AGENDA

- 01) Aussie Liners and Covers for Mine Waste - Williams
- 02) GCLs for Mine Waste – Benson
- 03) Case Study
- 04) Geosynthetics for Tailings Disposal - Stark
- 05) Tailings Drainage using Geocomposites – Saunier
- 06) Geosynthetics for Evaporation Mining - Stark

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

Master Class #3

Advances in Design and Construction with Geosynthetics for Mine Wastes and Closure

Australian Experience of Liners and Covers for Mine Wastes

Professor David Williams, UQ

(email: D.Williams@uq.edu.au)

GEOANZ #1 ADVANCES IN GEOSYNTHETICS

7–9 JUNE 2022 | BRISBANE CONVENTION & EXHIBITION CENTRE

Liners and covers applied to mine wastes

- Liners:
    - Evolution
    - Purpose
    - Determinants of liner performance and potential leakage rates
    - Example applications to mine wastes
- Covers:
    - Evolution
    - Purpose
    - Determinants of cover performance
    - Example applications to mine wastes

Evolution of liners beneath stored mine wastes

- Early mine waste storages had no designed liner
- This evolved to:
    - Selecting waste storage sites with natural clays (deep, uncracked)
    - Compacted clay liners (desiccation must be allowed for)
    - HDPE, GCL and bituminous geomembrane liners (under limited head, and exposure to UV and harsh chemistry/biology must be allowed for)
- Composite and leachate collection liners:
    - Combining benefits of clay and geosynthetics, and added safety of leachate collection and reduction of hydraulic gradient

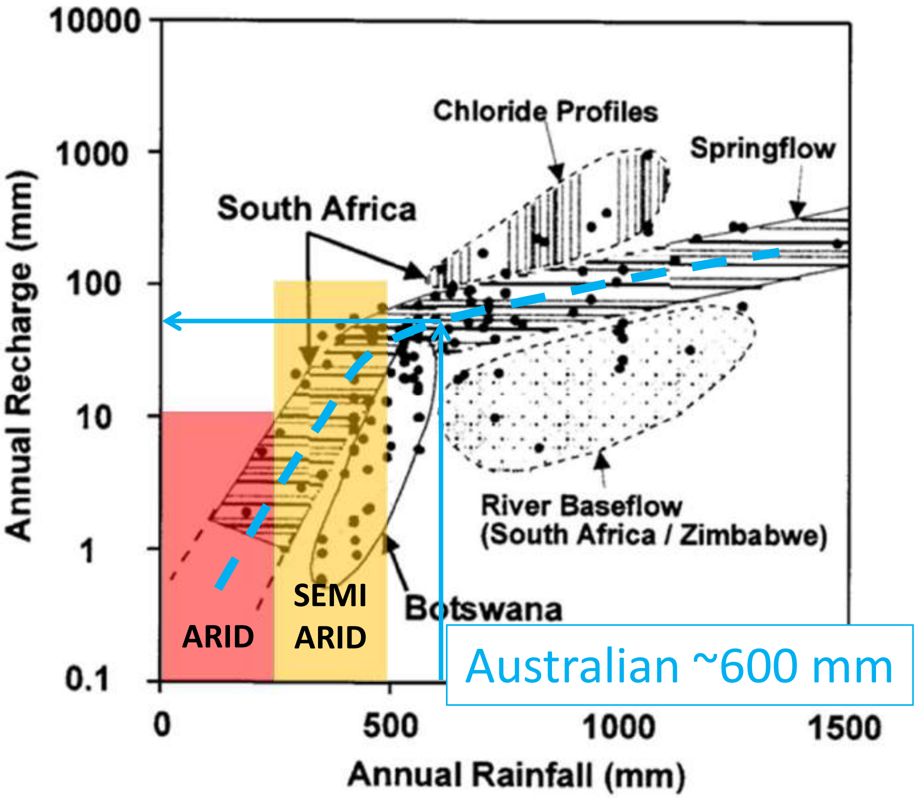
Purpose of liners on mine wastes

- Stored mine wastes add to natural recharge, and have the potential to contaminate the receiving environment
- Liner systems have evolved from a desire to limit potential environmental impacts from stored mine wastes
- Key means by which liners may limit potential environmental impacts:
  - Limiting transport of any contaminants by reducing seepage; and/or
  - Enabling leachate collection of any contaminants or oxidation product; and/or
  - Maintaining saturated conditions within the mine wastes to limit oxidation

Determinants of liner performance

- Climate
- Nature and reactivity of mine wastes
- Topography, surrounding landforms and land uses
- Proposed final land use and water resources at risk
- Appropriate liner selection and design
- Controlled liner material selection and construction
- Limiting exposure of liner to environmental degradation
- Required liner design life and liner longevity

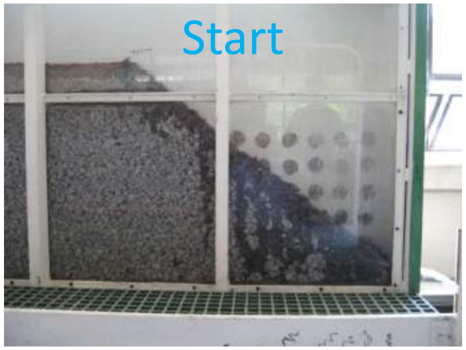
Natural recharge (Beekman *et al.* 1996)



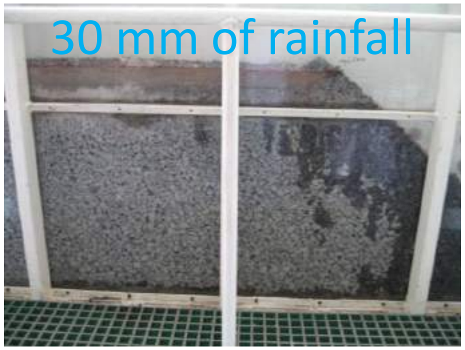
Av ~70 mm
2 x 10^{-9} m/s

Australian ~600 mm

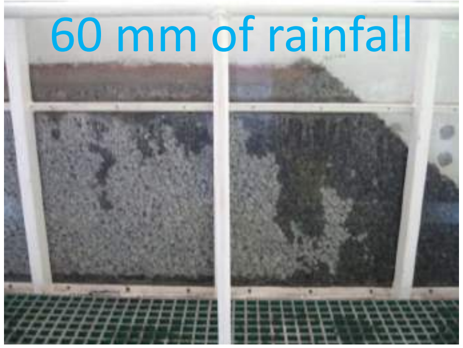
Wetting-up of a waste rock dump



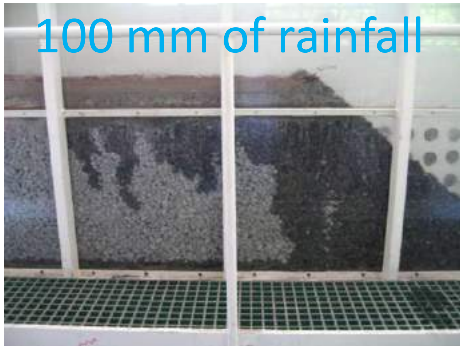
Start



30 mm of rainfall

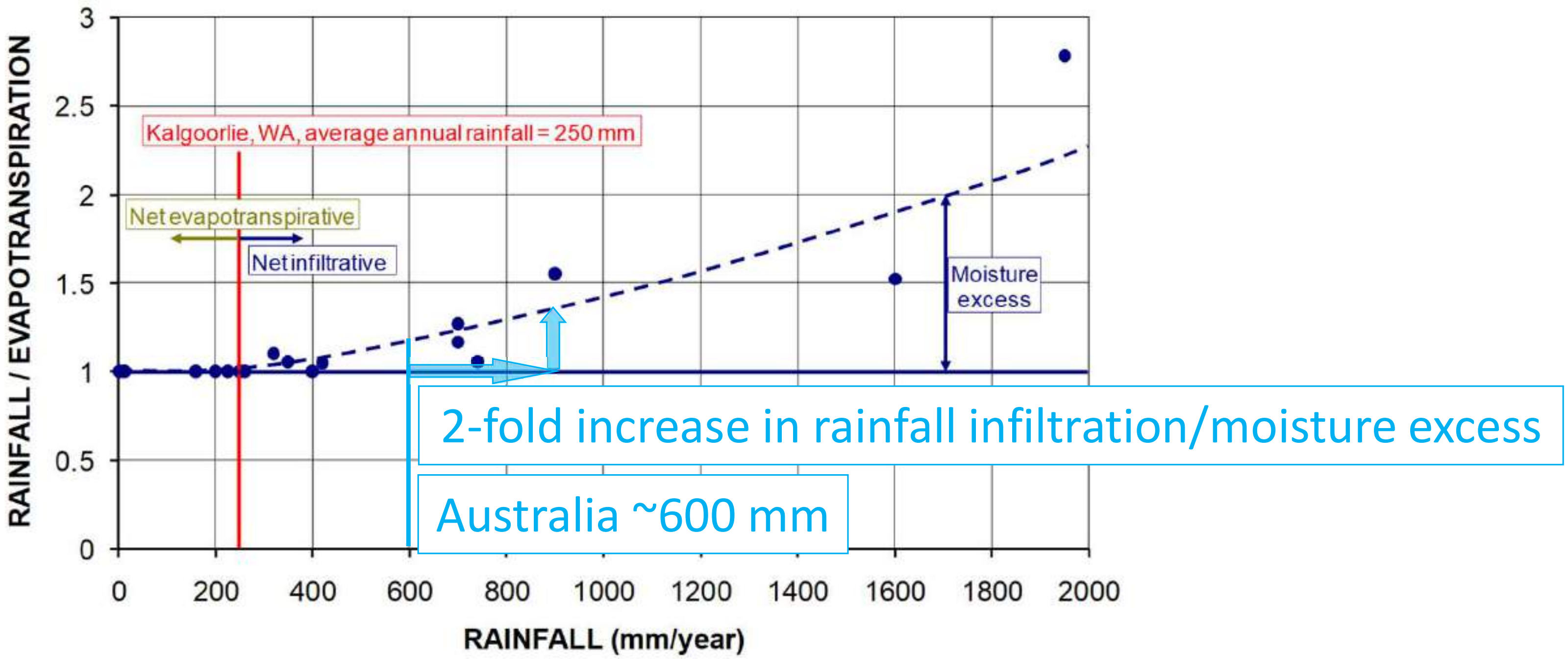


60 mm of rainfall



100 mm of rainfall

Increased rainfall infiltration into a waste rock dump



2-fold increase in rainfall infiltration/moisture excess

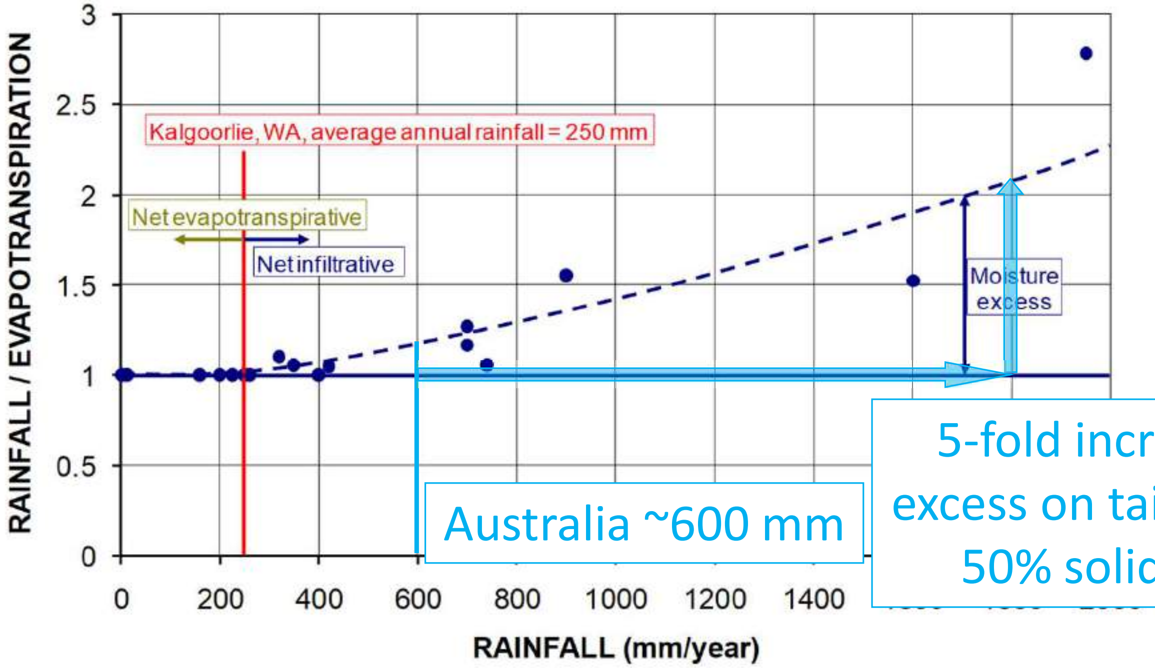
Australia ~600 mm

Tailings slurry deposition

Large decant pond

Small decant pond

Increased seepage due to tailings deposition



Australia ~600 mm

5-fold increase in moisture excess on tailings deposition at 50% solids and 1 m/year

How effective are liners generally?

- Poorly-compacted clayey soils
- Compacted clayey soils
- Natural clayey soils and weathered rock
- HDPE, GCL and bituminous geomembrane liners
- Composite soil and geomembrane liners

Potential leakage rates through liners

LINER	POTENTIAL LEAKAGE RATE			
	Under unit hydraulic gradient		Under 3 m head	
	(m/s)	(mm/year)	(m/s)	(mm/year)
Natural clay/weathered rock (>3 m)	10^{-9}	32	10^{-9}	32
Well-compacted clay (0.5 m)	10^{-8}	315	6×10^{-8}	1,890
Poorly-compacted clay (0.5 m)	10^{-7}	3,150	6×10^{-7}	18,900
HDPE geomembrane (1.5 mm): • Intact	10^{-15}	0.0003	2×10^{-12}	0.6
• In practice	10^{-11}	0.3	2×10^{-8}	600

Will pass ~3 times rainfall!

Will pass all stored water!

Will pass most rainfall!

Liners for heap leach pads

- Early heap leach pads were not lined, but lining (generally with an HDPE geomembrane) is now best practice, to recover as much pregnant solution as possible

Liners for mine water ponds

- Early mine water ponds were not lined
- Geomembrane liners are now common: to store pregnant solutions, to retain process chemicals and water, and to protect the environment

HDPE-lined slope and compacted tailings pond base

Liners for tailings storage facilities

- Tailings storage facilities were not lined in the past
- Lining (and drainage) is becoming more common, especially beneath the decant pond and where clay is in short supply, to protect surface and groundwater resources, and to meet regulatory requirements

Bituminous geomembrane on tailings dam slope

Sub-aqueous and sub-aerial (spigot) tailings disposal

Bituminous geomembrane seepage pond liners

Fully HDPE-lined tailings facility (rare)

Fully HDPE-lined tailings cell in North Queensland

Fully HDPE-lined tailings cell

Compacted clay, GCL and geotextile on tailings dam

Effectiveness of composite liner

Upstream compacted tailings and geotextile

HDPE-lined emergency spillway

Embankment construction using geotubes

Geotextiles used in underdrainage with riser

Geotextile used to reduce erosion and wave action

Some observations of geosynthetic use

- Geosynthetics are more likely to be used in tailings dam construction in wetter regions of Australia, particularly on Tasmania's West Coast:
    - ~2,000 mmpa rainfall – Evenly spread persistent "drizzle"
    - On existing tailings dams, liners will be restricted to the slopes of upper raises
    - Bituminous geomembranes and GCLs are preferred over HDPE because they are easier to install in the cool, wet climate
    - GCLs are typically laid on a geotextile for protection and may be overlain by compacted "clay" – A composite liner
    - Compacted tailings may be used in the upstream zone, with a geotextile separator, and rock in the downstream zone to lower the phreatic surface

Waste rock dumps?

- Waste rock dumps are rarely lined

Tailings facilities and some waste rock dumps have underdrains that may be geotextile-wrapped, although consideration must be given to the potential for these to clog physically (addressed by applying filter criteria), chemically and/or biologically

Lining pit slopes

- Pit slopes may be flooded, are rarely lined, although coating or lining has been considered to limit the oxidation of exposed sulfides

While liners used in mining applications have tended to follow landfill practices, they have not gone as far, rarely involving double geomembranes and leachate collection

Evolution of covers on mine wastes

- Early mine waste covers were intended to support revegetation
- This evolved to:
  - Rainfall-shedding (mounded) covers, comprising a sealing layer (compacted clay and/or geosynthetic), and a growth medium
  - Non-shedding covers to store rainfall infiltration and release it through evapotranspiration, known as:
    - Store and release (for use on mine wastes in dry climates) – Williams *et al.* (1997)
    - Evapotranspirative (ET), Phytocap, etc. (for use on municipal wastes in dry climates) – ACAP Benson and Albright (1998)
  - Capillary break layers to limit uptake of contaminants (difficult to get right!)

Simple vegetative covers directly on tailings

Natural revegetation of coal tailings

Planted vegetation on gold tailings

Purpose of covers on mine wastes

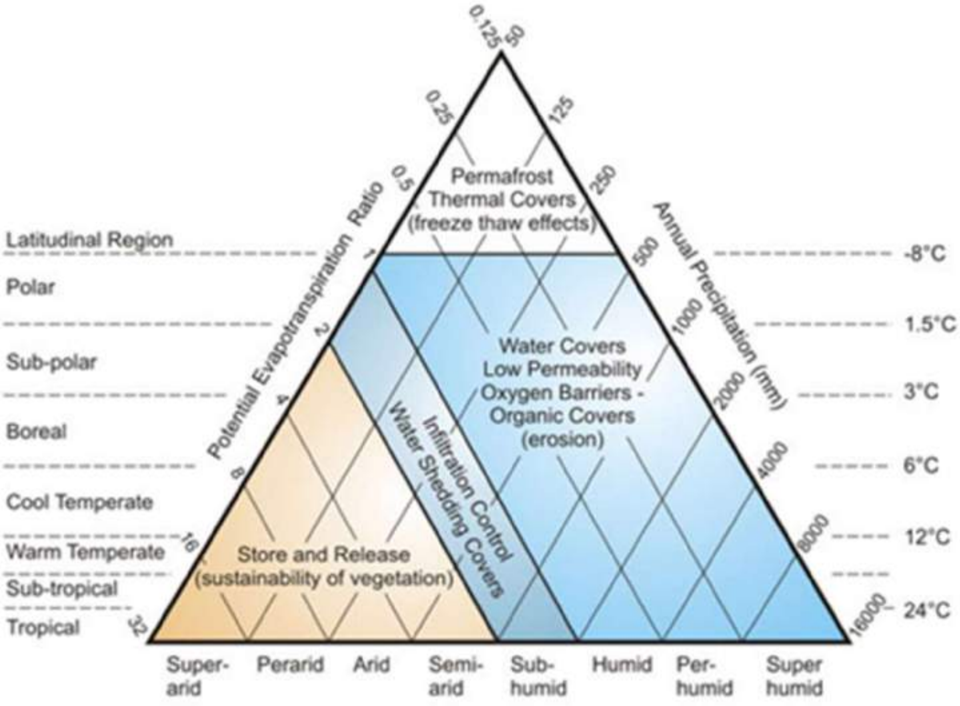
- Cover systems have evolved from a desire to limit potential environmental impacts from stored mine wastes
- Key means by which covers may limit potential environmental impacts are:
    - Limiting potential oxidation of stored mine wastes by restricting oxygen ingress (best achieved by storage below water, in wet climates), and/or
    - Limiting transport of any contaminants or oxidation products to the environment via rainfall runoff or seepage, or wind (applicable in dry climates)

Determinants of mine waste cover performance

- Climate
- Nature and reactivity of the mine wastes
- Topography, surrounding landforms and land uses
- Proposed final land use or ecological function
- Appropriate cover selection and design
- Controlled cover material selection and cover construction
- Cover maintenance and sustainability

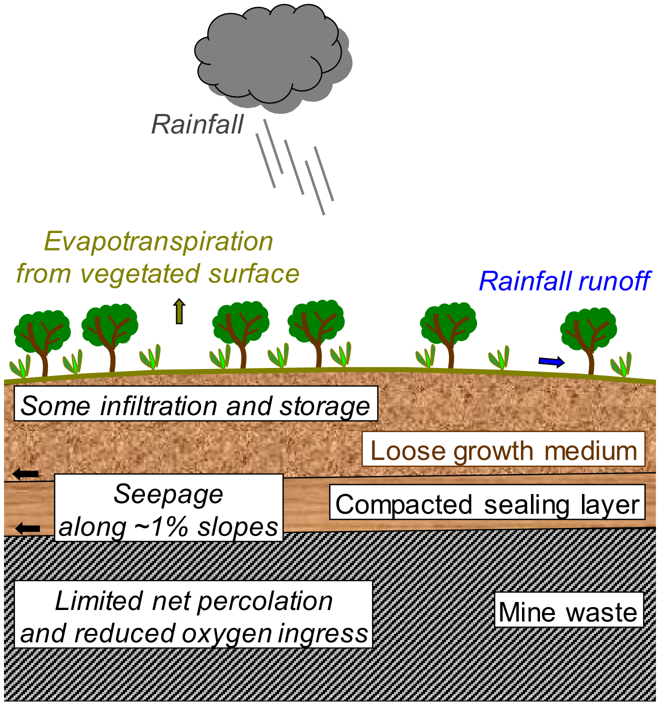
Selection of cover type based on climate

- Cover systems for mine waste tops are intended to limit oxygen ingress and/or net percolation of rainfall
- Water covers in wet climates (e.g., Canada and the wet tropics
- Rainfall-shedding covers in moist climates
- Robust store and release covers in dry climates (e.g., Australia)



(GARD Guide, 2009)

Rainfall-shedding



Rainfall

Evapotranspiration
from vegetated surface

Rainfall runoff

Some infiltration and storage

Loose growth medium

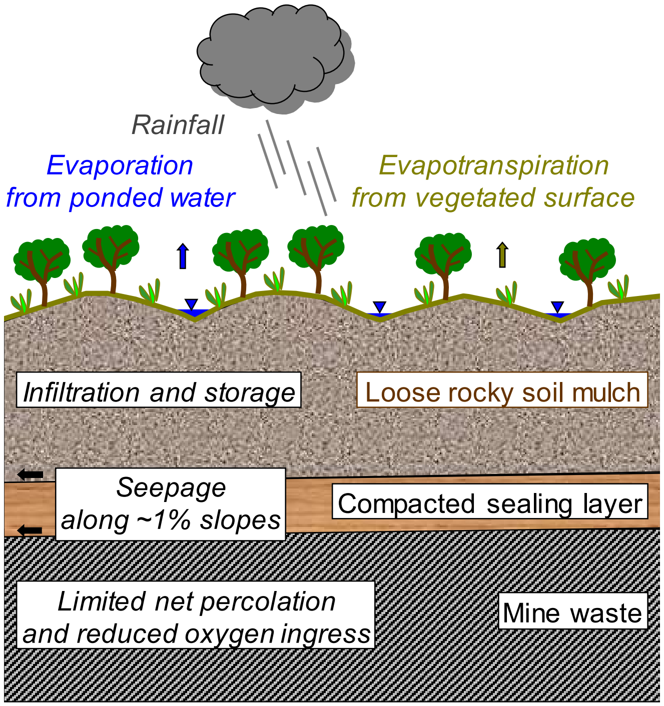
Seepage
along ~1% slopes

Compacted sealing layer

Limited net percolation
and reduced oxygen ingress

Mine waste

Store and release



Rainfall

Evaporation
from ponded water

Evapotranspiration
from vegetated surface

Infiltration and storage

Loose rocky soil mulch

Seepage
along ~1% slopes

Compacted sealing layer

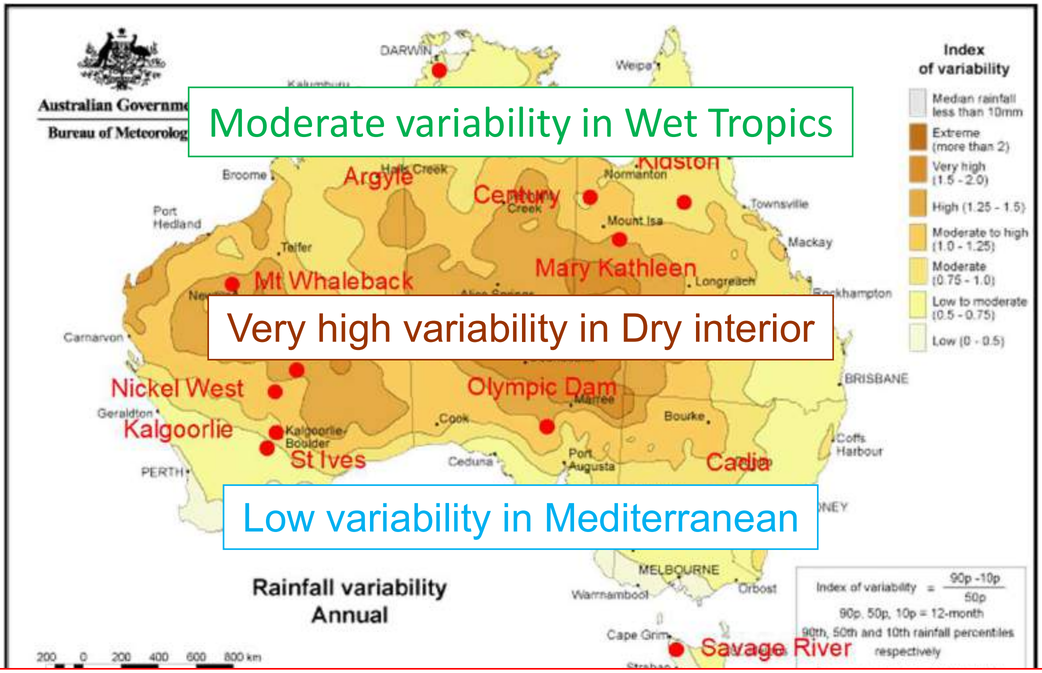
Limited net percolation
and reduced oxygen ingress

