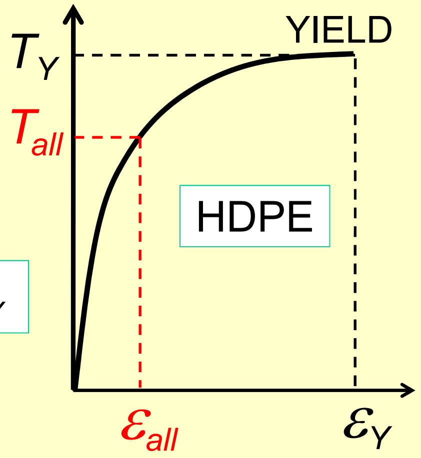
First, the allowable strain, ε_{all} ,
of the geomembrane is selected.

In the case of an HDPE geomembrane,
the allowable strain can be selected as
a **fraction** of the **yield strain**.

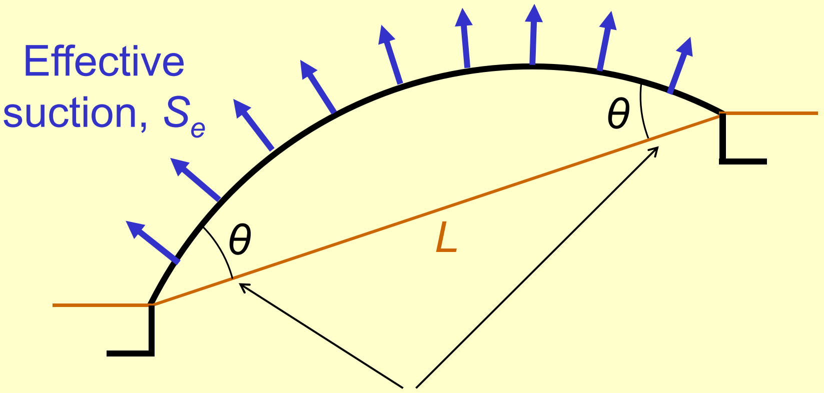
Because of the shape
of the tension-strain curve
of HDPE geomembranes,
if the allowable strain is
0.25 times the yield strain,
then the allowable tension is
0.7 times the yield tension.

$\varepsilon_{all} = 0.25\,\varepsilon_Y$ $T_{all} = 0.7\,T_Y$

This is for HDPE.



For other types of geomembrane,
allowable strains and tensions can be selected
using appropriate criteria.



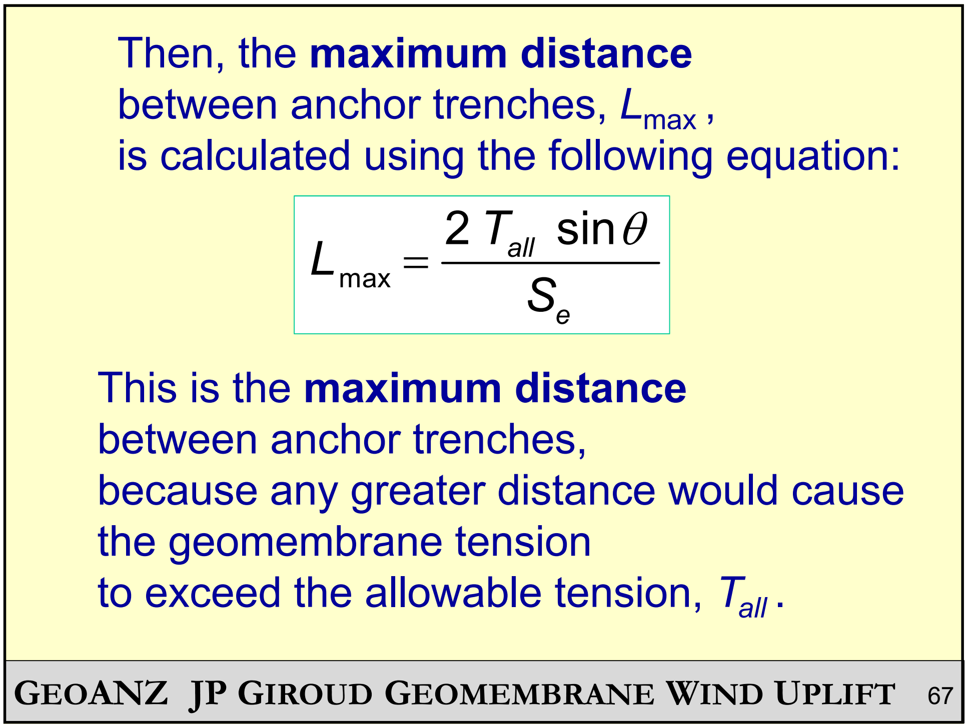
Then, the angle, θ, is calculated
by solving the following equation iteratively.