Mine waste

Influence of climate on cover performance

- In dry or seasonally dry climates, covers should:
  - Prevent exposure of stored mine wastes to air-borne mobilisation
  - Limit net percolation of rainfall into underlying mine wastes to limit transport of any oxidation products
- In wet climates, covers should either:
  - Shed incident rainfall
  - Drain excess rainfall infiltration, or
  - Infiltrate alkalinity from a thick alkaline cover to neutralise any acidity generated by underlying wastes

Australian rainfall variability



Moderate variability in Wet Tropics

Very high variability in Dry interior

Low variability in Mediterranean

Variability ("droughts and flooding rains") > 10 x Climate change trends

Rain → apathy; drought → awareness, concern & panic; relieved by subs. rain

“Droughts to flooding rains”

HDPE-lined drain and cover on toxic tailings

300 mm topsoil erodes if slope >10^o

Conclusions

- Stored mine wastes increase rainfall infiltration:
    - A waste rock dump is like a “sponge”, initially allowing about 50% rainfall infiltration, dropping to an average 20%, compared with say 10% naturally
    - Operation of a tailings storage facility can increase rainfall infiltration from say 10% to 50%
- Liners (geomembranes) are now common for heap leach pads, for mine water ponds, and increasingly for tailings storage facilities:
    - To recover as much pregnant solution as possible from heap leach pads
    - To protect the environment from potential contamination by mine or tailings waters

Conclusions

- The effectiveness and longevity of liners (and other geotextiles) needs to carefully be considered
- Geomembrane and composite liners for tailings storage facilities:
    - Necessarily focussed on the upstream slope of existing tailings storage facilities, relying on the consolidated tailings to limit base seepage
    - Initially concentrated on sealing the decant area
    - With fully-lined new facilities now being considered
- Use of geosynthetics in rehabilitation has been limited, to date involving sealing particularly contaminating tailings, less so waste rock

AGENDA

- 01) Aussie Liners and Covers for Mine Waste - Williams
- 02) GCLs for Mine Waste – Benson
- 03) Case Study
- 04) Geosynthetics for Tailings Disposal - Stark
- 05) Tailings Drainage using Geocomposites – Saunier
- 06) Geosynthetics for Evaporation Mining - Stark

Using GCLs in Liner Systems for Ore Processing and Mine Waste Containment

Craig H. Benson, PhD, PE, NAE

chbenson@chbenson.org

GEOANZ #1 ADVANCES IN GEOSYNTHETICS

7–9 JUNE 2022 | BRISBANE CONVENTION & EXHIBITION CENTRE

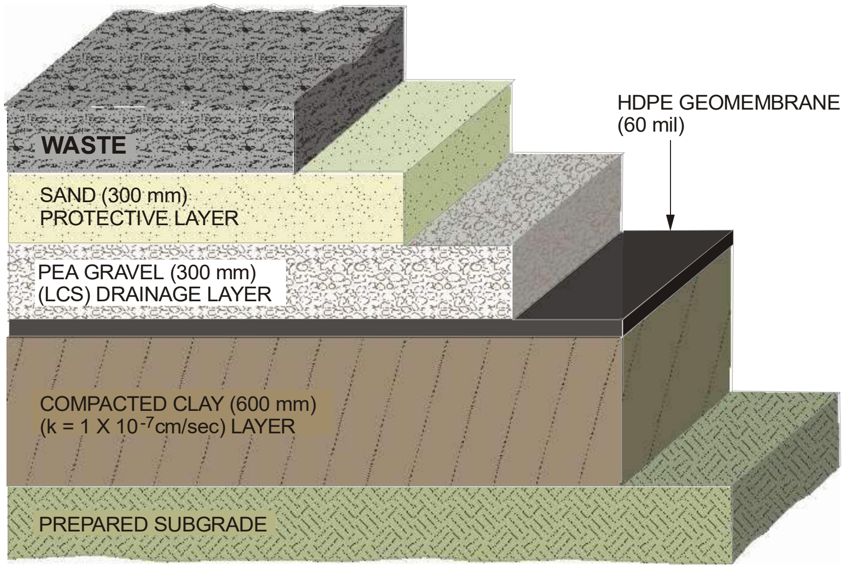
Topics for Today's Session

- What are geosynthetic clay liners (GCLs)?
- When do conventional GCLs with sodium bentonite (NaB) have low hydraulic conductivity, and when are they more permeable?
- What are bentonite-polymer composite GCLs, and why are they more effective than conventional GCLs with aggressive liquids?
- How can I determine if a GCL will have the low hydraulic conductivity needed for my liner application?

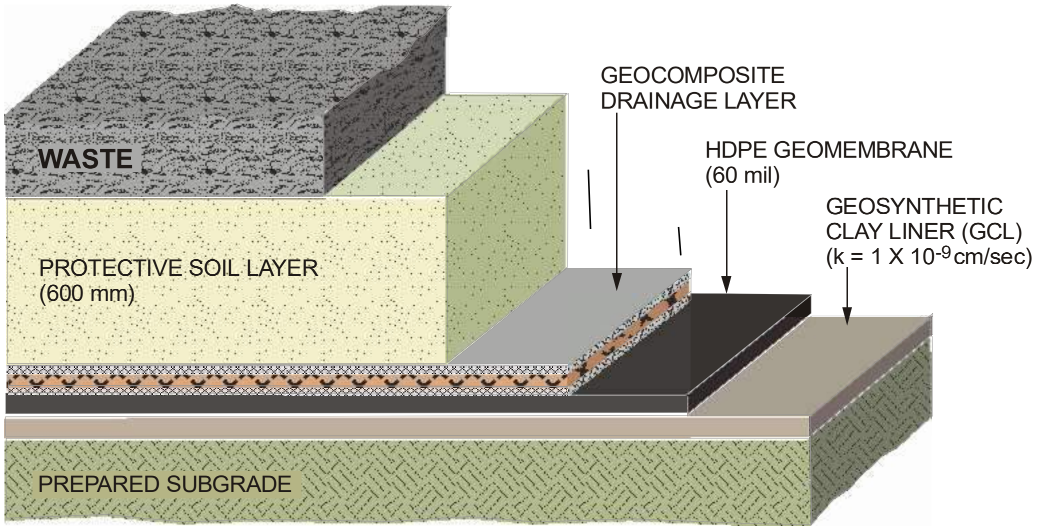
GCLs – Thin Factory-Manufactured Clay Liners

Geosynthetic Clay Liners Expedite Design and Construction & Preserve Airspace

Conventional Liner System



Alternative Design with Geosynthetic Clay Liner (GCL)



Figures courtesy M. Othman, Geosyntec Consultants

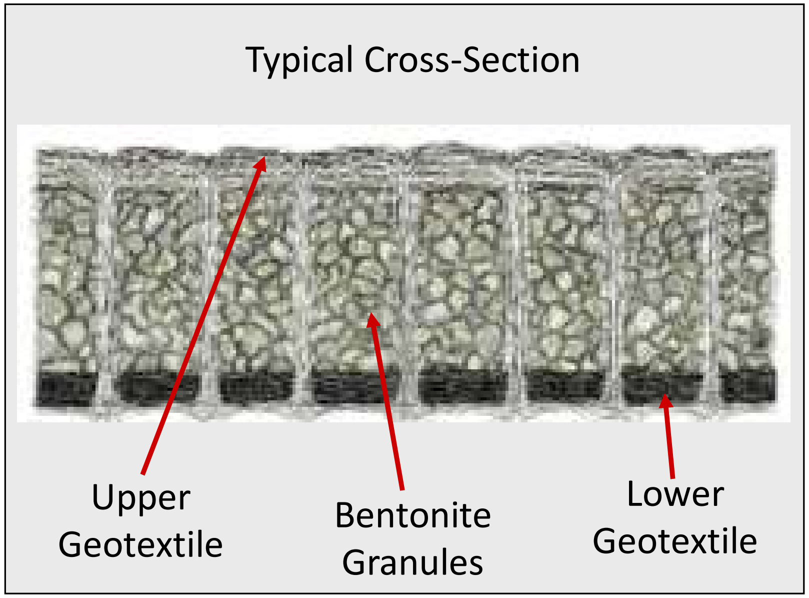
GCLs permit rapid and cost-effective construction, as well as savings in air space. Particularly advantageous in clay poor areas.

What makes a GCL Impervious?

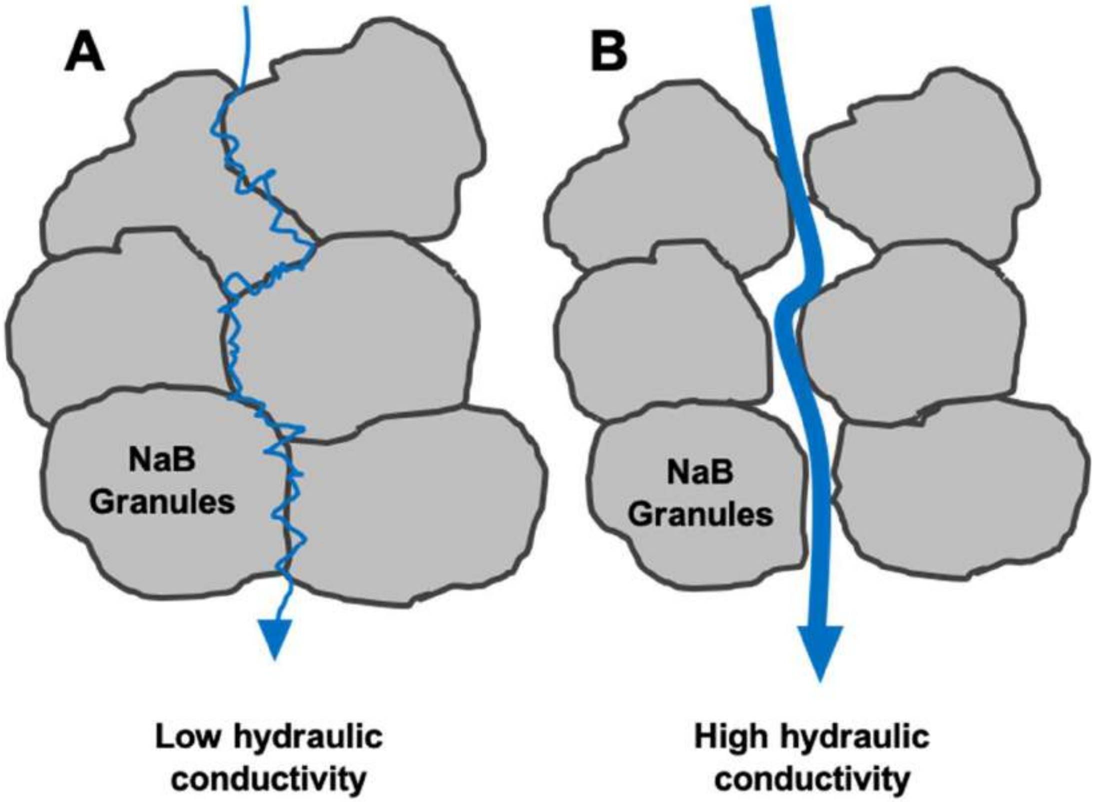
- For low hydraulic conductivity, **sodium (Na) bentonite** granules swell to from a gel (paste).

- Gel must be maintained to retain **low hydraulic (~ 10^{-11} m/s) conductivity**.

- ***If granules do not swell*** and form gel, **higher hydraulic conductivity (>10^{-7} m/s).**



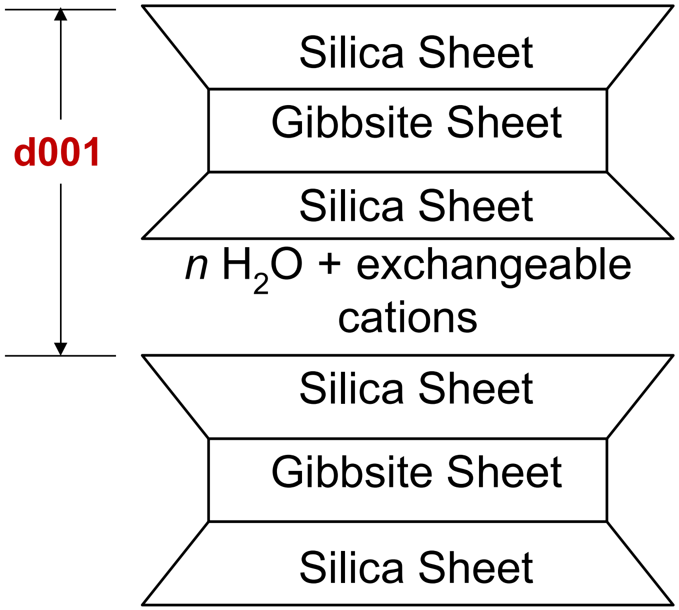
Mechanisms Controlling Hydraulic Conductivity of Bentonite



- When bentonite swells sufficiently, intergranular pores swell shut and hydraulic conductivity is low, as flow occurs through nanoscale pores (< 100 nm).
- When swell is constrained, and intergranular pores remain open, the hydraulic conductivity is higher as flow through microscale pores.
- Sensitive to the size of granules.

Bentonite is Primarily Montmorillonite, a Special Clay

d001 indicative of swell



d001

Silica Sheet

Gibbsite Sheet

Silica Sheet

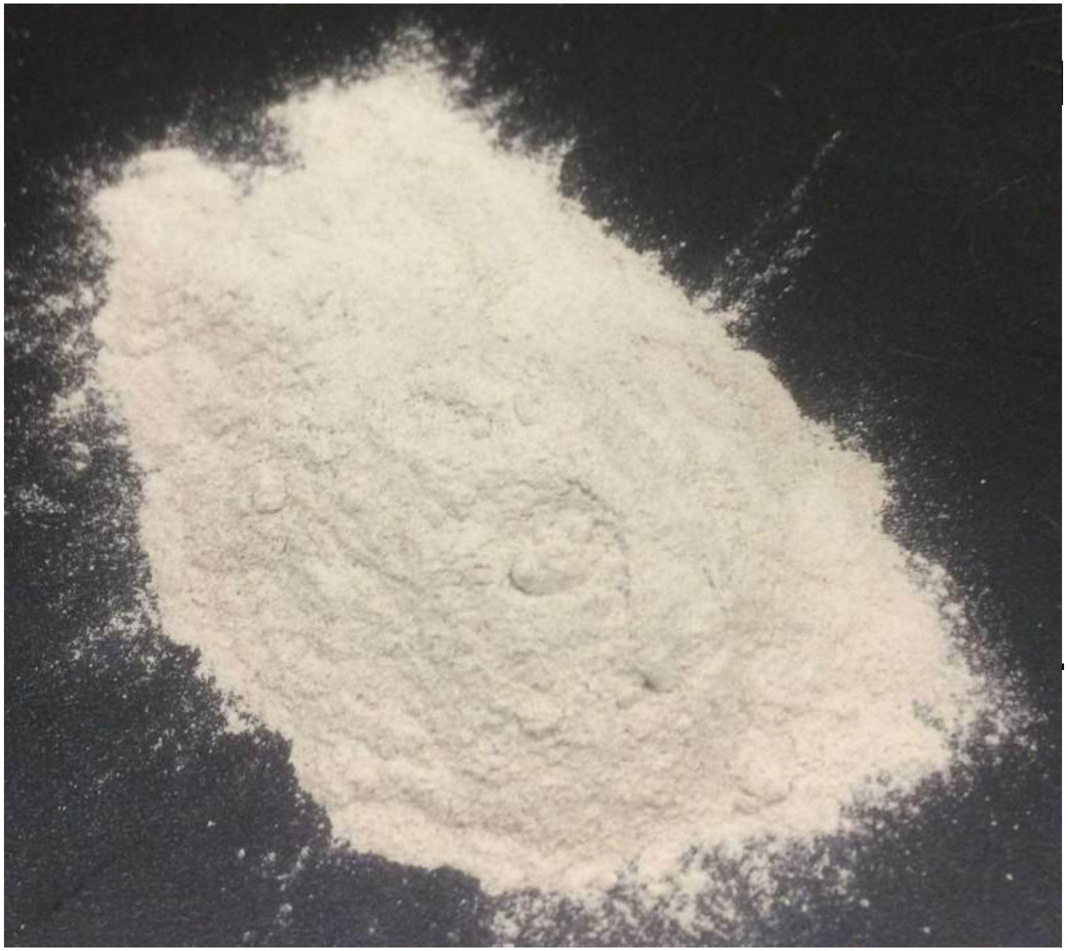
n H_2O + exchangeable cations

Silica Sheet

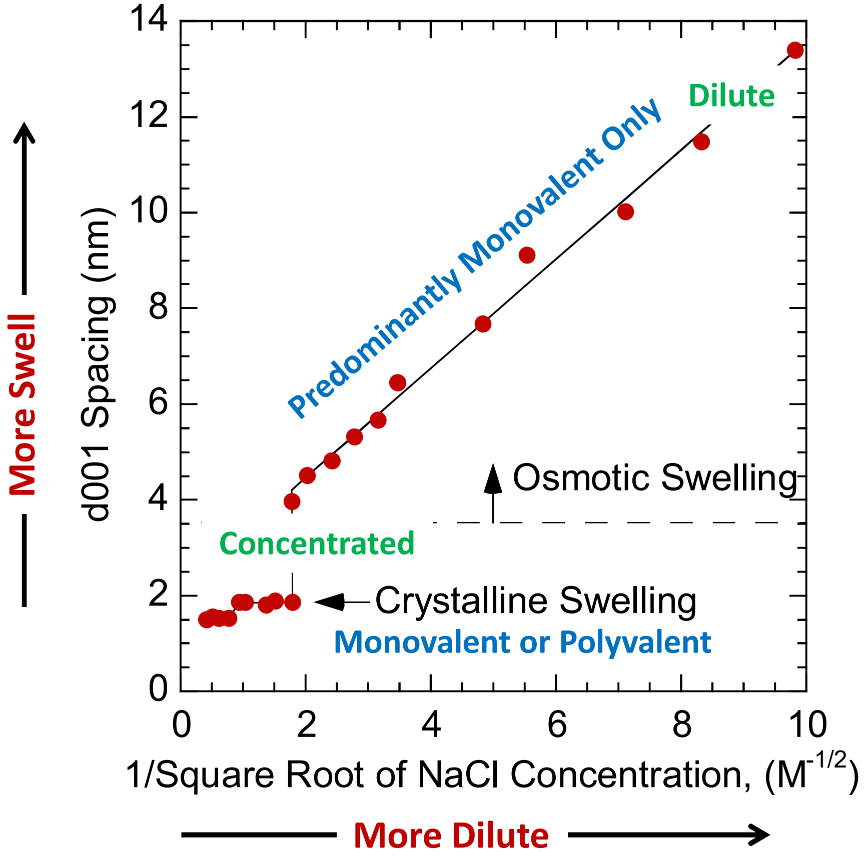
Gibbsite Sheet

Silica Sheet

Exchangeable cations include Na^+, K^+, Ca^{2+}, Mg^{2+}, and other cations in the solution being contained.



Bentonite Swelling – Geochemistry Matters!



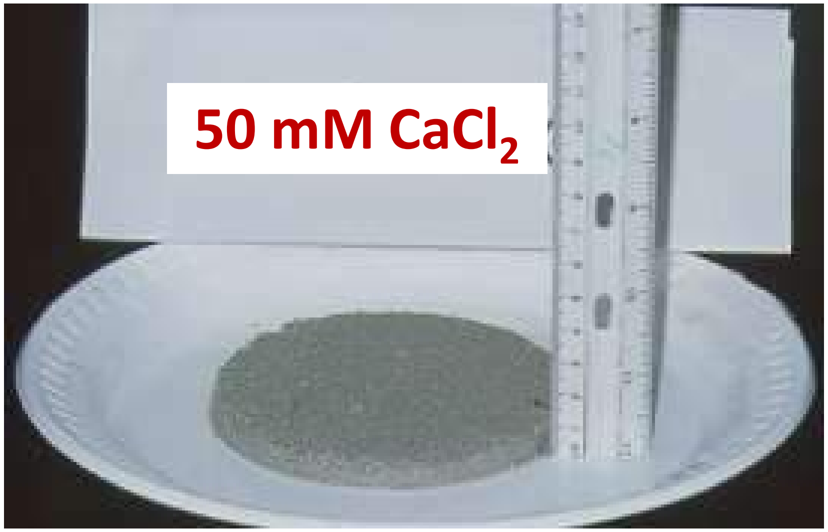
- When interlayer contains **monovalent cations** (e.g., Na+), significant swelling ("**osmotic swelling**") can occur, resulting in small inter-particle pores & low hydraulic conductivity.

- When the interlayer contains **divalent cations** (e.g., Ca^{2+}, Mg^{2+}), interlayer swell limited to 1 nm ("**crystalline swelling**"), resulting in larger inter-particle pores and **high hydraulic conductivity**.

Bentonite Swelling, Solution Chemistry, and Hydraulic Conductivity

GRI GCL-1 Swell Test

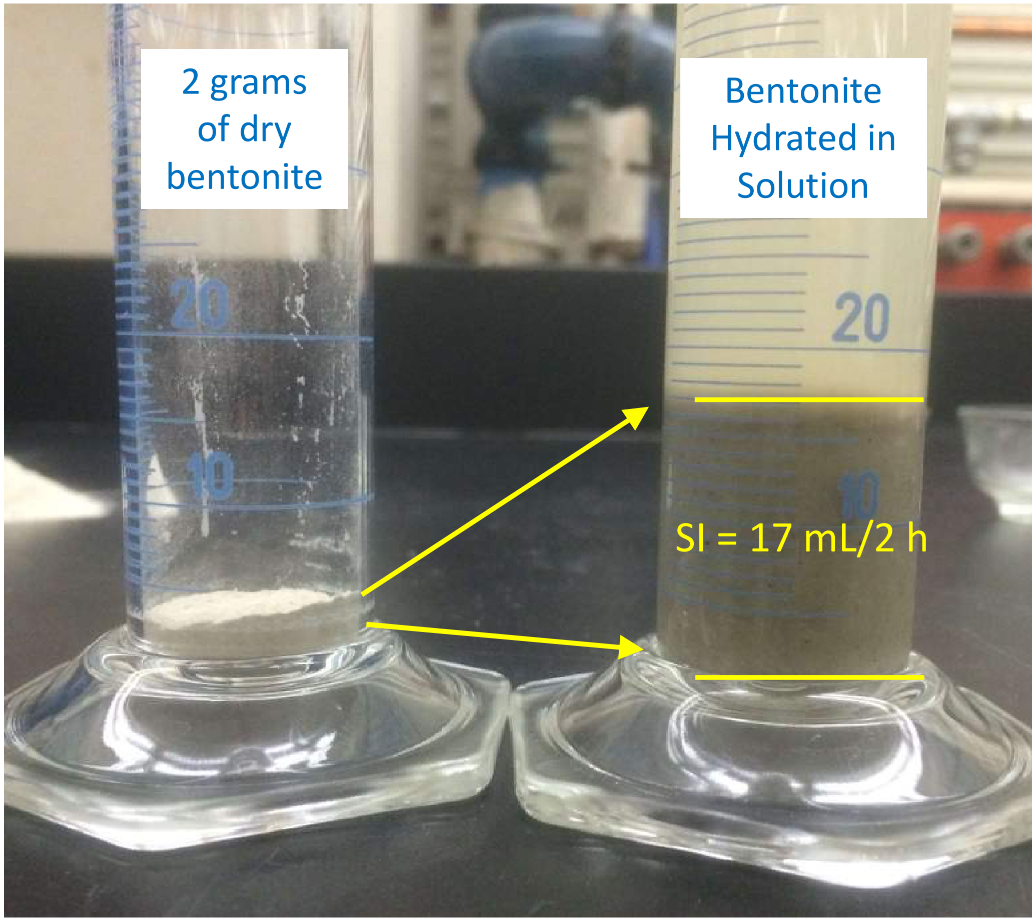
- Na-Bentonite in DI water (monovalent, Na^+) – crystalline & osmotic swell.
- Nanoscale pores and low hydraulic conductivity.