$$\frac{\theta}{\sin\theta} = 1 + \varepsilon_{all}$$

Iterations can be avoided by using
the following approximate equation:

$$2\sin\theta \approx \frac{\varepsilon_{all}^{1/2}}{\left(0.3467 + 0.3103\,\varepsilon_{all}\right)^{3/2}}$$

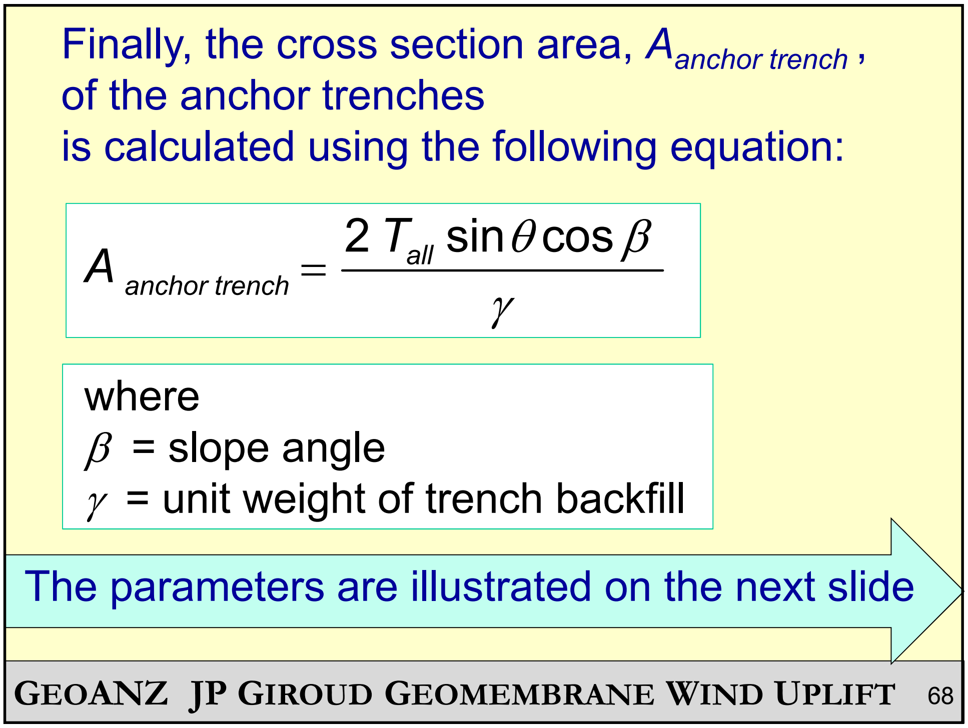
[Note: This equation has not been published yet.
It was developed during the preparation of this presentation.]



Then, the **maximum distance** between anchor trenches, L_{max} , is calculated using the following equation:

$$L_{\max} = \frac{2\,T_{all}\,\sin\theta}{S_e}$$

This is the **maximum distance** between anchor trenches, because any greater distance would cause the geomembrane tension to exceed the allowable tension, T_{all} .

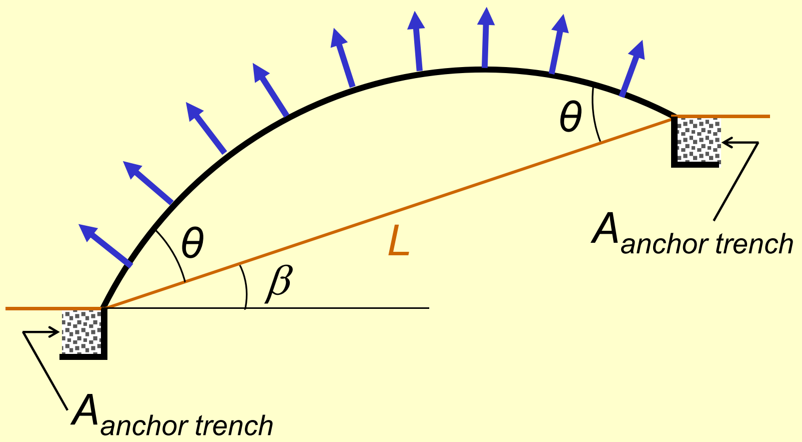


Finally, the cross section area, $A_{anchor\ trench}$, of the anchor trenches is calculated using the following equation:

$$A_{anchor\ trench} = \frac{2\,T_{all}\,\sin\theta\cos\beta}{\gamma}$$

where
β = slope angle
γ = unit weight of trench backfill

The parameters are illustrated on the next slide



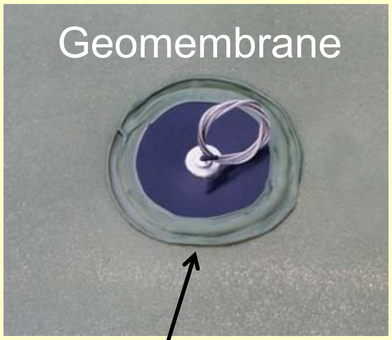
$$A_{anchor\ trench} = \frac{2\ T_{all} \sin\theta \cos\beta}{\gamma}$$

EIGHTH SUBJECT

ANCHORAGE USING GROUND ANCHORS

The geomembrane can be secured using ground anchors driven into the soil.

Driving the anchor into soil



Extrusion seam
around the anchor plate

Courtesy Platipus

The geomembrane is secured
using **multiple ground anchors**.

A ground anchor is characterized
by its **pullout resistance**,
which depends on
the anchor and the soil properties.

The required number of anchors per unit area is given by following equation.

$$N = \frac{S_e}{P}$$

where

N is the number of anchors per unit area

S_e is the effective suction

P is the anchor pull-out resistance

With S_e in Pascals and P in Newtons, the number of anchors per m^2 is obtained.

The number of anchors per m^2 is a **very small number**, which is not convenient.

It is preferable to give the **number of anchors per hectare**, which is 10,000 times higher.

$$N_{\text{per hectare}} = 10{,}000\, N_{\text{per square meter}}$$

Example: S_e = 908 Pa, P = 8000 N
The equations give N = 0.1135 anchor/m^2,
and $N_{\text{per hectare}}$ = 1135 anchors/hectare

The **distance** between ground anchors,
assuming a square pattern,
is given by the following equation.

$$d = \frac{1}{\sqrt{N}} = \sqrt{\frac{P}{S_e}} = \sqrt{\frac{10{,}000}{N_{per\ hectare}}}$$

Example: S_e = 908 Pa, P = 8000 N
N = 0.1135 anchor/m^2, and $N_{per\ hectare}$ = 1135/ha

The calculated distance is d = 2.97 m ≈ 3 m

Note: 908 Pa suction corresponds to 160 km/h wind.

It is important to note that the determination of the
required **number** of ground anchors
and the **distance** between ground anchors
is **independent** of
the **geomembrane type or properties**.

As a result, it is **easier to design**
the anchorage of geomembranes
by ground anchors than by anchor trenches.