Na-Bentonite in calcium (Ca^{2+}) rich water (divalent) – crystalline swelling only.

Visible pores and high hydraulic conductivity

ASTM D5890 Swell Index (SI) – Free Swell

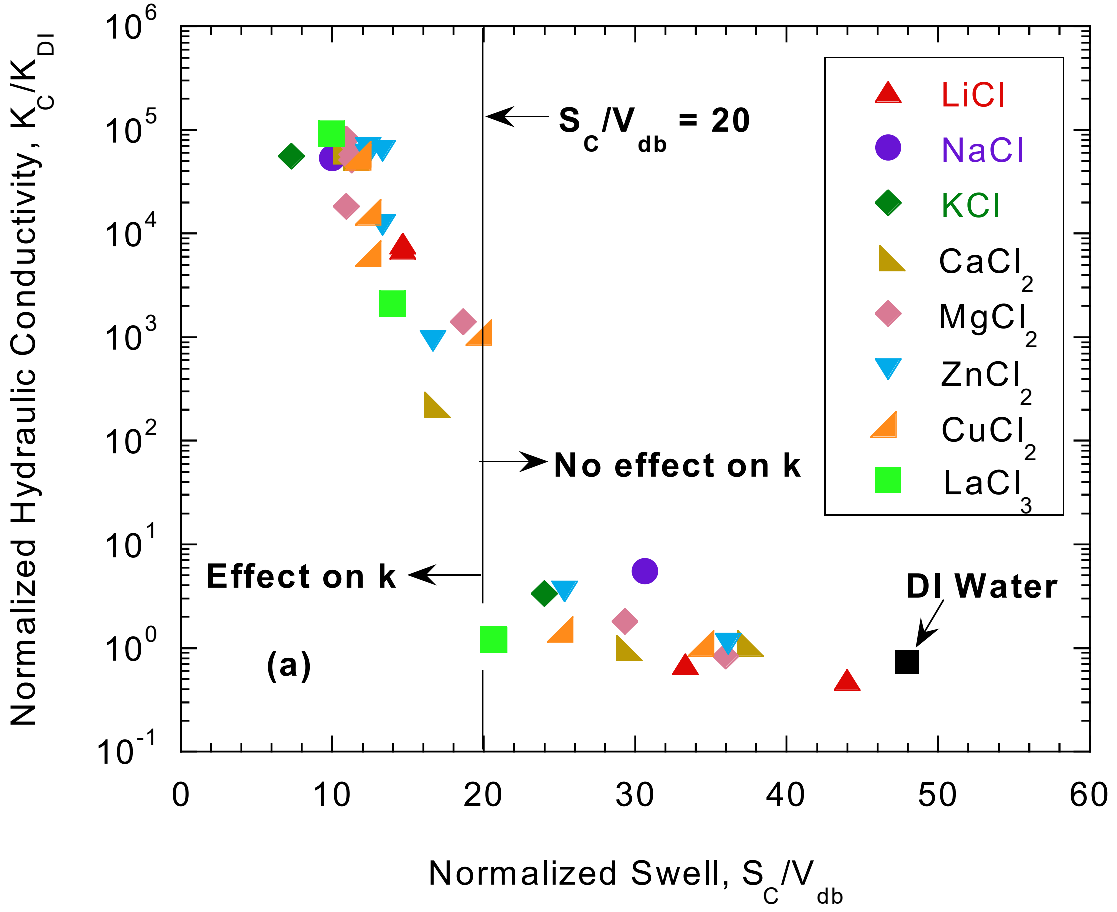


ASTM D5890 Swell Index Test

Miles bentonite, Queensland

Wyoming bentonite, USA

Hydraulic Conductivity and Swell Index (SI)



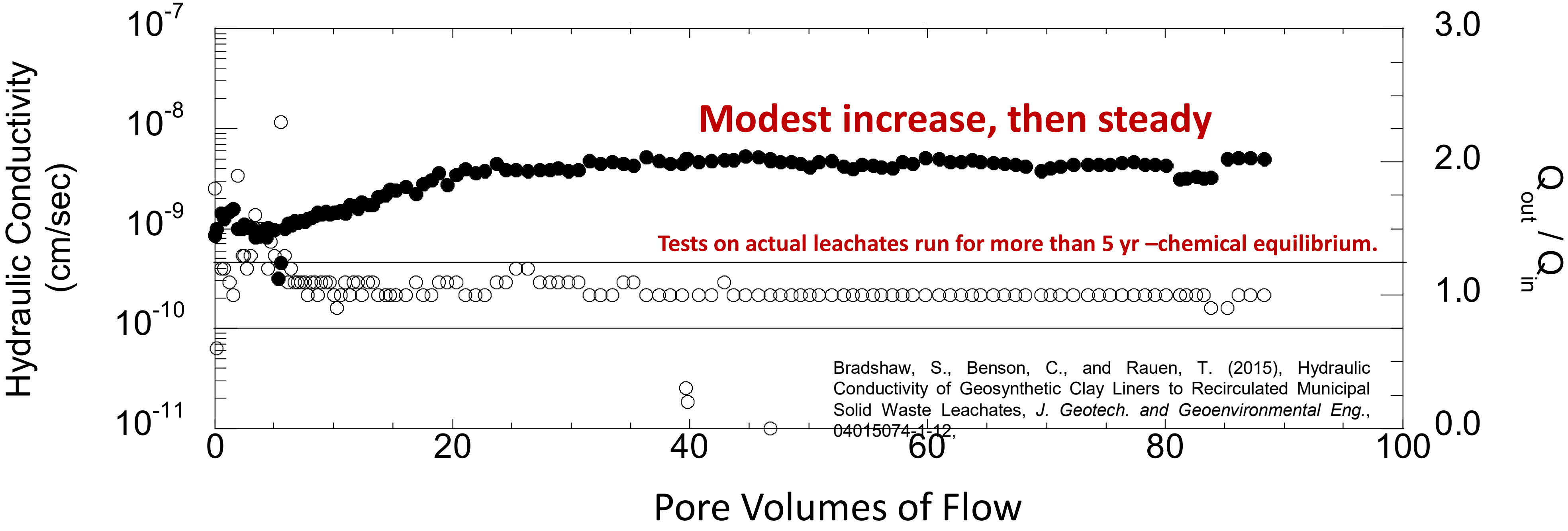
Jo, H., Katsumi, T., Benson, C., and Edil, T. (2001), Hydraulic Conductivity and Swelling of Non-Prehydrated GCLs Permeated with Single Species Salt Solutions, *J. of Geotech. and Geoenvironmental Eng.*, 127(7), 557-567.

- Normalized hydraulic conductivity to chemical solution (K_c) to DI water (K_{DI}).
- Normalized SI by volume of dry bentonite (2 g $\approx$ 0.7 mL).
- Unique to specific bentonite – granule size distribution, mineralogy, and surface chemistry.
- For this bentonite, SI must be > 15 mL/2g for $K_c<10^{-11}$ m/s

Hydraulic Conductivity Testing (ASTM D6766)

- **ASTM D6766** (*Standard Test Method for Evaluation of Hydraulic Properties of Geosynthetic Clay Liners Permeated with Potentially Incompatible Aqueous Solutions*) or equivalent.
- **Important testing considerations:**
  - Prehydration condition
  - Effective stress
  - Hydraulic equilibrium
  - Chemical equilibrium

Hydraulic Conductivity Testing to Confirm Suitability: May Go Slowly – Plan Ahead!



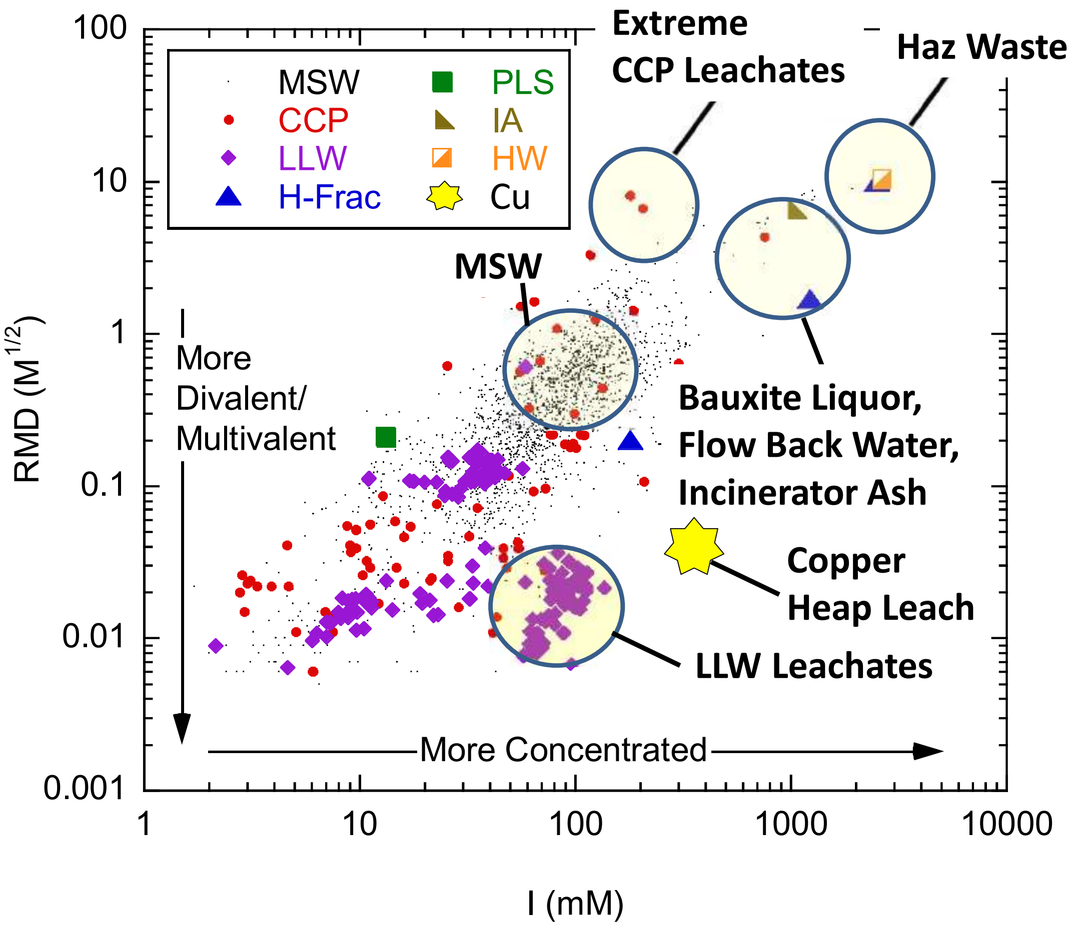
Modest increase, then steady

Tests on actual leachates run for more than 5 yr –chemical equilibrium.

Bradshaw, S., Benson, C., and Rauen, T. (2015), Hydraulic Conductivity of Geosynthetic Clay Liners to Recirculated Municipal Solid Waste Leachates, *J. Geotech. and Geoenvironmental Eng.*, 04015074-1-12,

For solutions with **modest ionic strength, hydraulic conductivity changes slowly**. **Plan ahead for long test times** to reach chemical equilibrium.

Aggressive Industrial Liquids & Leachates



$$I = \frac{1}{2}\sum_{i=1}^{n} c_i z_i^2$$

I = **ionic strength**

c_i = conc. ith ion

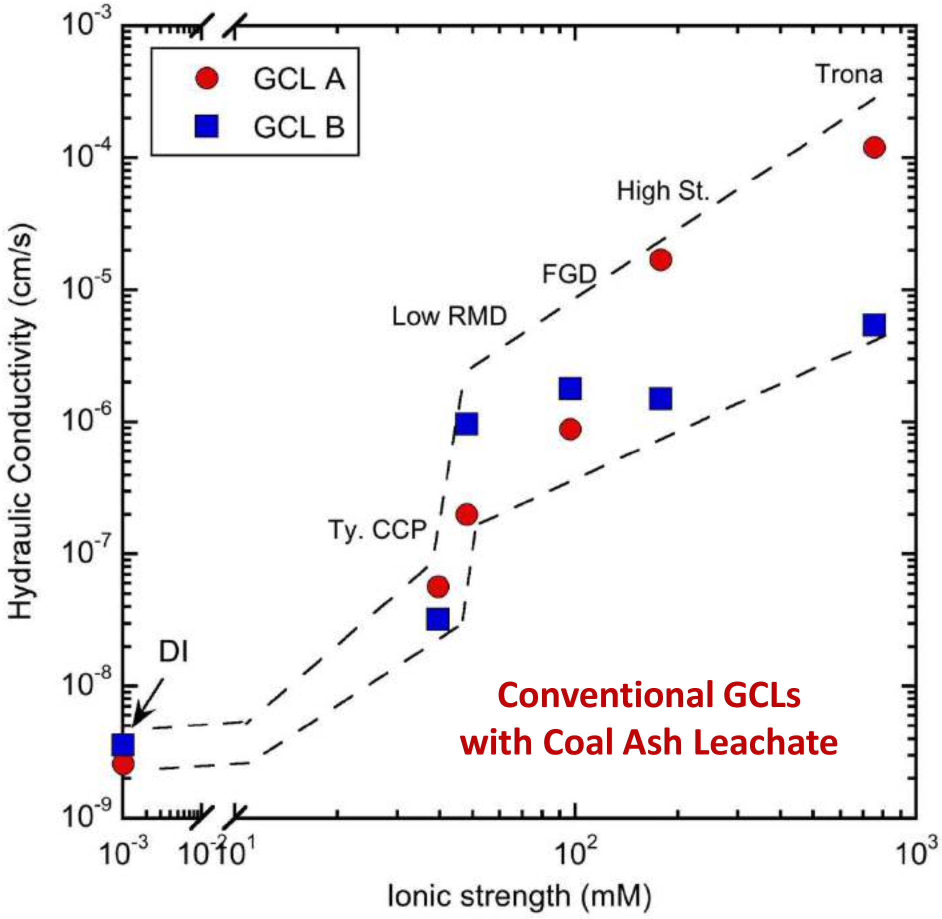
z_i = valence ith ion

$$RMD = \frac{M_M}{\sqrt{M_D}}$$

M_m = total molarity monovalent cations

M_D = total molarity polyvalent cations

Ionic Strength is Dominant Variable for Most Industrial Liquids



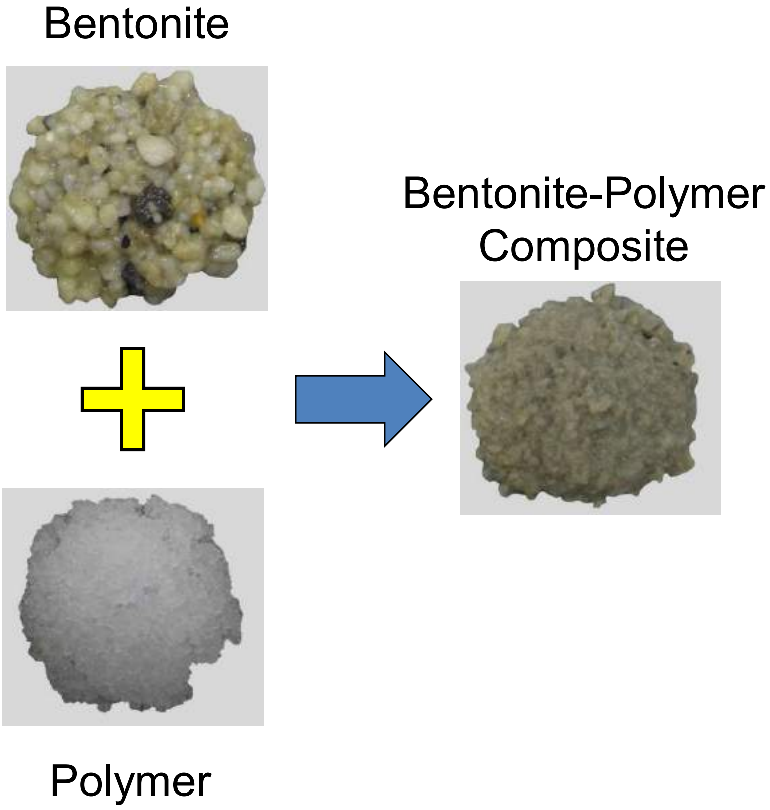
Conventional GCLs with Coal Ash Leachate

- Hydraulic conductivity strongly & directly related to ionic strength of leachate.
- Modest sensitivity to RMD of leachate

What if my Conventional NaB GCL is Too Permeable?

Bentonite-Polymer Composite GCLs

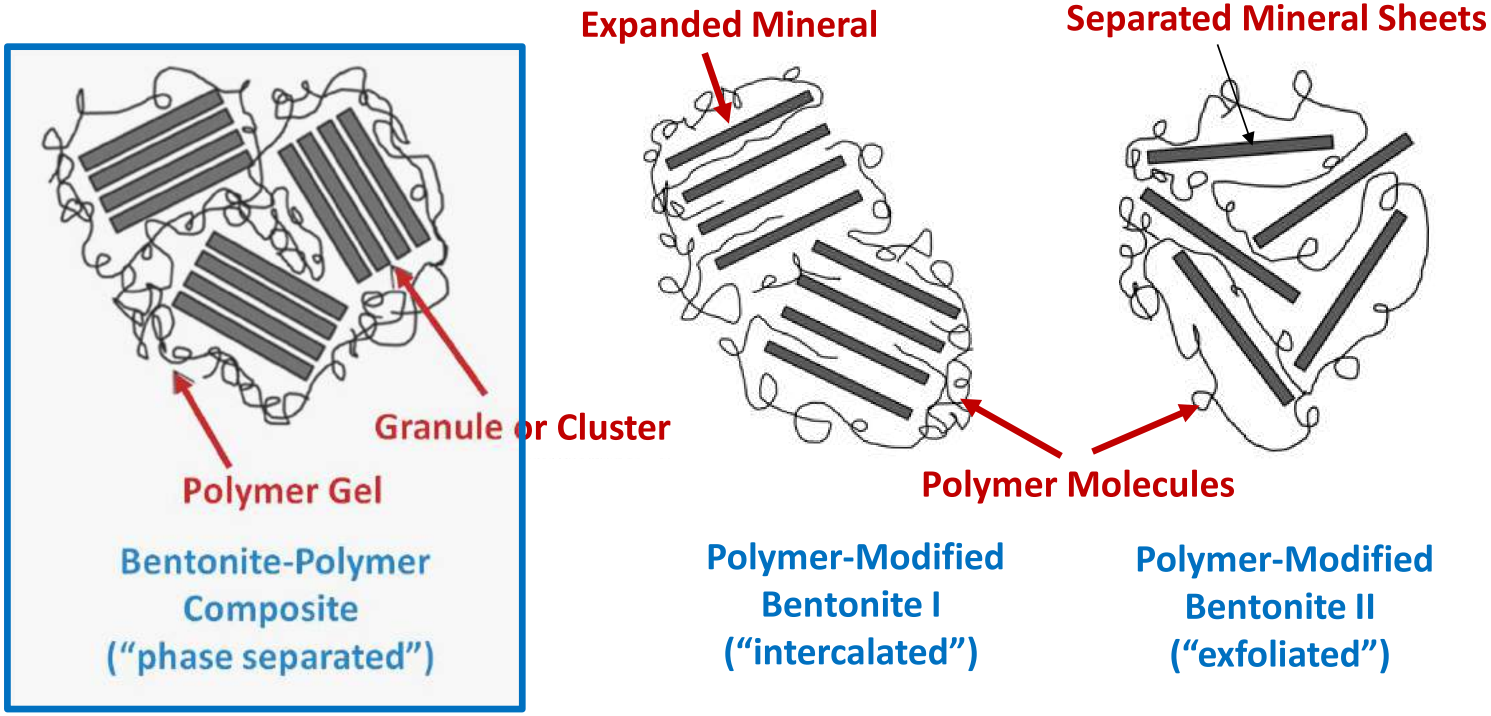
(aka PMGs or polymer-modified GCLs)



- Bentonite functions in less concentrated leachates, swelling and blocking flow channels.
- Polymer functions in more concentrated leachates, filling channels between bentonite granules for which swelling is modest.

Scalia, J. and Benson, C. (2016), Polymer Fouling and Hydraulic Conductivity of Mixtures of Sodium Bentonite and a Bentonite-Polymer Composite, *J. Geotech. Geoenvironmental Eng.*, 04016112.