However, it is necessary to check that
the **strains** in the geomembrane are **acceptable**
for the **considered geomembrane**.

The **average strain** in the **uplifted geomembrane must be calculated** to check if it is **acceptable**.

Calculating an average strain is difficult because the deformed geomembrane has a complex shape due to the multiple ground anchors.

An **approximate average strain** can be calculated with this equation (*adapted from an equation for linear tension-strain curves*).

$$\varepsilon_{approx} \approx \frac{0.3467\left(\dfrac{S_e\, d}{J}\right)^{2/3}}{1-0.3103\left(\dfrac{S_e\, d}{J}\right)^{2/3}} \approx 0.35\left(\dfrac{S_e\, d}{J}\right)^{2/3}$$

For a 1.5 mm thick HDPE geomembrane,
a tensile stiffness J = 450,000 N/m can be assumed for small strains (i.e. strains lower than 3%).

For the preceding example,
the approximate equation from the preceding slide, gives $\varepsilon_{approx} \approx 0.012 = 1.2\%$ for the average strain.

This strain is **small** compared to the 3 to 4% **allowable strain** for an HDPE geomembrane.

A **major advantage** of multiple ground anchors, compared to anchor trenches, is the small average strain and, therefore, the small deflection of the geomembrane.

The strain calculated in the preceding slide
is the **average strain**
in the uplifted geomembrane.

However, *whereas the geomembrane strain is almost uniformly distributed in a geomembrane uplifted between parallel anchor trenches*, there is **stress and strain concentration** in the geomembrane around a ground anchor.

The concentrated stress is calculated in the next slide.

The **highest stress** in the geomembrane takes place at the **edge of the plate** that covers the ground anchor.

This stress can be calculated using this equation:

$$\sigma = \frac{1.4\,P}{\pi\,D\,t_{GMB}}$$

Derived from Giroud et al. 1995b

where:
σ = stress
P = anchor pullout strength
D = plate diameter
t_{GMB} = geomembrane thickness

The 1.4 factor is for HDPE geomembranes.
Lower factors are to be used
with more extensible geomembranes.

Here is a **numerical application of the equation**.

For a **typical** 8000 N pullout strength of the anchor, and a 0.2 m plate diameter, the calculated stress is:

- ~ **18 MPa** for a 1.0 mm thick HDPE geomembrane; and
- ~ **12 MPa** for a 1.5 mm thick HDPE geomembrane.

The yield stress of an HDPE geomembrane, is **17** to **19 MPa**. Therefore:

the **1.0 mm** HDPE geomembrane is likely to rupture

the **1.5 mm** HDPE geomembrane has a factor of safety of about 1.5.

There is good agreement between these calculations and a few available full-scale test results.

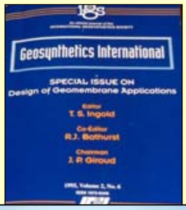
The above example is related to a typical ground anchor used at full capacity.

This occurs in case of high-velocity wind and/or large spacing between anchors.

However, the preceding example corresponds to a real case.

Therefore, the evaluation of the concentrated stress around a ground anchor is an **essential design step**.