Types of Bentonite-Polymer Mixtures



Expanded Mineral

Separated Mineral Sheets

Granule or Cluster

Polymer Gel

Polymer Molecules

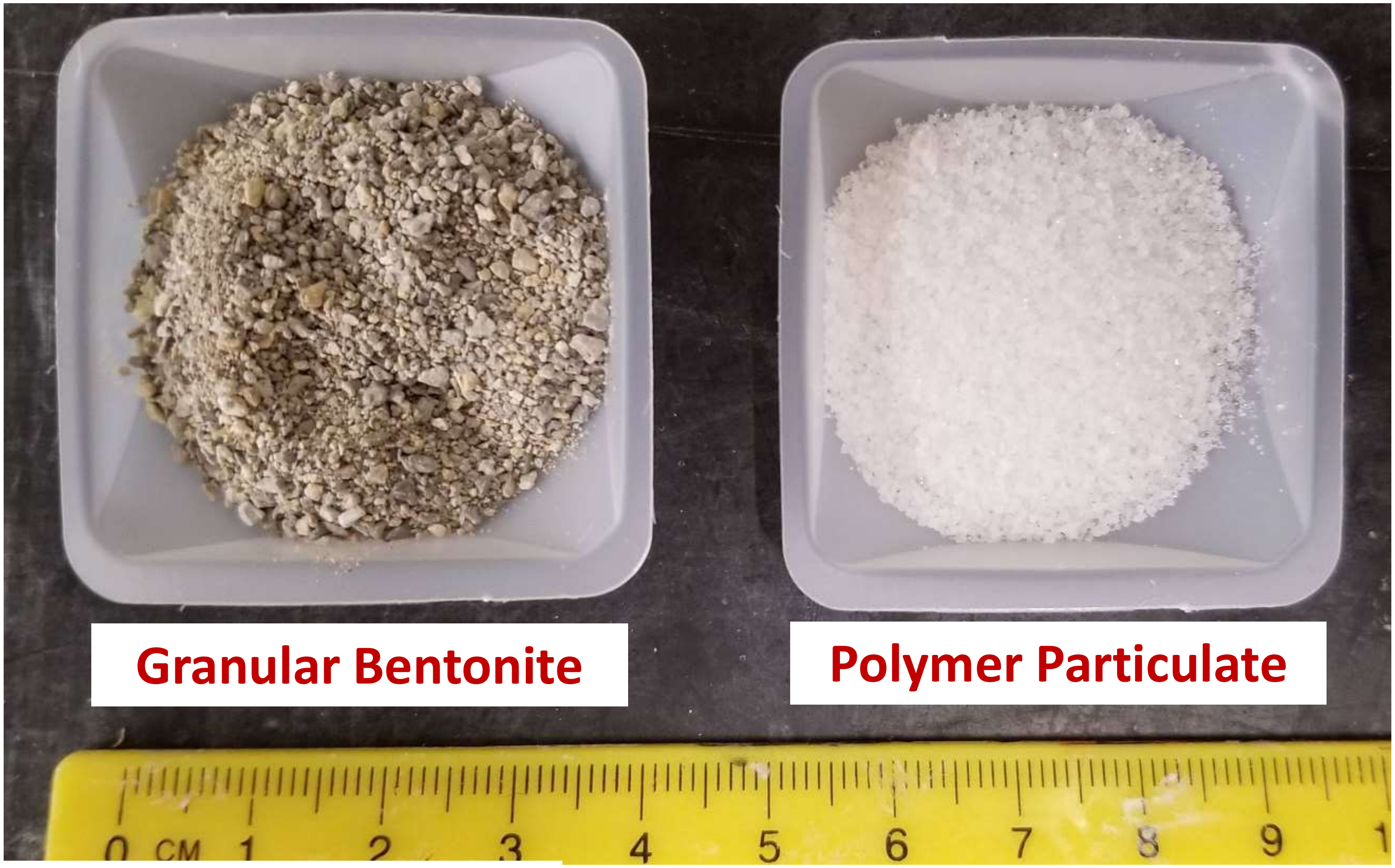
Bentonite-Polymer Composite ("phase separated")

Polymer-Modified Bentonite I ("intercalated")

Polymer-Modified Bentonite II ("exfoliated")

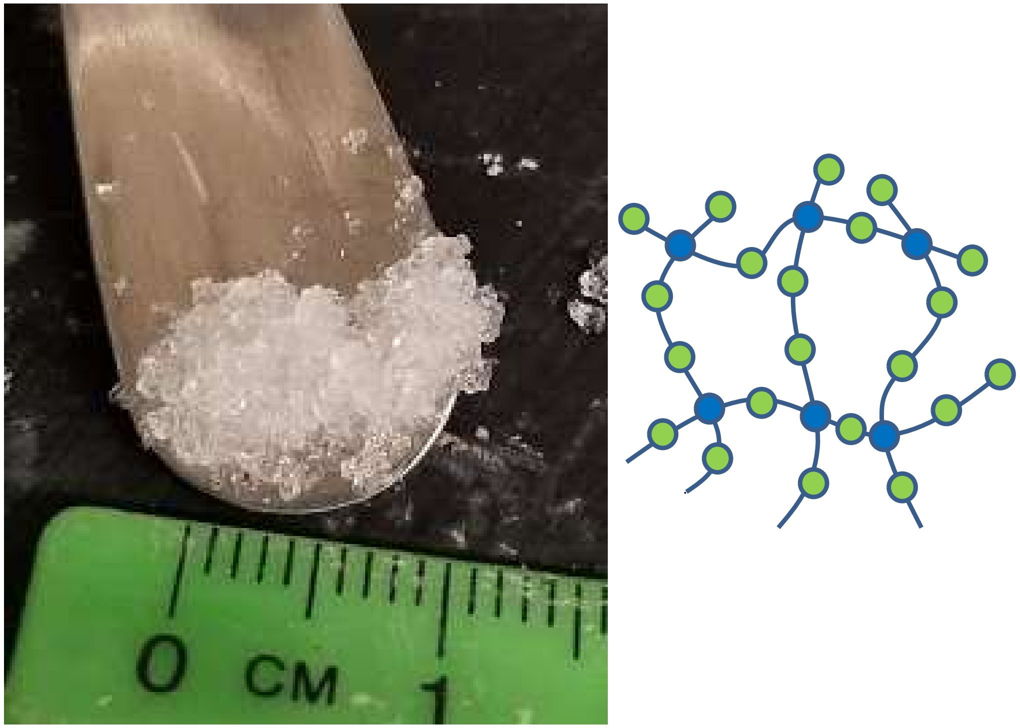
adapted from: Kim S. and Palomino, A. (2011), Factors influencing the synthesis of tunable clay–polymer nanocomposites using bentonite and polyacrylamide, *Applied Clay Science*, 51 (2011) 491–498

Dry Mixture: Granular Bentonite and Polymer Particulate

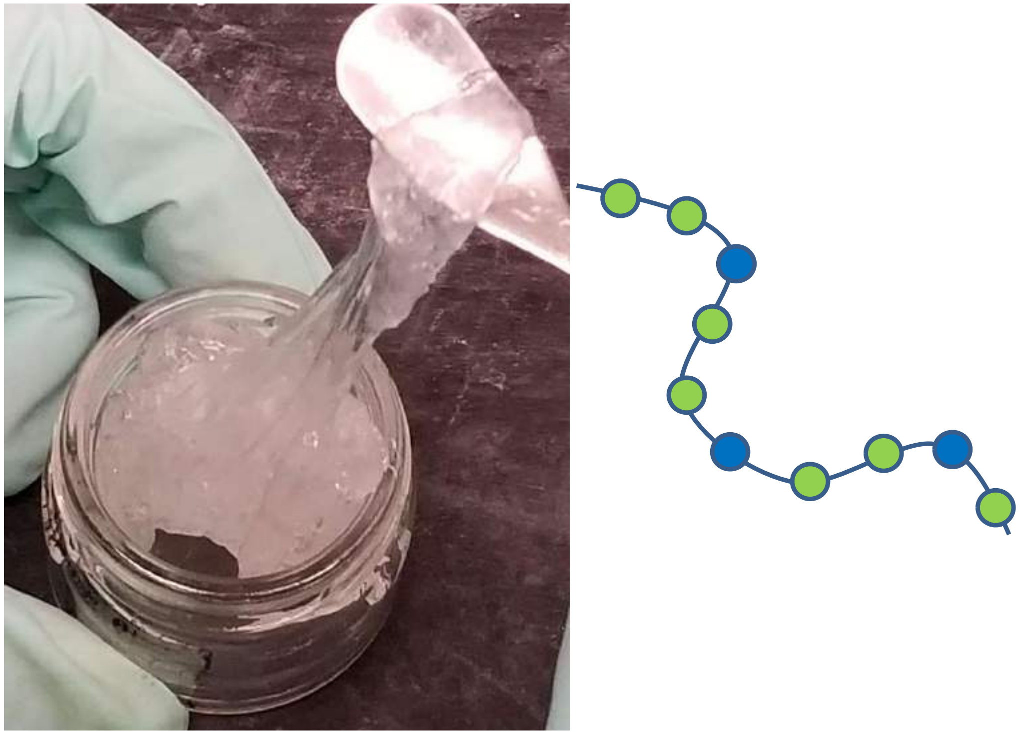


Types of Polymers in BPC GCLs

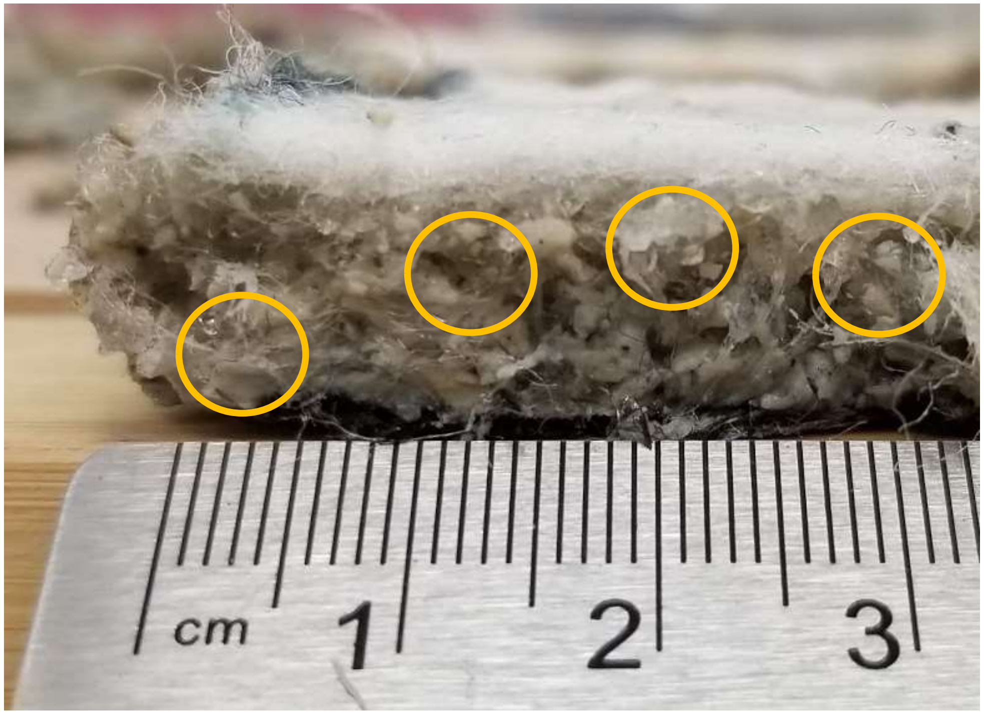
Cross-Linked Polymer



Linear Polymer



Superabsorbent polymers also used (baby diapers).



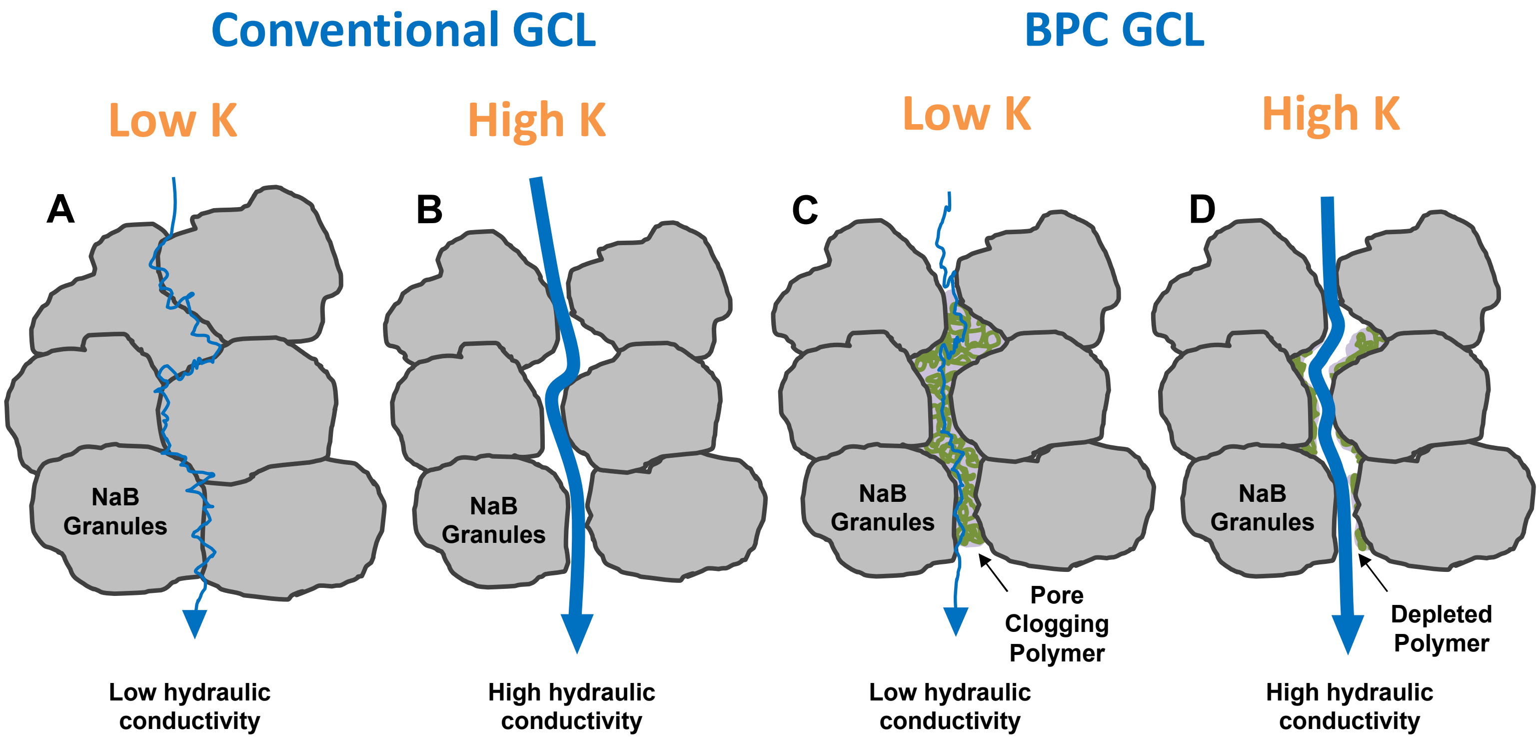
Cross-Linked Polymer

Hydrated gel granules evident as separate phase.

Linear Polymer

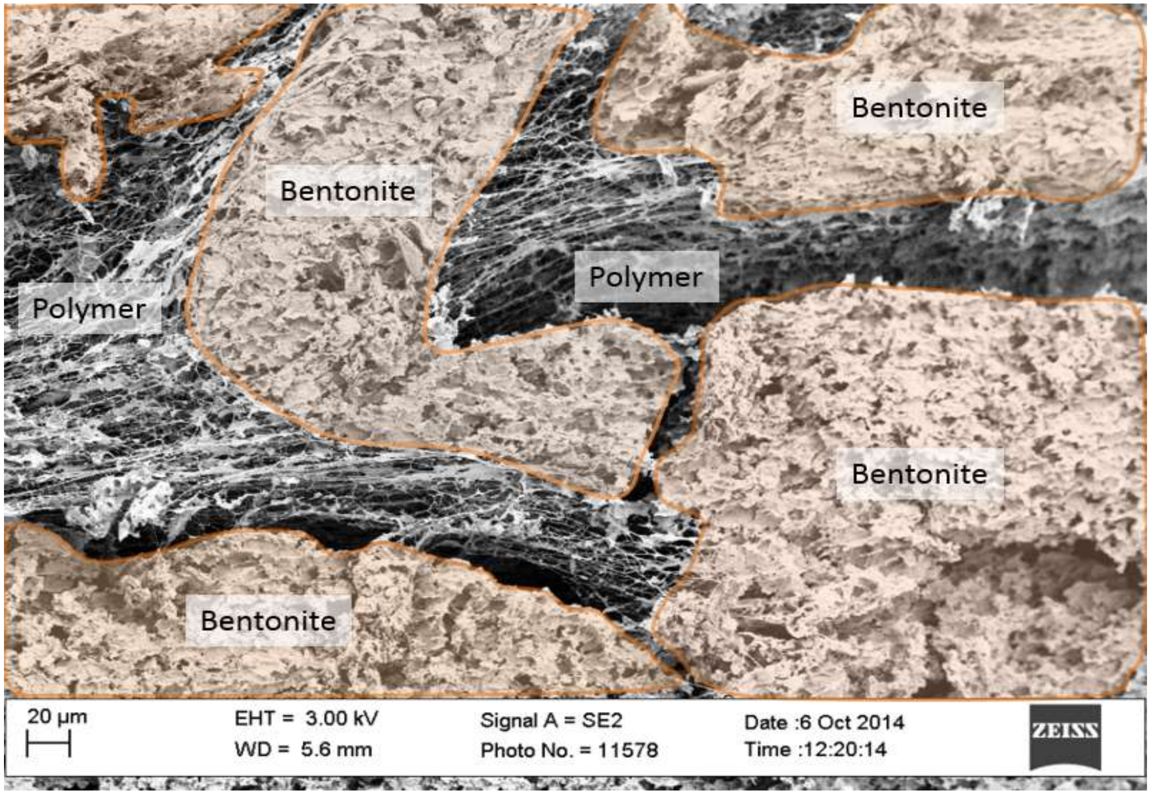
No gel visibly evident as separate phase but woven in pore space.

Mechanisms Controlling Hydraulic Conductivity of BPC GCLs

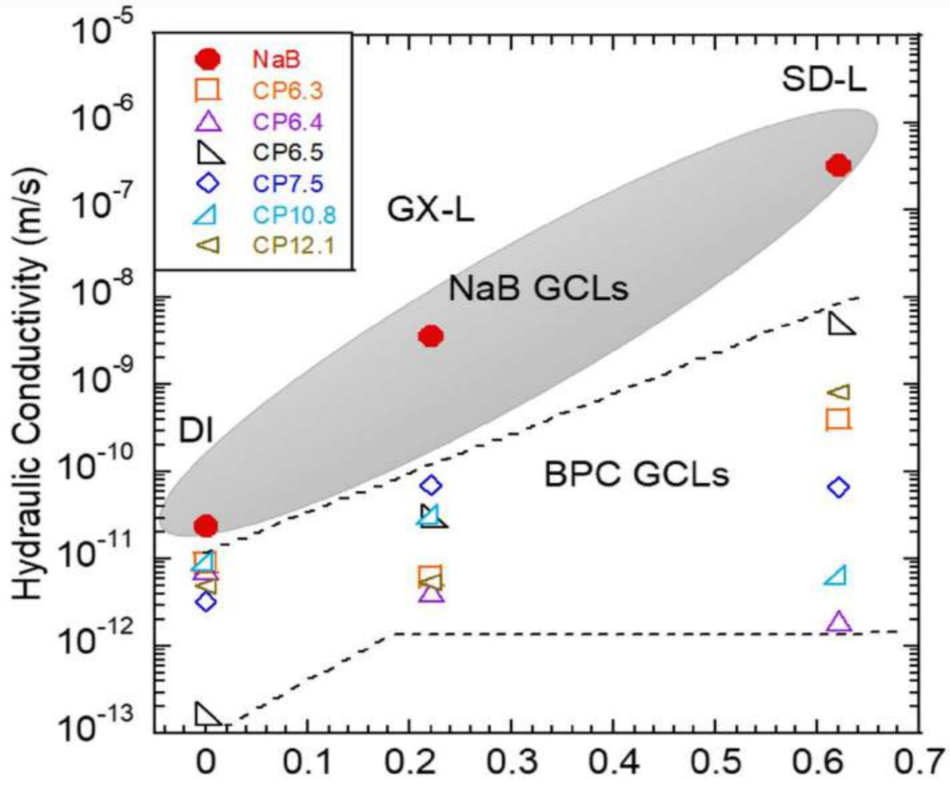


BPCs are Composite Materials – BPCs Not Surface-Modified Clays

Polymer Hydrogel Clogging Mechanism



Bentonite-Polymer GCLs & Bauxite Liquors



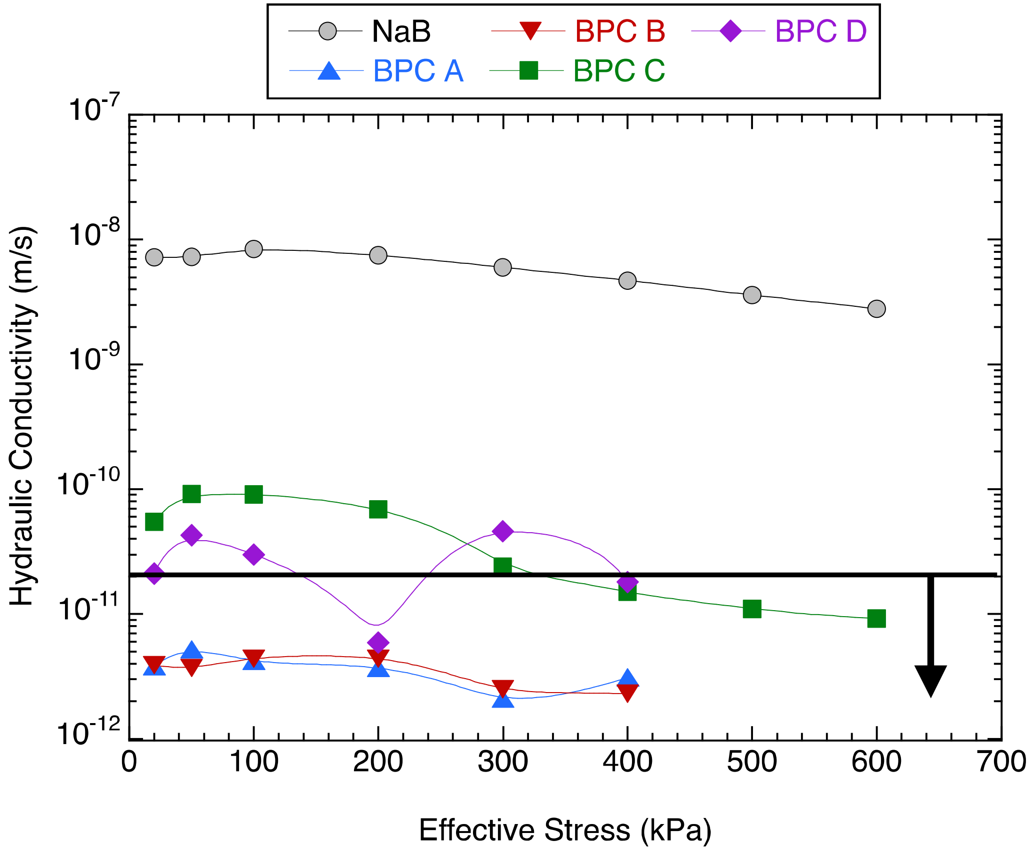
- Solid Symbols: NaB GCLs, Open Symbols: BPC GCLs, Numbers: polymer loading.

- BPC GCLs have lower hydraulic conductivity than NaB GCLs at all ionic strengths.

- BPC hydraulic conductivity varies with product and polymer loading.

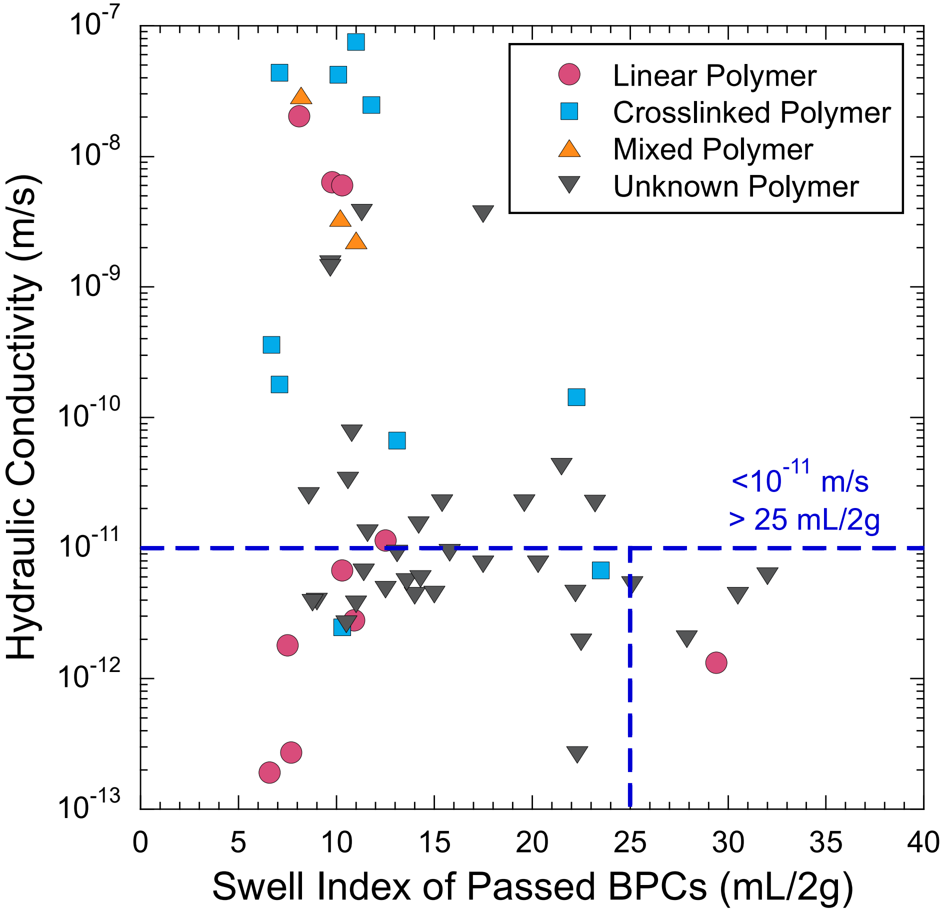
Li, Q., Chen, J., Benson, C., and Chen, D. (2020), Hydraulic Conductivity of Bentonite-Polymer Composite Geosynthetic Clay Liners Permeated with Bauxite Liquor, *J. Geotextiles and Geomembranes*, 49, 420-429.

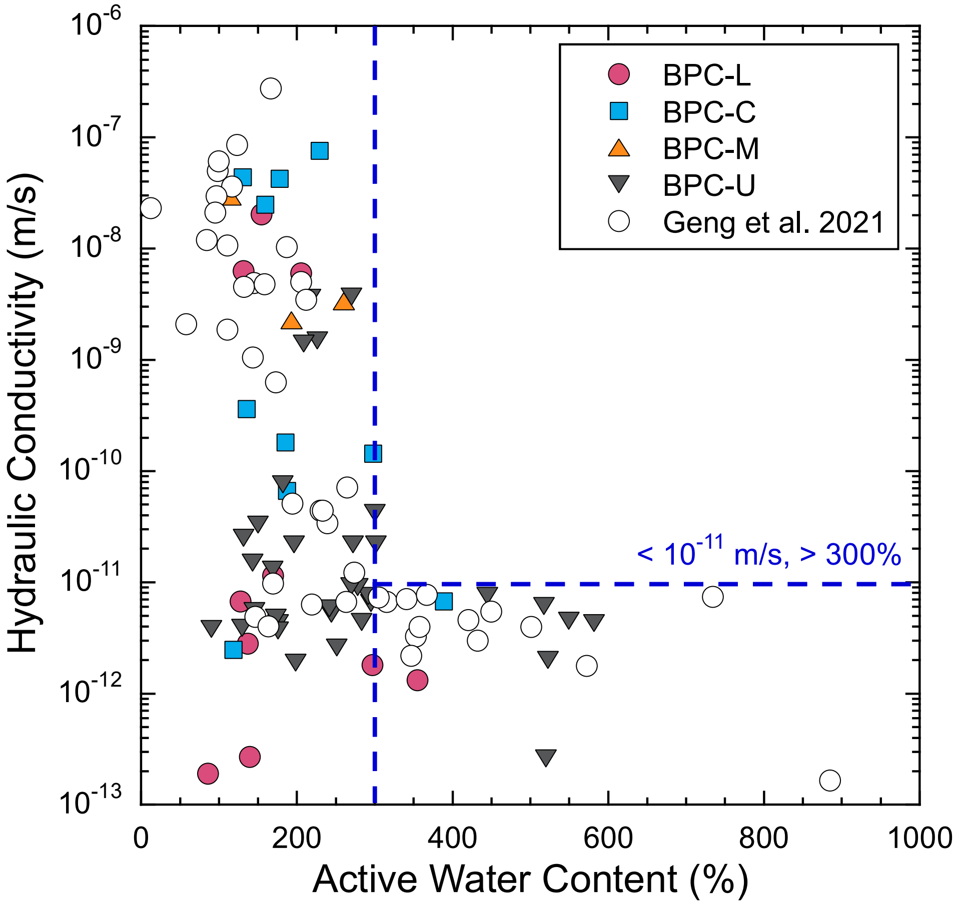
Bentonite-Polymer GCLs & Copper Heap Leach Solution



- Acidic divalent leachate: I = 303 mM, RMD = $0.02^{0.5}$, pH 2.2, A_r = 1.7.
- BPC GCLs have lower hydraulic conductivity than NaB GCL at all overburden pressures.
- BPC hydraulic conductivity varies between products.

Screening Tests to Evaluate BPC GCLS





Key Take Away Messages

- Hydraulic conductivity of **conventional NaB GCLs controlled by swelling of bentonite** granules – intergranular pores must swell shut to achieve low hydraulic conductivity. **Strongly influenced by geochemistry**.
- Ionic strength ("total concentration") of solution most important factor affecting swelling of bentonite and hydraulic conductivity of NaB GCLs in industrial solutions, but RMD can be important as well.
- For aggressive leachates, **BPC GCLs *can* have low hydraulic conductivity** when NaB GCLs are too permeable. Polymer gel must clog and be retained in intergranular pores.
- Swell index tests useful for screening NaB GCLs for suitability; **swell index not effective for BPC GCL**s (addresses swelling, but not clogging). New tests in development.
- Hydraulic conductivity testing will be required and long test times are common. **Plan ahead**.

Papers on GCLs can be downloaded here:

https://uwmadison.box.com/s/ewo1532zm0uf63k5r5or4fegaib4pt8f

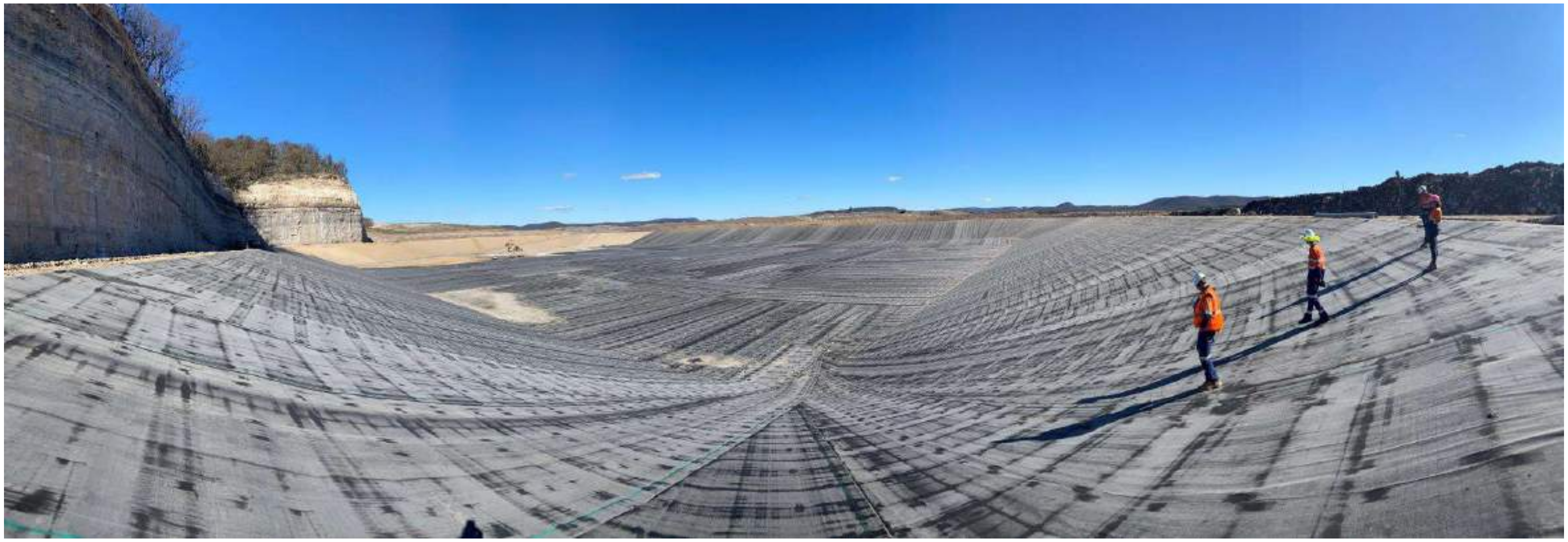
AGENDA

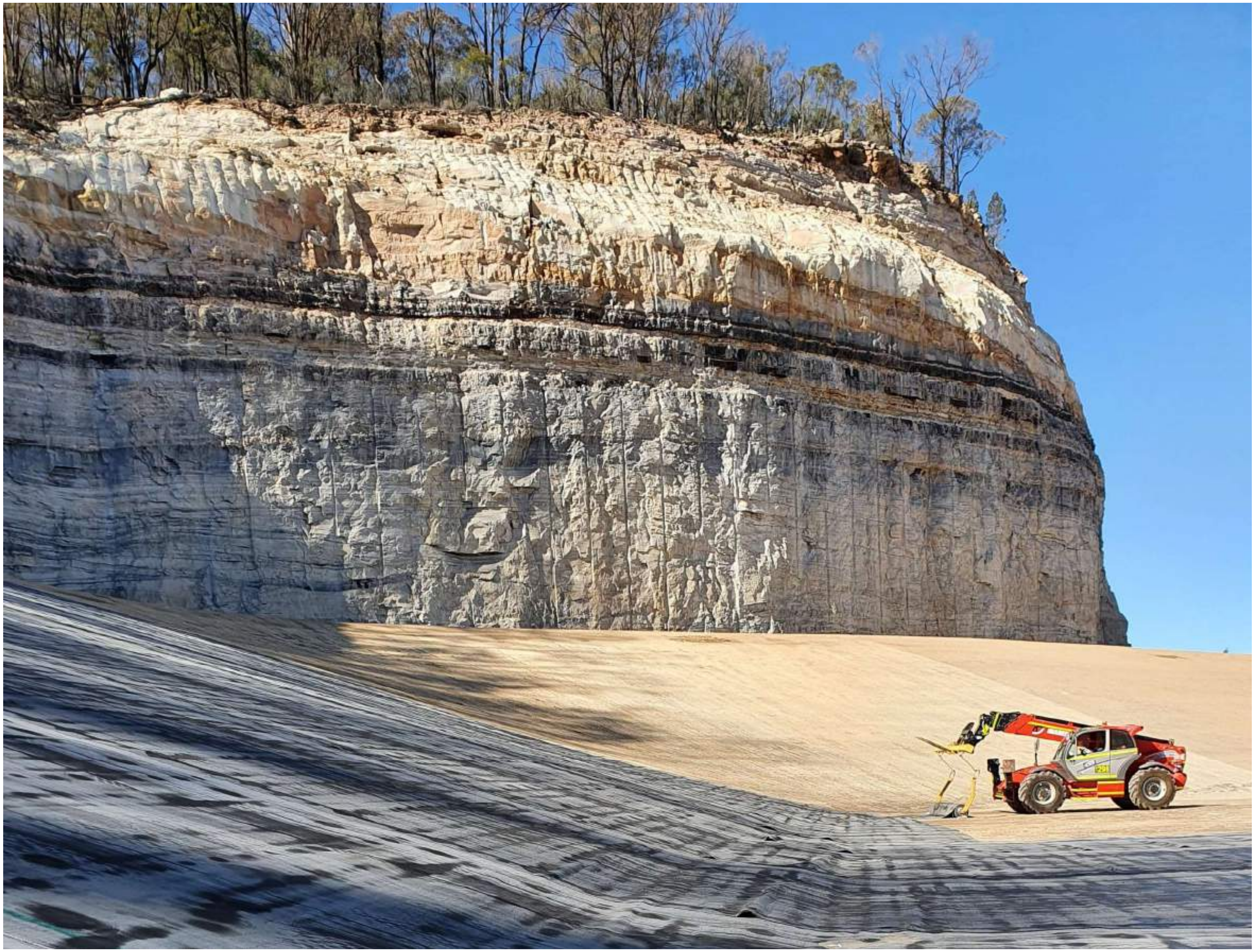
- 01) Aussie Liners and Covers for Mine Waste - Williams
- 02) GCLs for Mine Waste – Benson
- 03) Case Study
- 04) Geosynthetics for Tailings Disposal - Stark
- 05) Tailings Drainage using Geocomposites – Saunier
- 06) Geosynthetics for Evaporation Mining - Stark

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

COLETANCHE

BITUMINOUS GEOMEMBRANE FOR
WATERPROOFING CIVIL ENGINEERING STRUCTURES





DVG-39J


LEISTER

www.coletanche.com

info@axter.com.au

@COLETANCHE

Thank you

pkendall@axter.com.au

COLETANCHE

GEOANZ #1 ADVANCES IN GEOSYNTHETICS

7–9 JUNE 2022 | BRISBANE CONVENTION & EXHIBITION CENTRE

AGENDA

- 01) Aussie Liners and Covers for Mine Waste - Williams
- 02) GCLs for Mine Waste – Benson
- 03) Case Study
- 04) Geosynthetics for Tailings Disposal - Stark
- 05) Tailings Drainage using Geocomposites – Saunier
- 06) Geosynthetics for Evaporation Mining - Stark

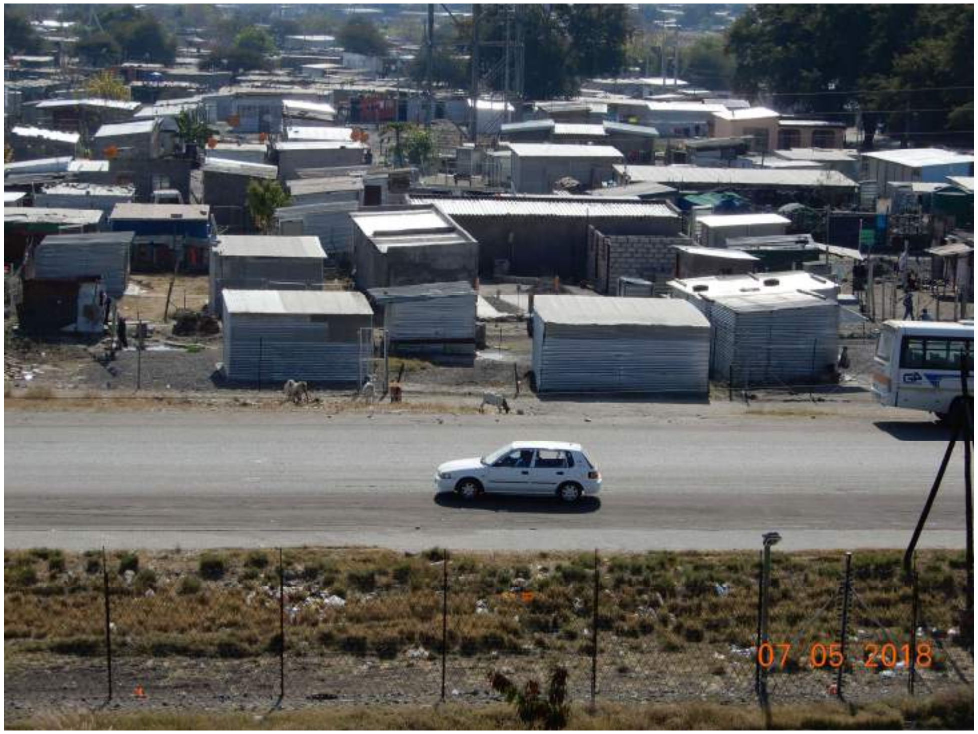
Outline

- Stability Issues
- Bottom Liner Systems
- Installation
- Summary

Tailings Beach and Drainage

Tailings Beach and Drainage

Tailings Placement



Tailings Placement

07 05 2018

07 05 2018

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

Tailings Placement


07.05.2018


07.05.2018

Tailings Placement

Saturated Tailings & Flow Failure

Fundao Tailings Dam

BBC News Photographs

Size of Tailings Dams

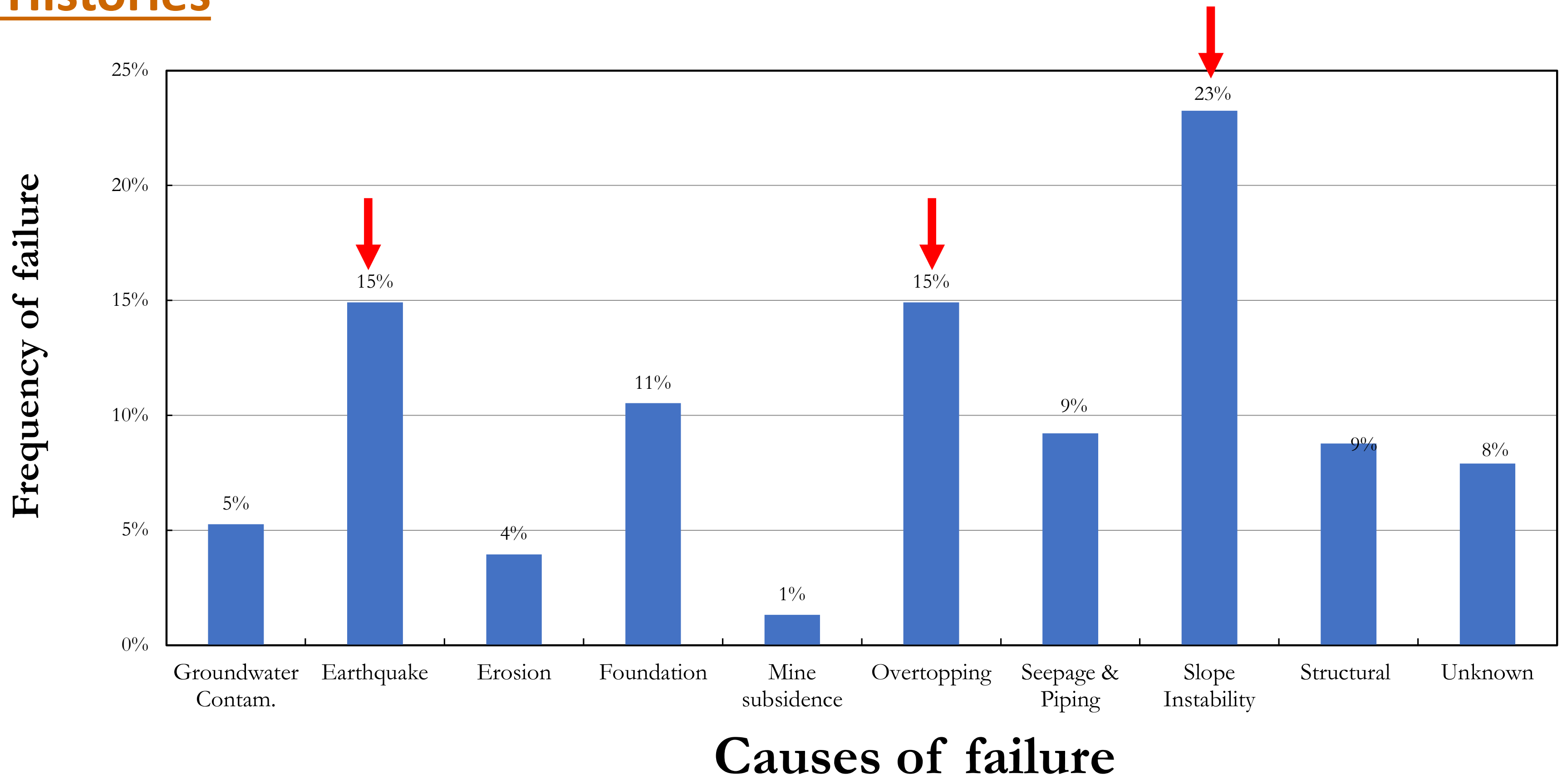
What is largest dam?

- Earth volume - Syncrude Tailings Dam–706,320,000 yd^3
- Concrete volume - Three Gorges- 35, 506,315 yd^3/Grand Coulee-11,975,520 yd^3

- Earth height - Nurek Dam, Tajikistan – 984 feet
- Concrete height - Jinping-1 Dam, China – 1,001 feet

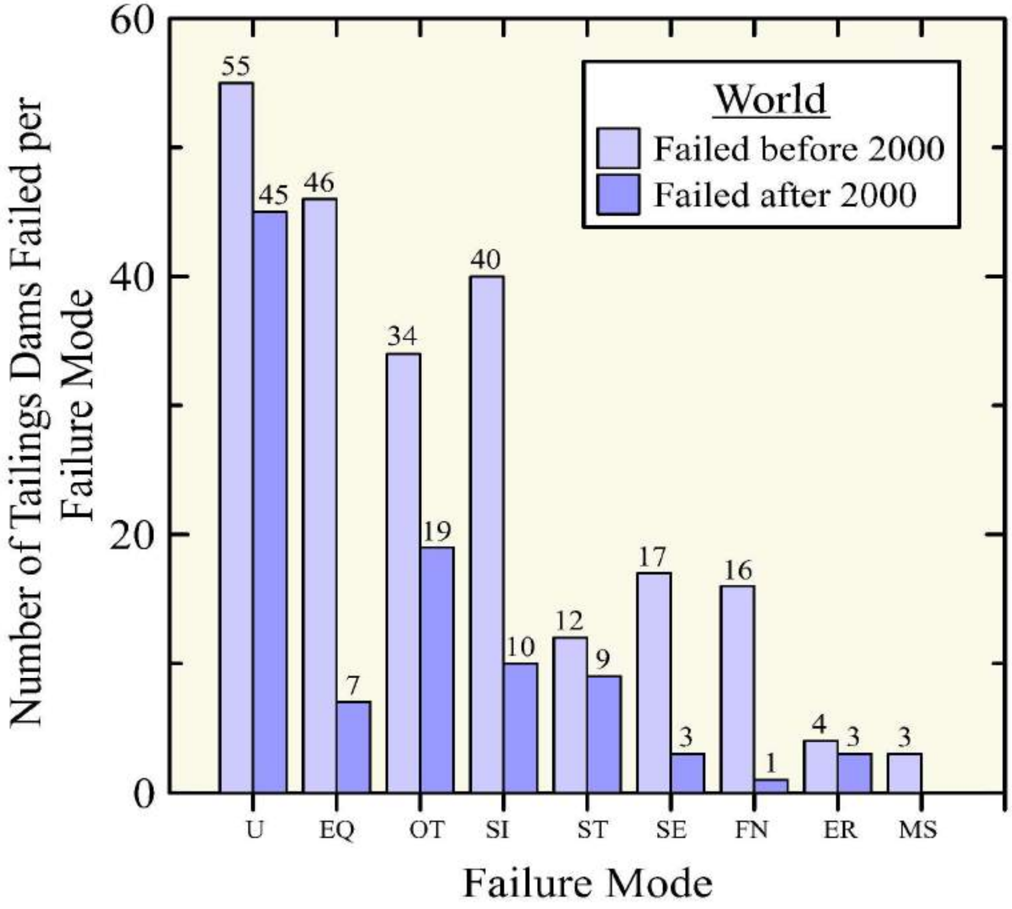
http://www.usbr.gov/lc/hooverdam/History/essays/biggest.html

228 Case Histories



Stark, T.D., Moya, J., and Lin, J. (2020)."Rates and Causes of Tailings Dam Failures," ACCEPTED *Geotechnical and Geological Engineering Journal,* October, 2021.

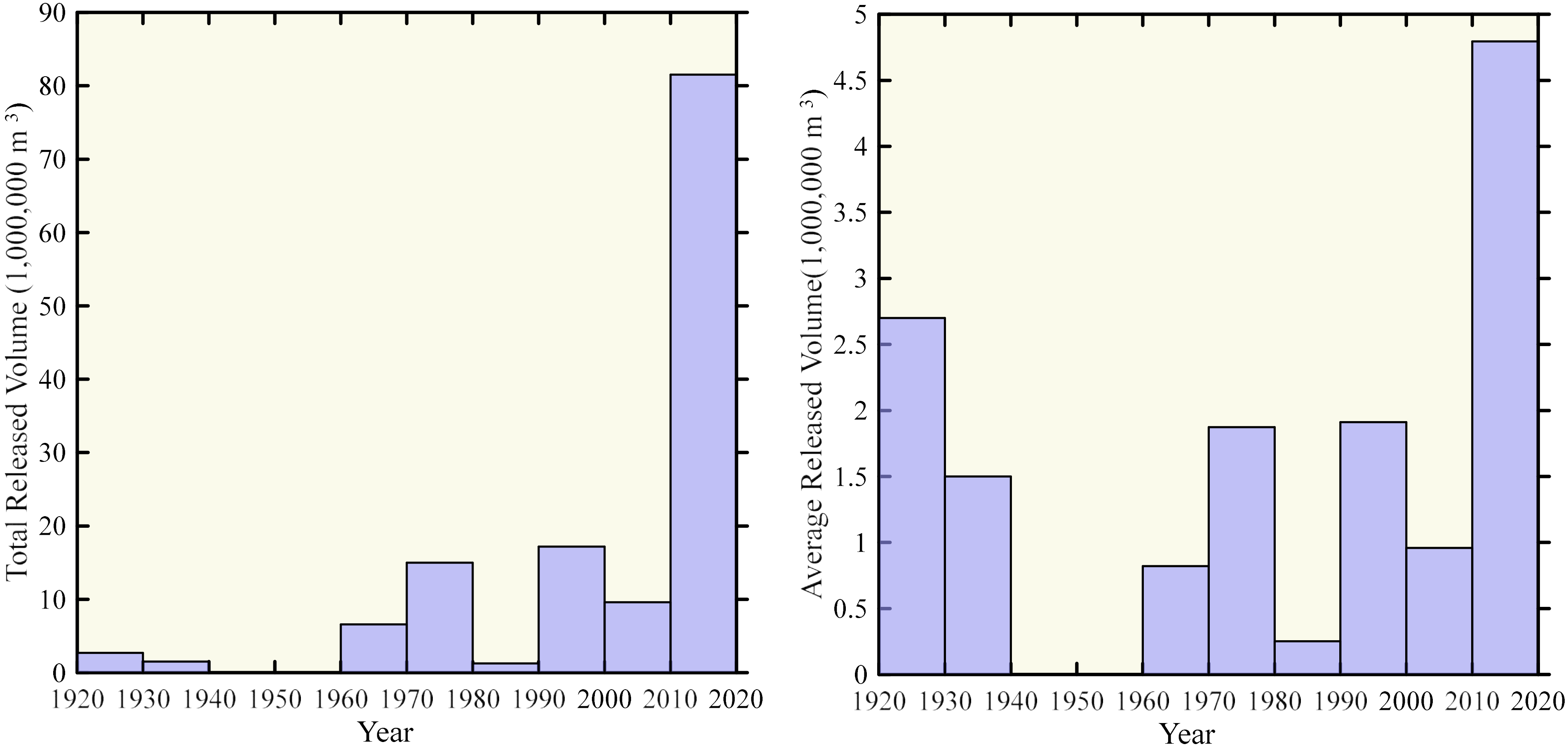
Failure Modes and Timing



U - Unknown
EQ - Earthquake
OT - Overtopping
SI - Slope instability
ST - Structural
SE - Seepage
FN - Foundation
ER - Erosion
MS - Mine subsidence

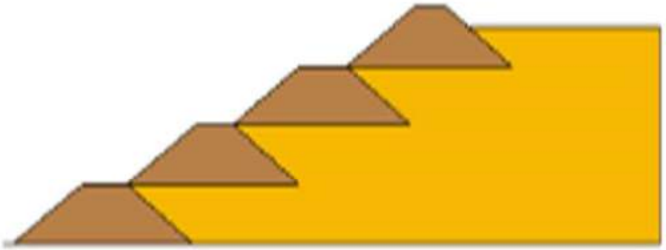
Stark, T.D., Moya, J., and Lin, J. (2020)."Rates and Causes of Tailings Dam Failures," ACCEPTED *Geotechnical and Geological Engineering Journal,* October, 2021.