There are many other interesting design cases, but this would require more time.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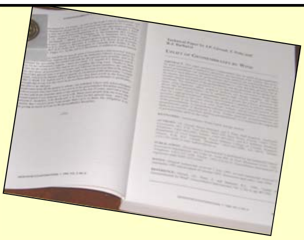
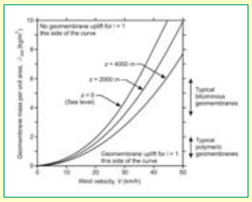
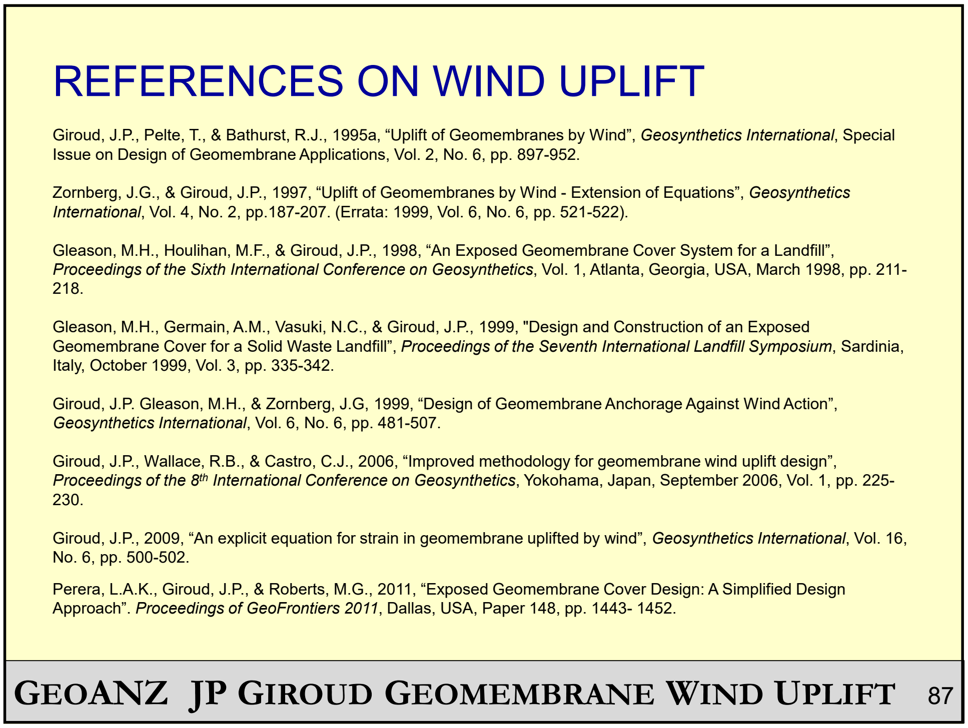


Thank you







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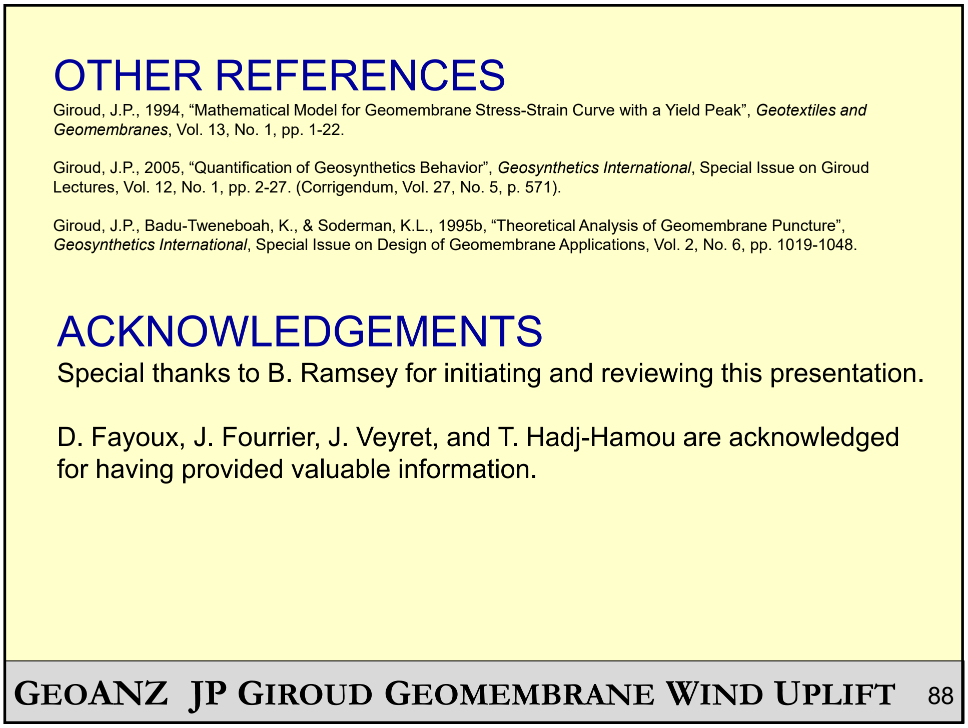