Released Volume Every 10 Years

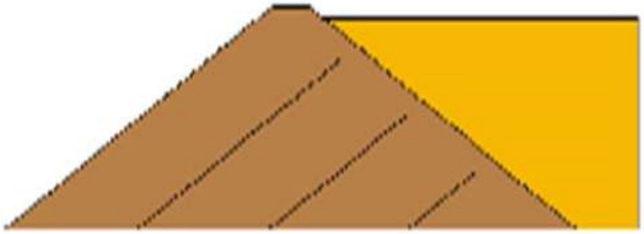


Stark, T.D., Moya, J., and Lin, J. (2020)."Rates and Causes of Tailings Dam Failures," ACCEPTED *Geotechnical and Geological Engineering Journal,* October, 2021.

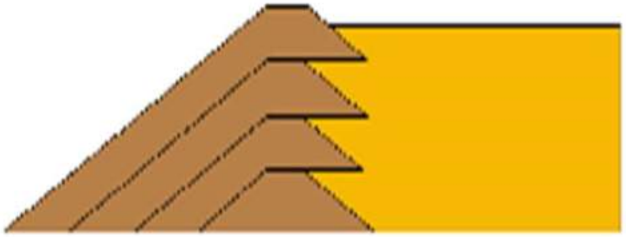
Tailings Dam Construction



(a) Upstream

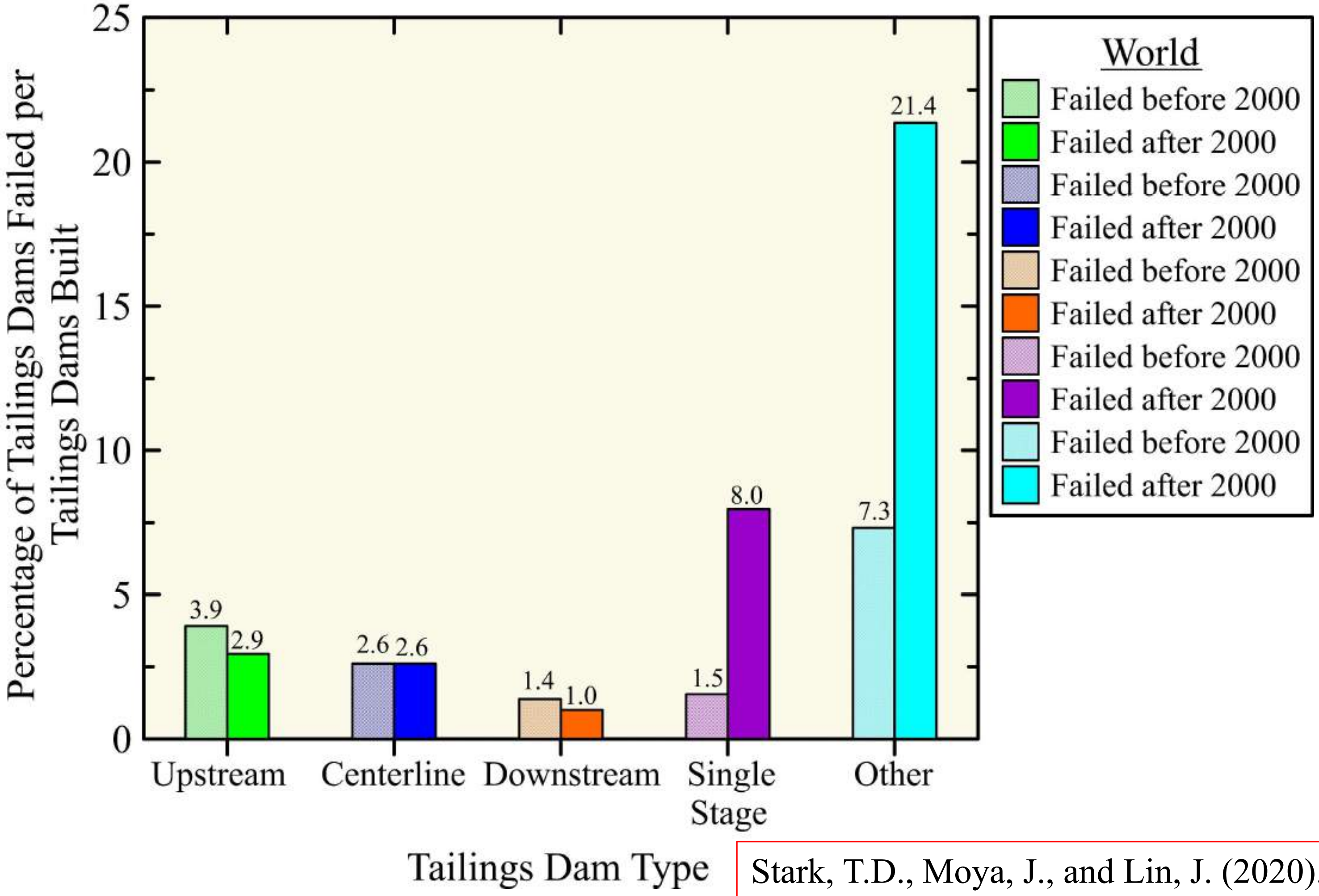


(b) Downstream



(c) Centreline

Tailings Dam Construction



Stark, T.D., Moya, J., and Lin, J. (2020)."Rates and Causes of Tailings Dam Failures," ACCEPTED *Geotechnical and Geological Engineering Journal,* October, 2021.

Outline

- Stability Issues
- Bottom Liner Systems
- Installation
- Summary

Operating Hard Rock Tailings Impoundments

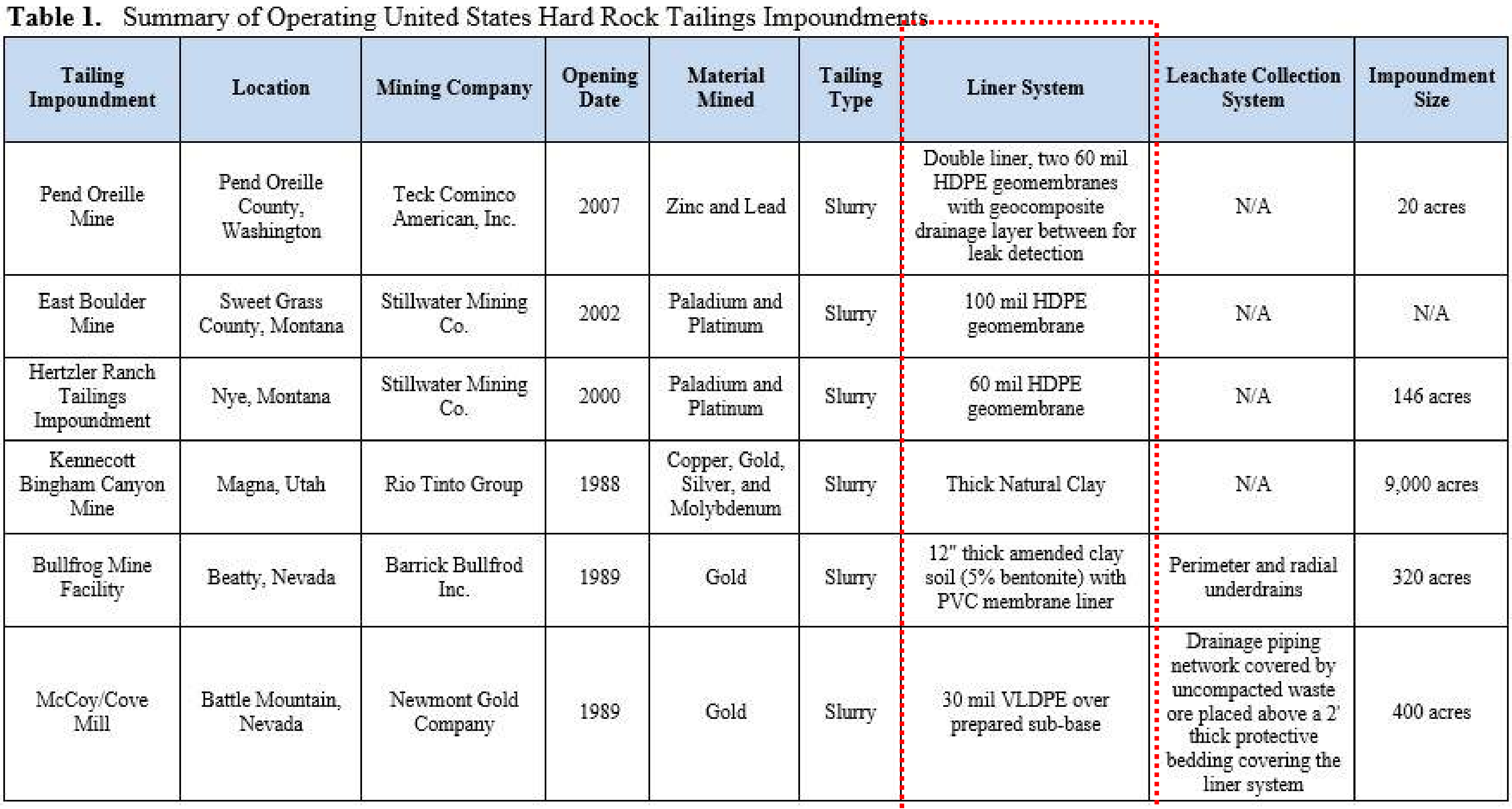


Table 1. Summary of Operating United States Hard Rock Tailings Impoundments

Tailing Impoundment	Location	Mining Company	Opening Date	Material Mined	Tailing Type	Liner System	Leachate Collection System	Impoundment Size
Pend Oreille Mine	Pend Oreille County, Washington	Teck Cominco American, Inc.	2007	Zinc and Lead	Slurry	Double liner, two 60 mil HDPE geomembranes with geocomposite drainage layer between for leak detection	N/A	20 acres
East Boulder Mine	Sweet Grass County, Montana	Stillwater Mining Co.	2002	Paladium and Platinum	Slurry	100 mil HDPE geomembrane	N/A	N/A
Hertzler Ranch Tailings Impoundment	Nye, Montana	Stillwater Mining Co.	2000	Paladium and Platinum	Slurry	60 mil HDPE geomembrane	N/A	146 acres
Kennecott Bingham Canyon Mine	Magna, Utah	Rio Tinto Group	1988	Copper, Gold, Silver, and Molybdenum	Slurry	Thick Natural Clay	N/A	9,000 acres
Bullfrog Mine Facility	Beatty, Nevada	Barrick Bullfrod Inc.	1989	Gold	Slurry	12" thick amended clay soil (5% bentonite) with PVC membrane liner	Perimeter and radial underdrains	320 acres
McCoy/Cove Mill	Battle Mountain, Nevada	Newmont Gold Company	1989	Gold	Slurry	30 mil VLDPE over prepared sub-base	Drainage piping network covered by uncompacted waste ore placed above a 2' thick protective bedding covering the liner system	400 acres

Proposed Hard Rock Tailings Impoundments

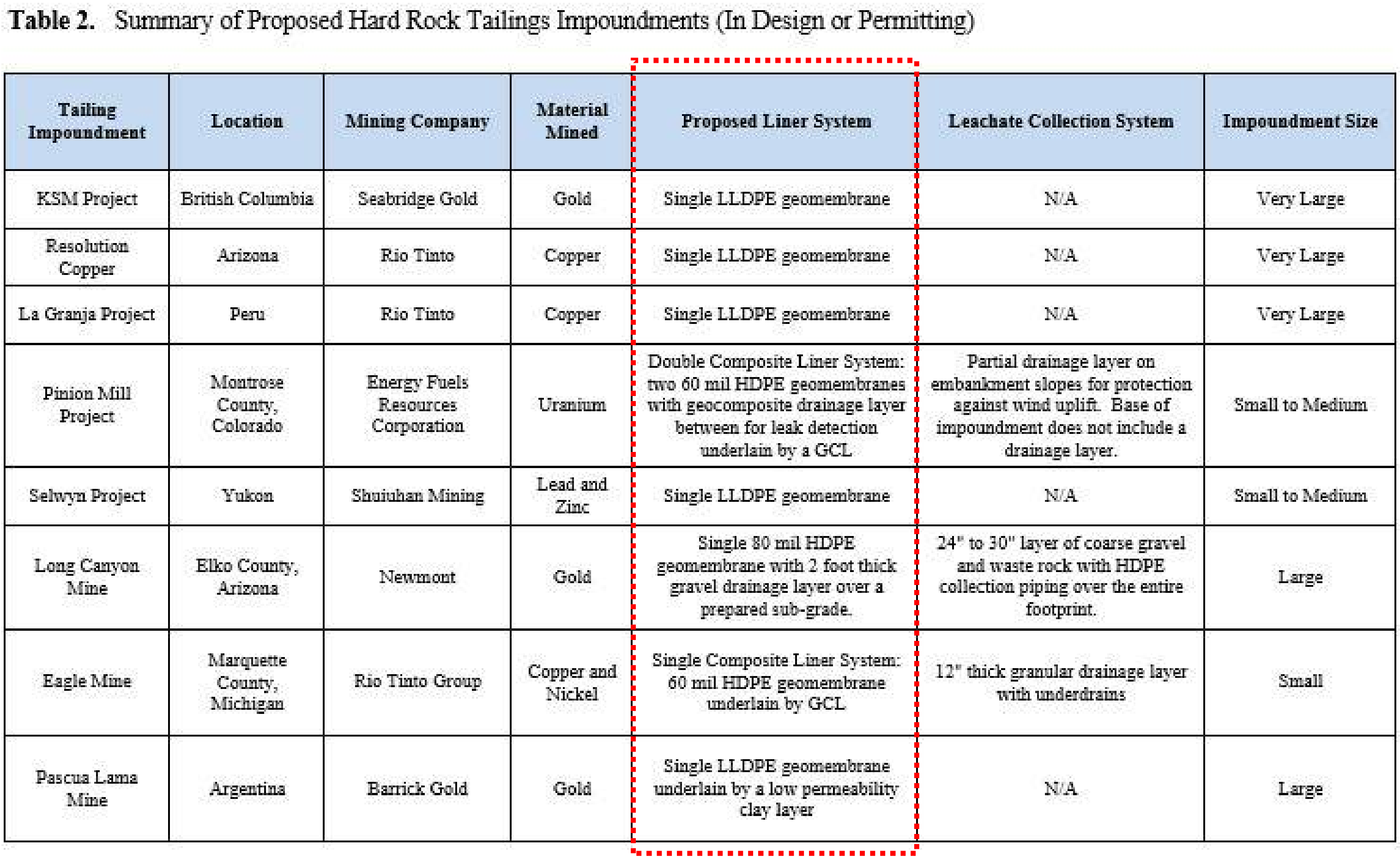


Table 2. Summary of Proposed Hard Rock Tailings Impoundments (In Design or Permitting)

Tailing Impoundment	Location	Mining Company	Material Mined	Proposed Liner System	Leachate Collection System	Impoundment Size
KSM Project	British Columbia	Seabridge Gold	Gold	Single LLDPE geomembrane	N/A	Very Large
Resolution Copper	Arizona	Rio Tinto	Copper	Single LLDPE geomembrane	N/A	Very Large
La Granja Project	Peru	Rio Tinto	Copper	Single LLDPE geomembrane	N/A	Very Large
Pinion Mill Project	Montrose County, Colorado	Energy Fuels Resources Corporation	Uranium	Double Composite Liner System: two 60 mil HDPE geomembranes with geocomposite drainage layer between for leak detection underlain by a GCL	Partial drainage layer on embankment slopes for protection against wind uplift. Base of impoundment does not include a drainage layer.	Small to Medium
Selwyn Project	Yukon	Shuiuhan Mining	Lead and Zinc	Single LLDPE geomembrane	N/A	Small to Medium
Long Canyon Mine	Elko County, Arizona	Newmont	Gold	Single 80 mil HDPE geomembrane with 2 foot thick gravel drainage layer over a prepared sub-grade.	24" to 30" layer of coarse gravel and waste rock with HDPE collection piping over the entire footprint.	Large
Eagle Mine	Marquette County, Michigan	Rio Tinto Group	Copper and Nickel	Single Composite Liner System: 60 mil HDPE geomembrane underlain by GCL	12" thick granular drainage layer with underdrains	Small
Pascua Lama Mine	Argentina	Barrick Gold	Gold	Single LLDPE geomembrane underlain by a low permeability clay layer	N/A	Large

Proposed Hard Rock Tailings Impoundments

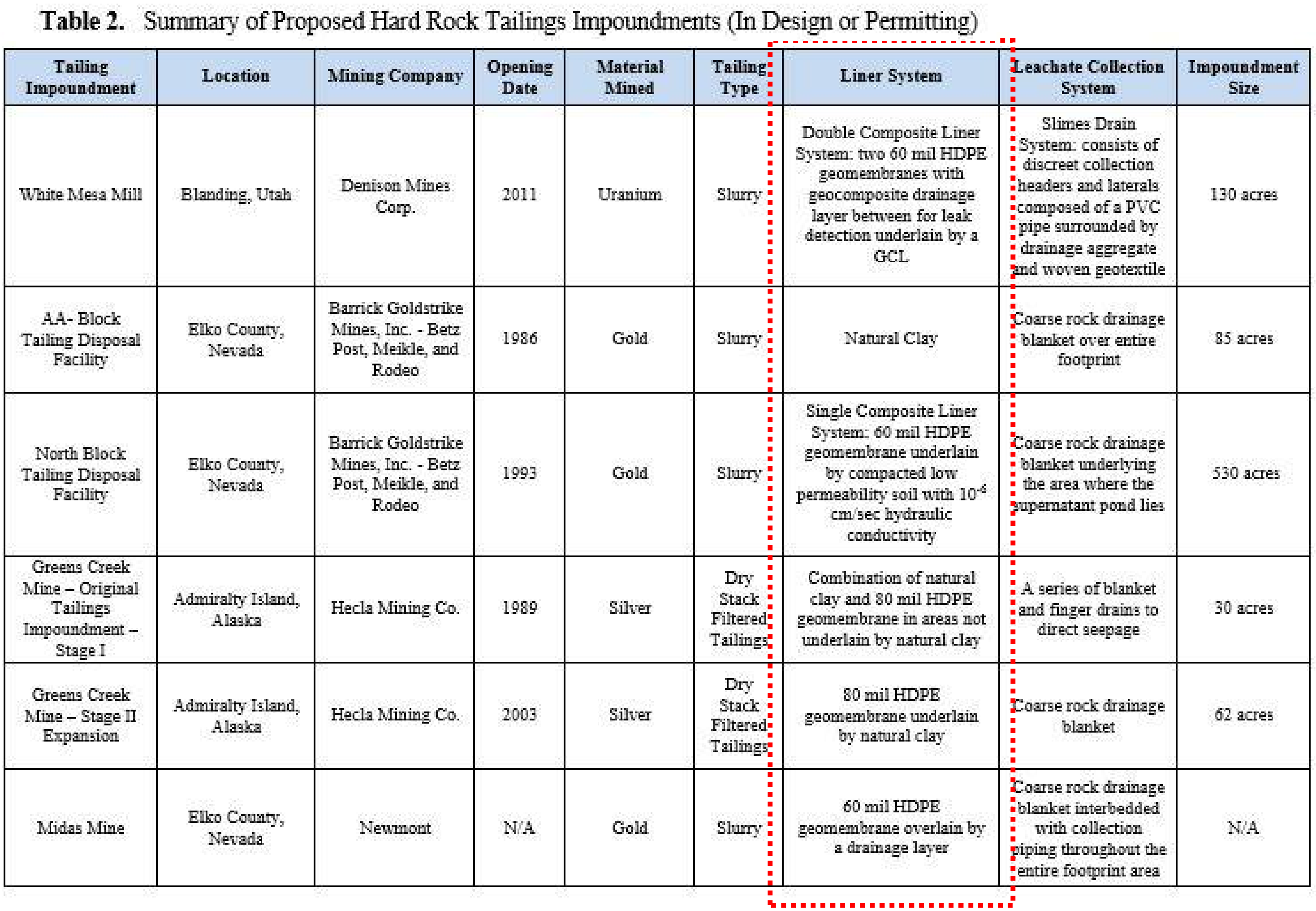


Table 2. Summary of Proposed Hard Rock Tailings Impoundments (In Design or Permitting)

Tailing Impoundment	Location	Mining Company	Opening Date	Material Mined	Tailing Type	Liner System	Leachate Collection System	Impoundment Size
White Mesa Mill	Blanding, Utah	Denison Mines Corp.	2011	Uranium	Slurry	Double Composite Liner System: two 60 mil HDPE geomembranes with geocomposite drainage layer between for leak detection underlain by a GCL	Slimes Drain System: consists of discreet collection headers and laterals composed of a PVC pipe surrounded by drainage aggregate and woven geotextile	130 acres
AA- Block Tailing Disposal Facility	Elko County, Nevada	Barrick Goldstrike Mines, Inc. - Betz Post, Meikle, and Rodeo	1986	Gold	Slurry	Natural Clay	Coarse rock drainage blanket over entire footprint	85 acres
North Block Tailing Disposal Facility	Elko County, Nevada	Barrick Goldstrike Mines, Inc. - Betz Post, Meikle, and Rodeo	1993	Gold	Slurry	Single Composite Liner System: 60 mil HDPE geomembrane underlain by compacted low permeability soil with 10^{-6} cm/sec hydraulic conductivity	Coarse rock drainage blanket underlying the area where the supernatant pond lies	530 acres
Greens Creek Mine – Original Tailings Impoundment – Stage I	Admiralty Island, Alaska	Hecla Mining Co.	1989	Silver	Dry Stack Filtered Tailings	Combination of natural clay and 80 mil HDPE geomembrane in areas not underlain by natural clay	A series of blanket and finger drains to direct seepage	30 acres
Greens Creek Mine – Stage II Expansion	Admiralty Island, Alaska	Hecla Mining Co.	2003	Silver	Dry Stack Filtered Tailings	80 mil HDPE geomembrane underlain by natural clay	Coarse rock drainage blanket	62 acres
Midas Mine	Elko County, Nevada	Newmont	N/A	Gold	Slurry	60 mil HDPE geomembrane overlain by a drainage layer	Coarse rock drainage blanket interbedded with collection piping throughout the entire footprint area	N/A

Tailings Storage Facilities

Tailings Storage Facilities

60 mil/1.5 mm HDPE

Tailings Storage Facilities

Tailings Storage Facilities

Tailings Storage Facilities

60 mil/1.5 mm HDPE

Tailings Storage Facilities

Dimensional Stability

Dimensional Stability

Interconnected Wrinkles

- **R.K. Rowe et al. (2012 & 2017):**

Rowe et al. (2012). Can. Geotech. J. **49**: 1196–1211
Rowe et al. (2017). J. Geotech. Geoenviron. Eng., 2017, 143(8): 04017033-1 to 04017033-8

Interconnected Wrinkles

- **R.K. Rowe et al. (2012 & 2017):**
- Typical wrinkle width: 0.2 to 0.3 m (0.7 to 1.0 ft)
- Typical wrinkle height: 0.06 to 0.2 m (0.2 to 0.7 ft)
- Wrinkle area: 2 to 30% of entire area
- Typical wrinkle length if 5% of area has wrinkles: 200 m (655 ft) – interconnected
- Wrinkles dominate behavior

Rowe et al. (2012). Can. Geotech. J. **49**: 1196–1211

Rowe et al. (2017). J. Geotech. Geoenviron. Eng., 2017, 143(8): 04017033-1 to 04017033-8

Tailings Dam Protection

Photograph by David Gilbert - Peru

Summary

- Stability Issues – consider dynamic loads
- Drainage
- Tailings Dam Failure cause environmental impact
- Geosynthetics

Tailings drainage using multilinear drainage geocomposites

Pascal Saunier, P.Eng.
AFITEX-Texel inc.
psaunier@afitextexel.com

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

AGENDA

- 01) Aussie Liners and Covers for Mine Waste - Williams
- 02) GCLs for Mine Waste – Benson
- 03) Case Study
- 04) Geosynthetics for Tailings Disposal - Stark
- 05) Tailings Drainage using Geocomposites – Saunier
- 06) Geosynthetics for Evaporation Mining - Stark

CONTENT

4 families of Drainage Geocomposites

Description of Multilinear Drainage Geocomposites (MIDG)

Use of MIDG in Mining Applications

- **Double Lined Pond**
- **Cycloned Sand Dam**
- **Dam Expansion**
- **Final Closure**
- **Dewatering in TSF**
- **Dry Stack**

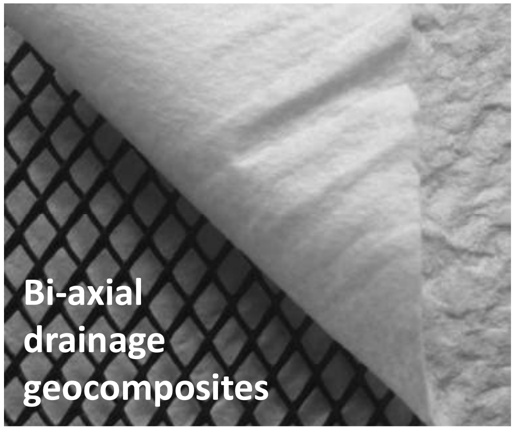
Conclusion

4 FAMILIES OF DRAINAGE GEOCOMPOSITES

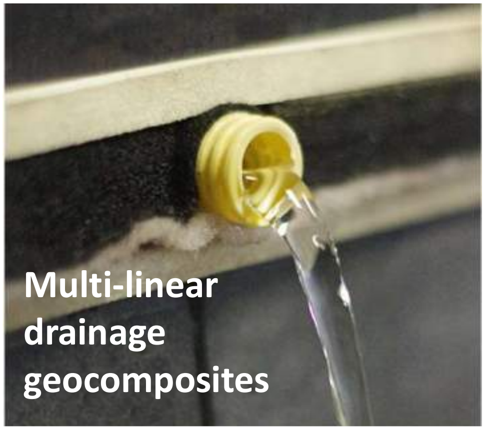
ASTM INTERNATIONAL

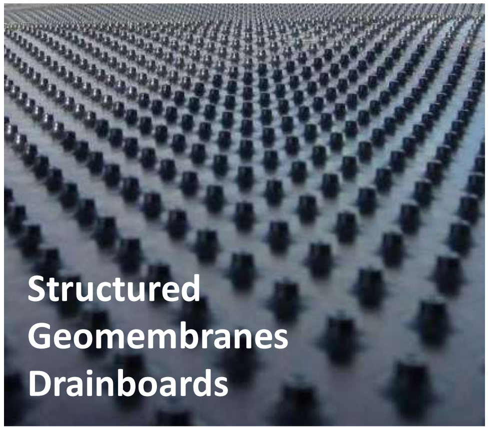
Designation: D7931 – 17

Standard Guide for Specifying Drainage Geocomposites[1]

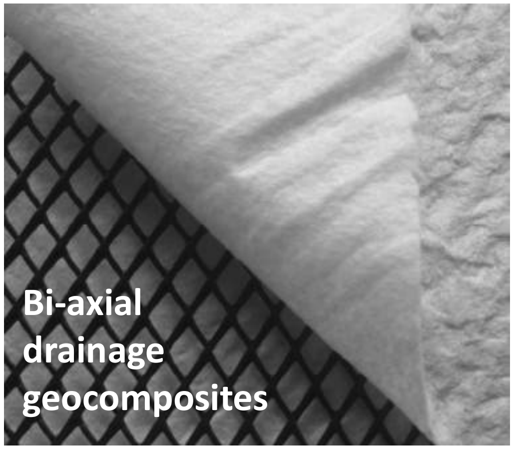

Bi-axial drainage geocomposites


Tri-axial drainage geocomposites


Multi-linear drainage geocomposites


Structured Geomembranes Drainboards

4 FAMILIES OF DRAINAGE GEOCOMPOSITES


Bi-axial drainage geocomposites

- Largely used products all over the world
- Different manufacturers
- Different resign quality, ribs shape, aperture
- The geotextiles are heat bonded to the core
- Sensitive to intrusion and creep
- Cheap products in average

4 FAMILIES OF DRAINAGE GEOCOMPOSITES

- High performance net products
- Few manufacturers
- Good resign quality, large aperture
- The geotextiles are heat bonded to the core
- Less sensitive to intrusion and creep than bi-axial
- More expensive products in average

4 FAMILIES OF DRAINAGE GEOCOMPOSITES

- More and more used products
- Very few manufacturers
- Different heights of studs
- The geotextile is manually placed on top of the studs
- Sensitive to intrusion and creep
- Uneasy product to install

DESCRIPTION OF MULTI-LINEAR DRAINAGE GEOCOMPOSITES (MIDG)

ASTM INTERNATIONAL

Designation: D4439 – 17

Standard Terminology for Geosynthetics[1]

multi-linear drainage geocomposite, *n*—a manufactured product composed of a series of parallel single drainage conduits regularly spaced across its width sandwiched between two or more geosynthetics.

DESCRIPTION OF MULTI-LINEAR DRAINAGE GEOCOMPOSITES (MIDG)





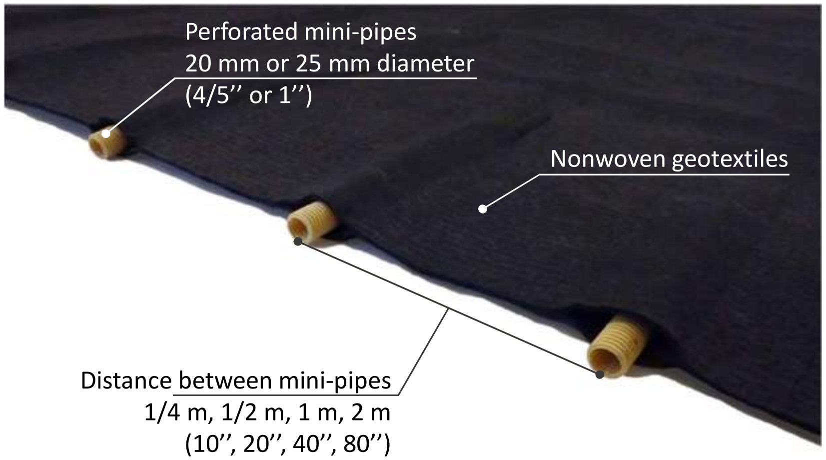
DESCRIPTION OF MULTI-LINEAR DRAINAGE GEOCOMPOSITES (MIDG)

Multi Linear drainage geocomposite: DRAINTUBE®

Drainage geocomposite with drainage conduits regularly spaced between two geotextiles instead of a geonet core

Drainage conduits:

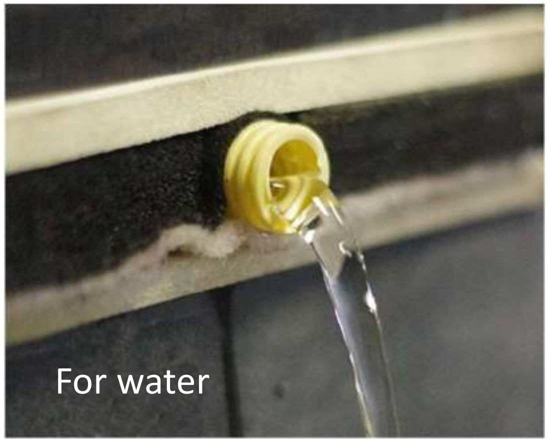
- Perforated PP mini-pipes,



DESCRIPTION OF MULTI-LINEAR DRAINAGE GEOCOMPOSITES (MIDG)

Main characteristics:

- Generally Large Rolls 4 m x 75+ m
- Various Geotextiles layers (from 100 g/m^2 to 2000 g/m^2)
- Conduits with high compressive resistance (if mini-pipes)
- Transmissivity function of the quantity of conduits vs thickness of core
- Light and Flexible product
- No peel adhesion issue
- No creep, No geotextile intrusion
- Large options in filtration


For water


For gas


For leachate

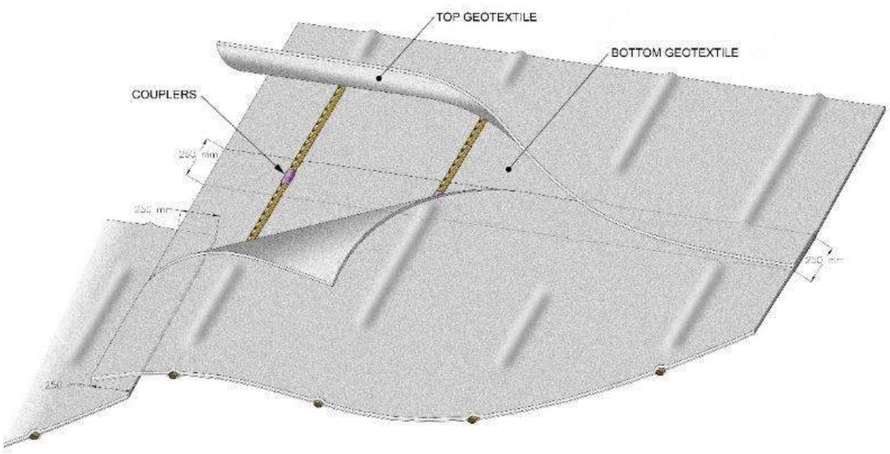
DESCRIPTION OF MULTI-LINEAR DRAINAGE GEOCOMPOSITES (MIDG)

Installation

DESCRIPTION OF MULTI-LINEAR DRAINAGE GEOCOMPOSITES (MIDG)

Installation

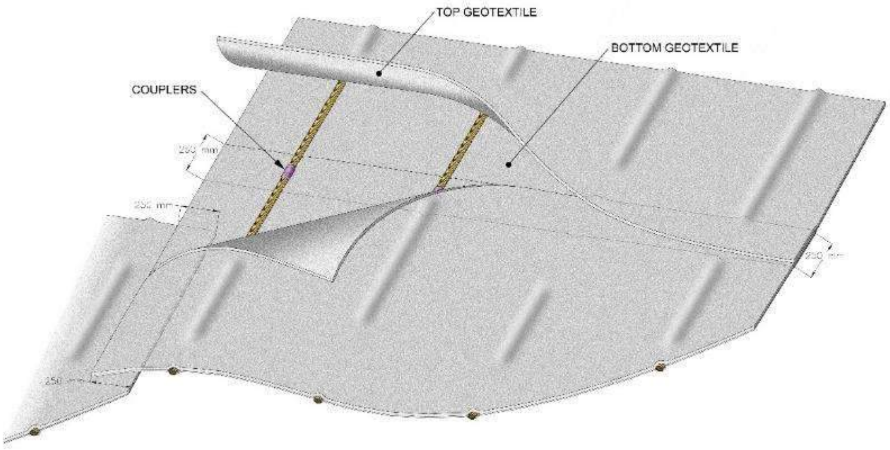
Welding, Sewing, additional overlap



DESCRIPTION OF MULTI-LINEAR DRAINAGE GEOCOMPOSITES (MIDG)

Installation

Welding, Sewing, additional overlap



DESCRIPTION OF MULTI-LINEAR DRAINAGE GEOCOMPOSITES (MIDG)

Backfill

DESCRIPTION OF MULTI-LINEAR DRAINAGE GEOCOMPOSITES (MIDG)

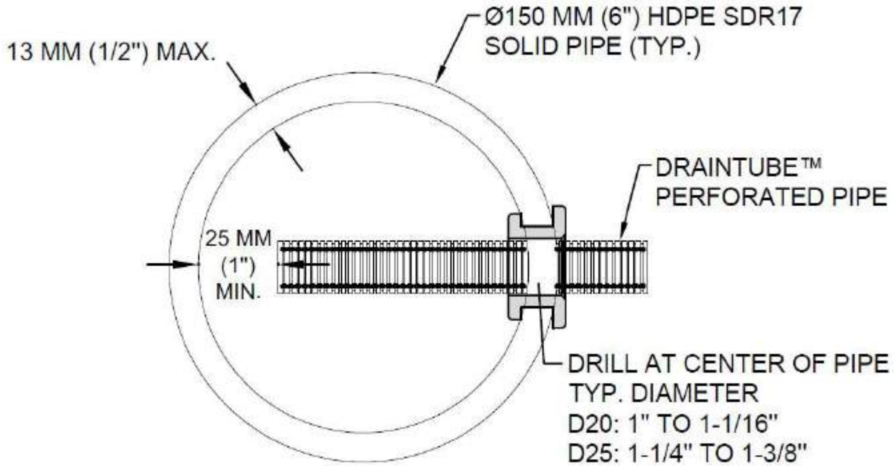
Connection to collector trench / ditch

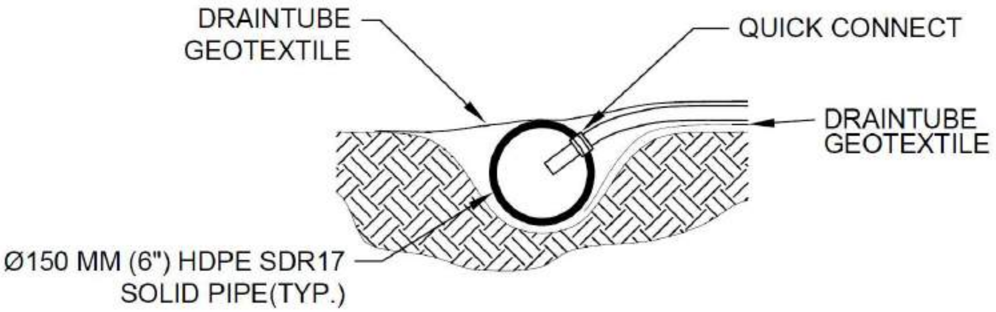
DESCRIPTION OF MULTI-LINEAR DRAINAGE GEOCOMPOSITES (MIDG)

Quick Connect System

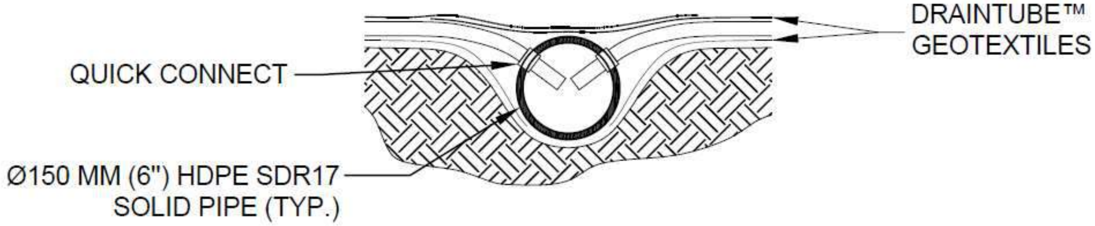
DESCRIPTION OF MULTI-LINEAR DRAINAGE GEOCOMPOSITES (MIDG)

Quick Connect System





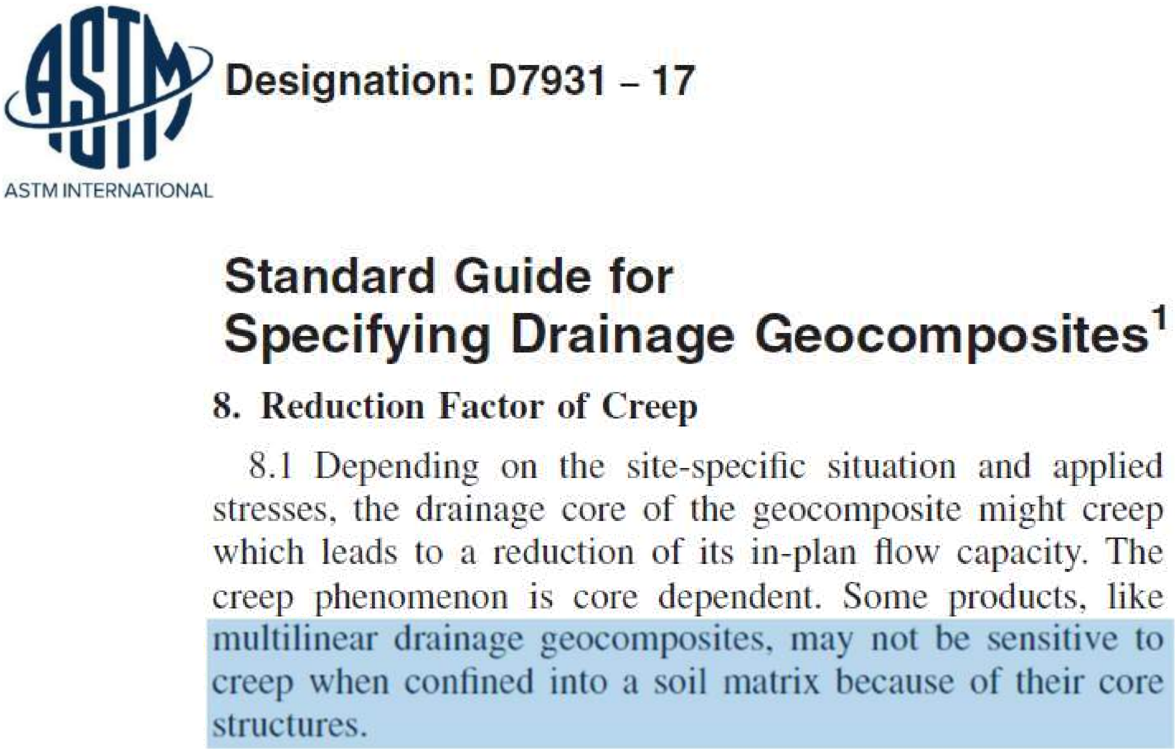
<u>Simple connection</u>



Double connection

DESCRIPTION OF MULTI-LINEAR DRAINAGE GEOCOMPOSITES (MIDG)

DRAINTUBE is also included in **ASTM D7931** Standard Guide for Specifying Drainage Geocomposites.



ASTM INTERNATIONAL

Designation: D7931 – 17

Standard Guide for
Specifying Drainage Geocomposites[1]

8. Reduction Factor of Creep

8.1 Depending on the site-specific situation and applied stresses, the drainage core of the geocomposite might creep which leads to a reduction of its in-plan flow capacity. The creep phenomenon is core dependent. Some products, like multilinear drainage geocomposites, may not be sensitive to creep when confined into a soil matrix because of their core structures.

DESCRIPTION OF MULTI-LINEAR DRAINAGE GEOCOMPOSITES (MIDG)

GSI White Paper #4 (Koerner)

Reduction Factors (RFs) Used in Geosynthetic Design

$$Q_{allow} = \frac{Q_{ult}}{RF_{in} \, . RFcr \, . RFcc \, . RFbc}$$

q_{allow} = allowable (or design) flow rate or transmissivity,

q_{ult} = ultimate (or as-manufactured) flow rate or transmissivity,

RF_{IN} = reduction factor for intrusion of geotextiles or geomembranes into the core of drainage product,

RF_{CR} = reduction factor for creep of the drainage core or covering geosynthetics,

RF_{CC} = reduction factor for chemical clogging of drainage core, and

RF_{BC} = reduction factor for biological clogging of drainage core.

DESCRIPTION OF MULTI-LINEAR DRAINAGE GEOCOMPOSITES (MIDG)

GSI White Paper #4 (Koerner)
Reduction Factors (RFs) Used in Geosynthetic Design

$$Q_{allow} = \frac{Q_{ult}}{RF_{in} \,.\, RFcr \,.\, RFcc \,.\, RFbc}$$

q_{allow} = allowable (or design) flow rate or transmissivity,

q_{ult} = ultimate (or as-manufactured) flow rate or transmissivity,

RF_{IN} = reduction factor for intrusion of geotextiles or geomembranes into the core of drainage product,

RF_{CR} = reduction factor for creep of the drainage core or covering geosynthetics,

RF_{CC} = reduction factor for chemical clogging of drainage core, and

RF_{BC} = reduction factor for biological clogging of drainage core.

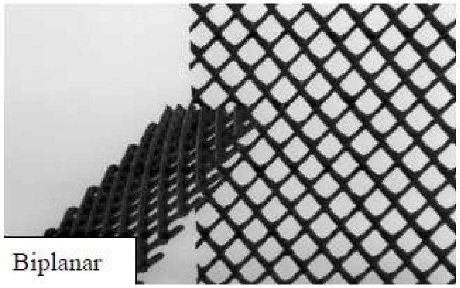
DESCRIPTION OF MULTI-LINEAR DRAINAGE GEOCOMPOSITES (MIDG)

Reduction factor for creep and geotextile intrusion

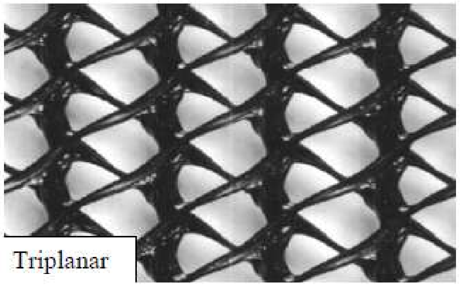
Function of the shape of the drainage core

For geonet drainage core

Reduction of the drainage capacity under load



Biplanar



Triplanar

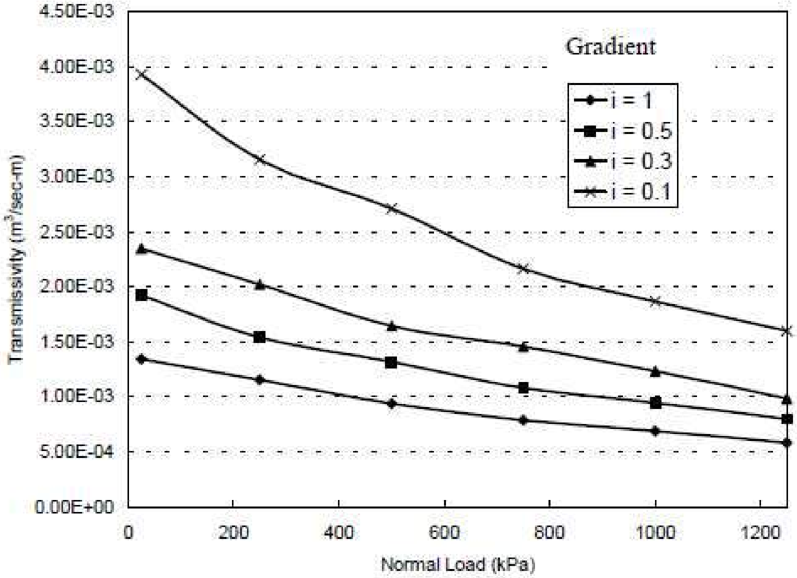


Figure 2.3 Transmissivity data vs. normal loads for a triplanar geonet laminated with a 270g/m^2 nonwoven on each side with soil as a top boundary and aluminum plate lower boundary (ASTM D4716).