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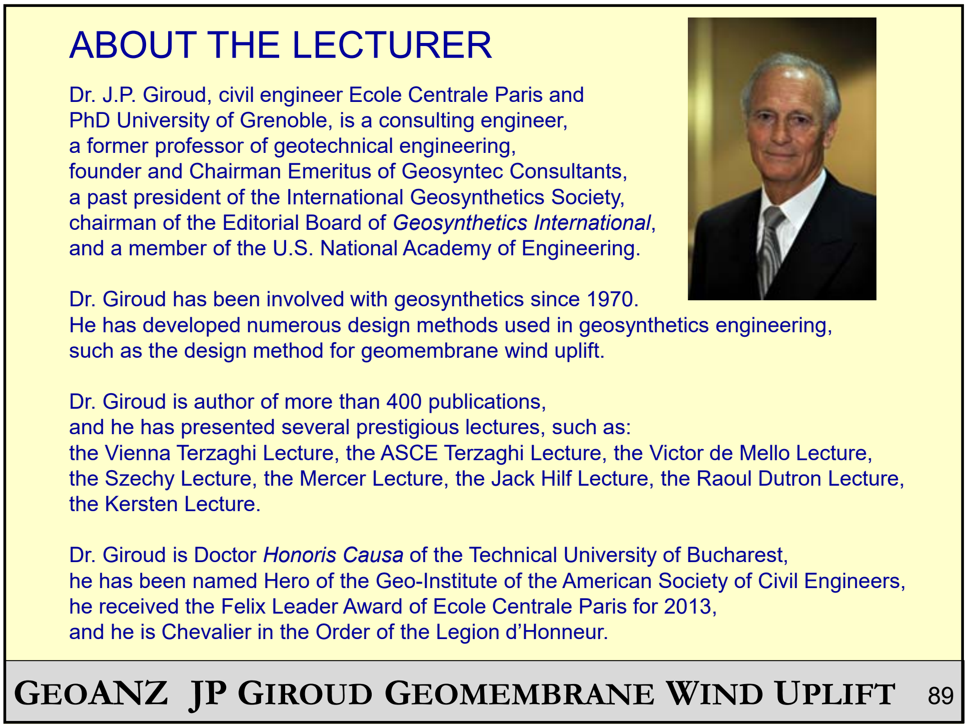

ABOUT THE LECTURER

Dr. J.P. Giroud, civil engineer Ecole Centrale Paris and PhD University of Grenoble, is a consulting engineer, a former professor of geotechnical engineering, founder and Chairman Emeritus of Geosyntec Consultants, a past president of the International Geosynthetics Society, chairman of the Editorial Board of *Geosynthetics International*, and a member of the U.S. National Academy of Engineering.

Dr. Giroud has been involved with geosynthetics since 1970. He has developed numerous design methods used in geosynthetics engineering, such as the design method for geomembrane wind uplift.

Dr. Giroud is author of more than 400 publications, and he has presented several prestigious lectures, such as: the Vienna Terzaghi Lecture, the ASCE Terzaghi Lecture, the Victor de Mello Lecture, the Szechy Lecture, the Mercer Lecture, the Jack Hilf Lecture, the Raoul Dutron Lecture, the Kersten Lecture.

Dr. Giroud is Doctor *Honoris Causa* of the Technical University of Bucharest, he has been named Hero of the Geo-Institute of the American Society of Civil Engineers, he received the Felix Leader Award of Ecole Centrale Paris for 2013, and he is Chevalier in the Order of the Legion d'Honneur.