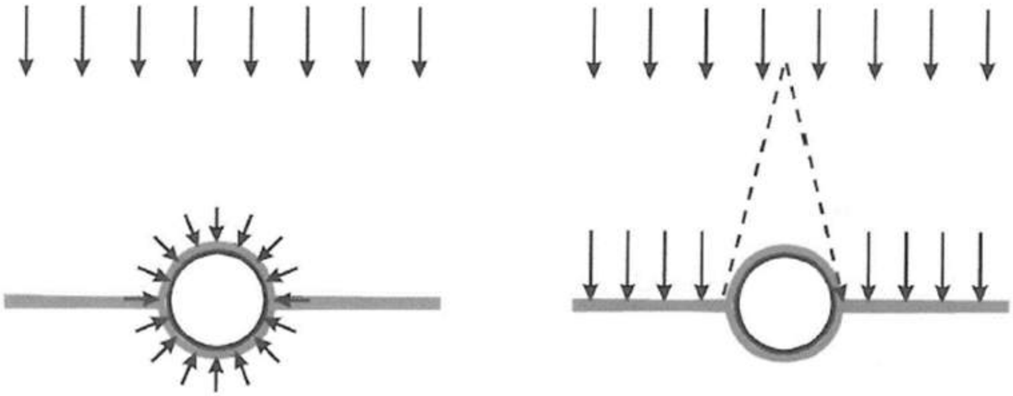
DESCRIPTION OF MULTI-LINEAR DRAINAGE GEOCOMPOSITES (MIDG)

Reduction factor for creep and geotextile intrusion

Function of the shape of the drainage core

For DRAINTUBE

Arching effect when confined in soil



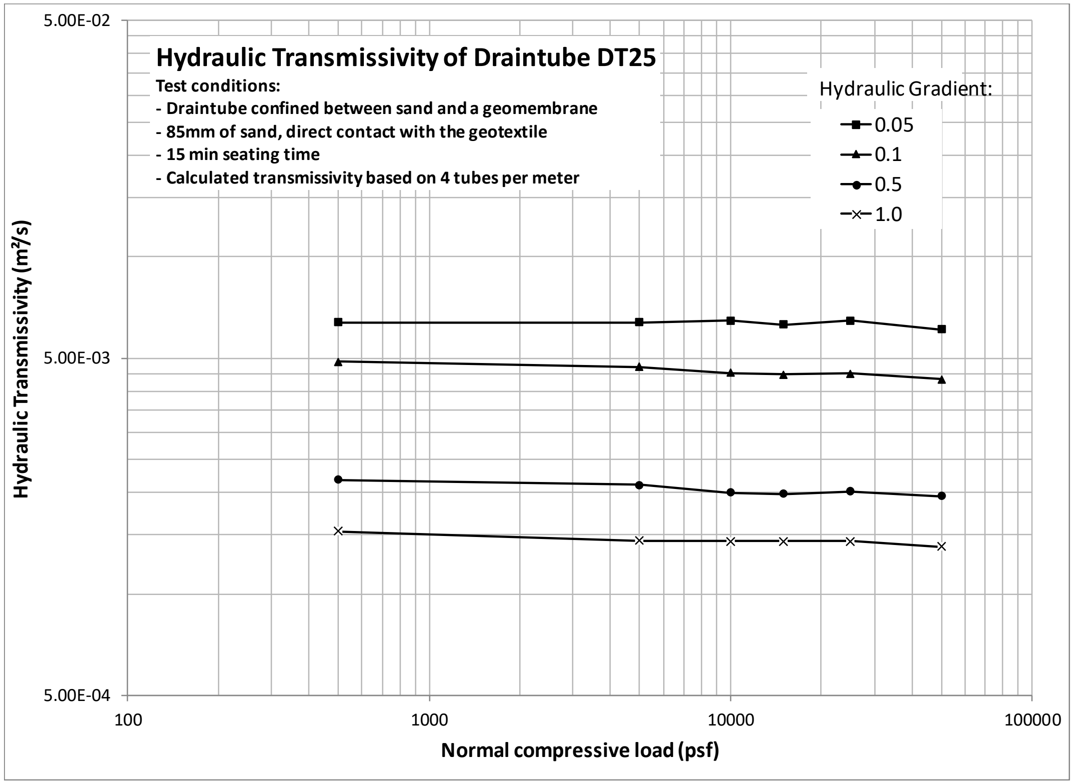
DESCRIPTION OF MULTI-LINEAR DRAINAGE GEOCOMPOSITES (MIDG)

Reduction factor for creep and geotextile intrusion

Function of the shape of the drainage core

For DRAINTUBE

Arching effect when confined in soil



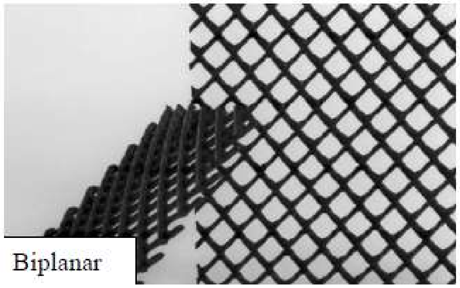
DESCRIPTION OF MULTI-LINEAR DRAINAGE GEOCOMPOSITES (MIDG)

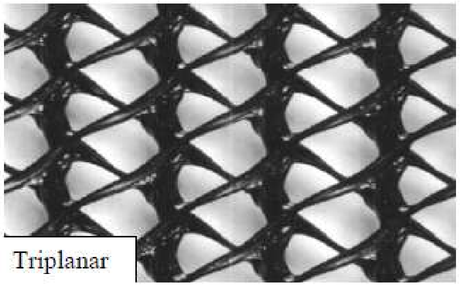
Reduction factor for creep and geotextile intrusion

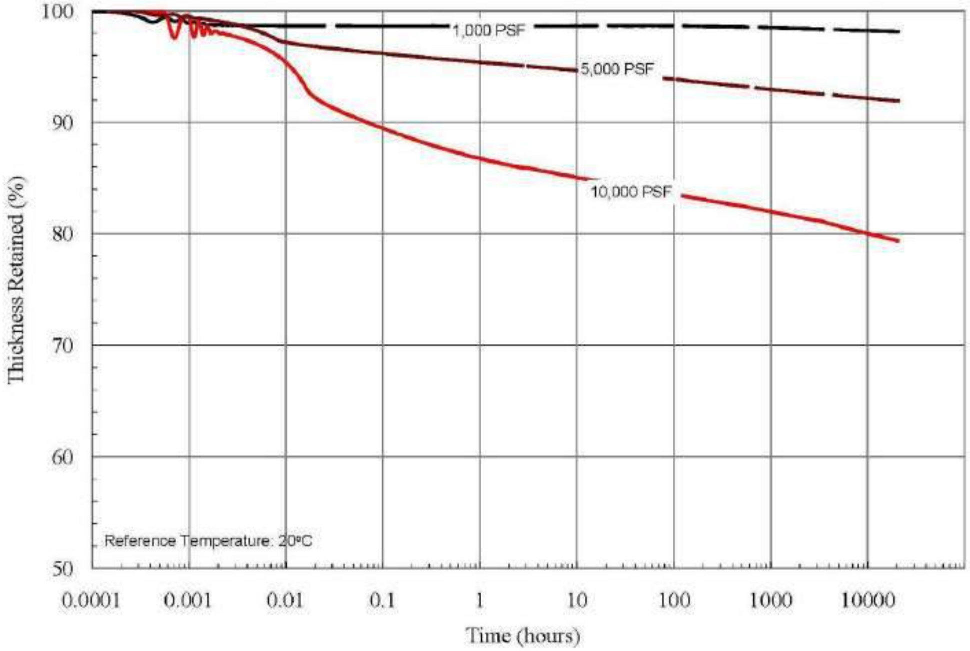
Function of the shape of the drainage core

For geonet drainage core

Reduction of the drainage capacity over time


Biplanar


Triplanar



Creep Curves for a 250 mil geonet

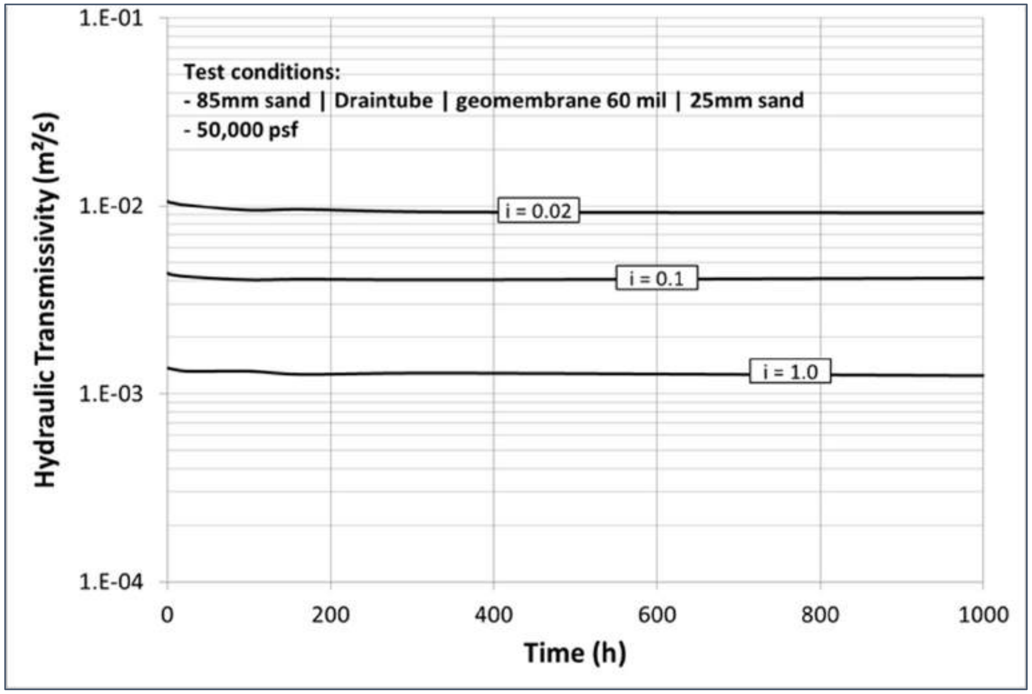
DESCRIPTION OF MULTI-LINEAR DRAINAGE GEOCOMPOSITES (MIDG)

Reduction factor for creep and geotextile intrusion

Function of the shape of the drainage core

For DRAINTUBE

Arching effect when confined in soil

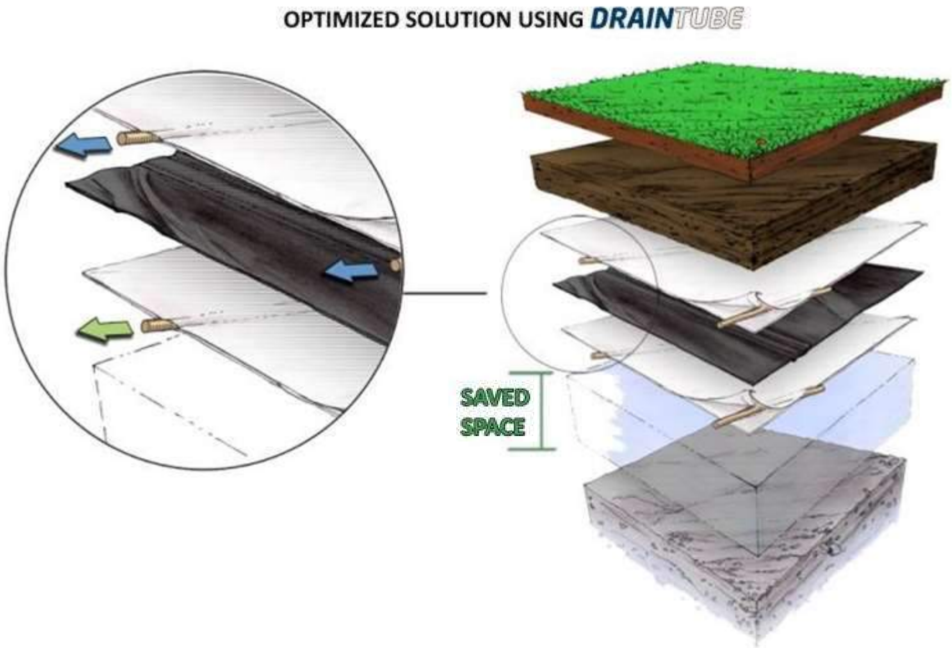


Published related reference

Assessment of the Resistance of Drain Tubes planar drainage geocomposites to high compressive loads
Eric Blond (SAGEOS) and Pascal Saunier (AFITEX-Texel), ***ICG 2010***

USE OF MIDG IN MINING APPLICATIONS

Run-off drainage / Gas venting on final covers



Case Study : HSPP, BC – 2014 / 15

USE OF MIDG IN MINING APPLICATIONS

Case Study : Gibraltar, BC – 2010

USE OF MIDG IN MINING APPLICATIONS

Case Study : McKay River - Suncor, AB – 2013

USE OF MIDG IN MINING APPLICATIONS

Case Study : Eustis Mine, Qc – 2008 - 2010

USE OF MIDG IN MINING APPLICATIONS

Case Study : CMM, MB – 2011

USE OF MIDG IN MINING APPLICATIONS

Tailings dewatering in TSF

Case Study : North American Palladium, ON - 2017

USE OF MIDG IN MINING APPLICATIONS

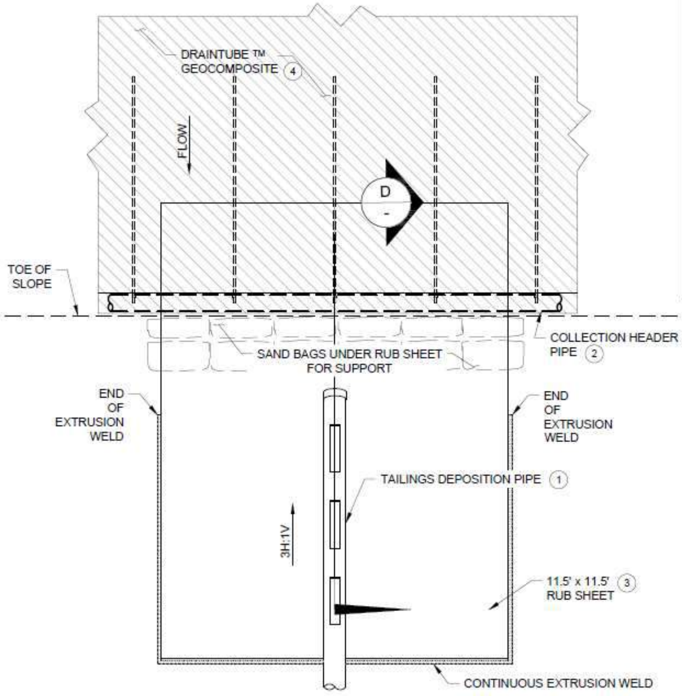
- Coarser particles falling first = creation of a 'perfect' filter

(a) after 5 minutes *(b) after 15 minutes* *(c) after 2 h 45 min* *(d) after 66 hours*

USE OF MIDG IN MINING APPLICATIONS

USE OF MIDG IN MINING APPLICATIONS

USE OF MIDG IN MINING APPLICATIONS



1/110 TAILINGS DEPOSITION DETAIL (TYP.)
N.T.S.

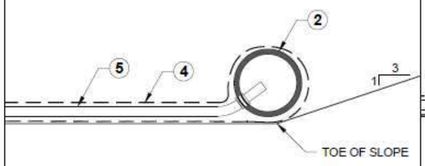
① 8"Ø HDPE SDR 21

② 6"Ø PERFORATED CPE PIPE

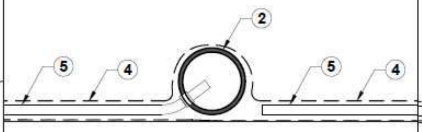
③ RUB SHEET CONSISTS OF 60-MIL HDPE GEOMEMBRANE

④ DRAINTUBE™ GEOCOMPOSITE 340P FT1 GEOCOMPOSITE BY AFITEX-TEXEL GEOSYNTHETICS INC. (SEE NOTE 2)

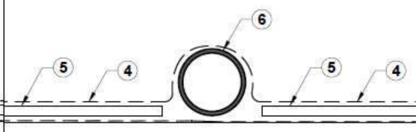
⑤ 1"Ø PERFORATED DRAINTUBE™ "MINI-PIPES" (SEE NOTE 2)



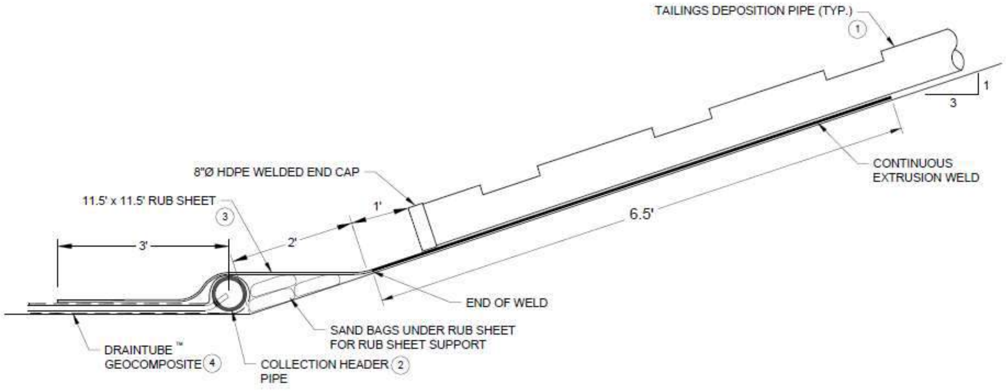
A/110 COLLECTION HEADER PIPE/DRAINTUBE DETAIL, N.T.S. (SEE NOTE 2)



B/110 COLLECTION HEADER PIPE/DRAINTUBE DETAIL, N.T.S. (SEE NOTE 2)

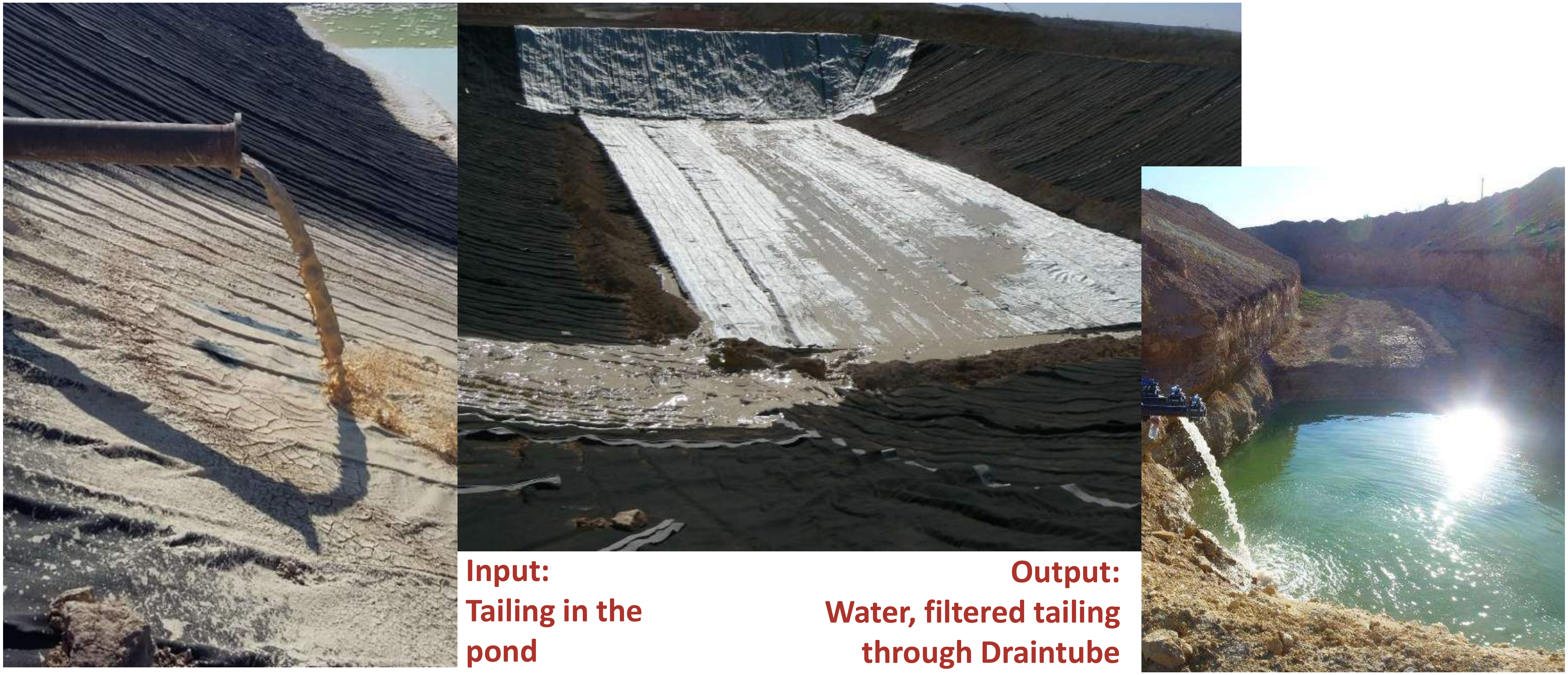


C/110 COLLECTION HEADER PIPE/DRAINTUBE DETAIL, N.T.S. (SEE NOTE 2)



D/- TAILINGS DEPOSITION SECTION DETAIL
N.T.S.

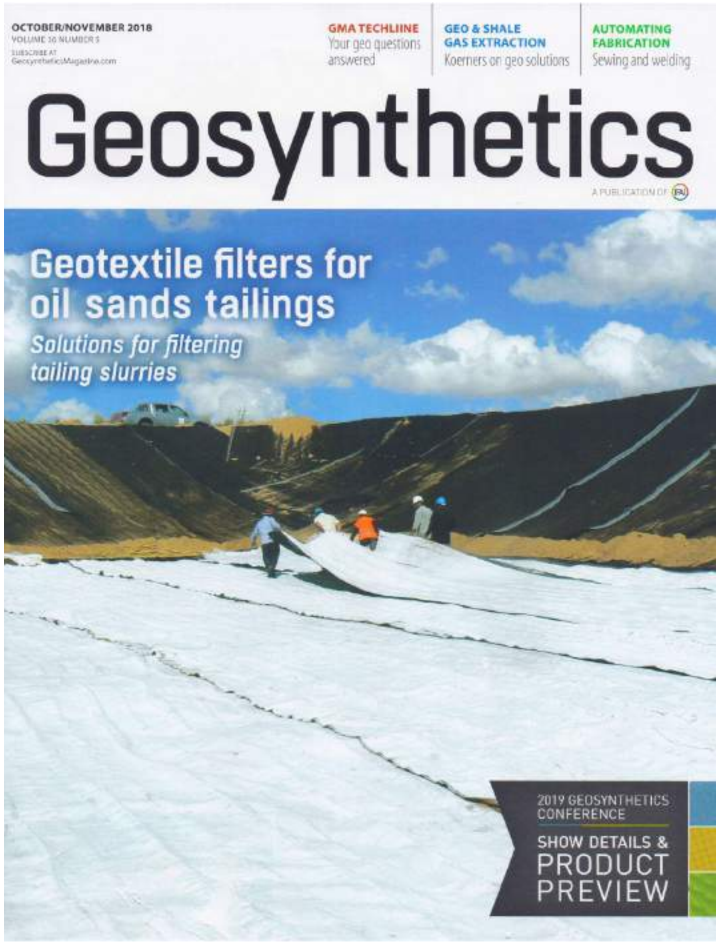
USE OF MIDG IN MINING APPLICATIONS



Input:
Tailing in the pond

Output:
Water, filtered tailing through Draintube

USE OF MIDG IN MINING APPLICATIONS



OCTOBER/NOVEMBER 2018
VOLUME 36 NUMBER 5
SUBSCRIBE AT
GeosyntheticsMagazine.com

GMA TECHLIINE
Your geo questions answered

GEO & SHALE GAS EXTRACTION
Koerners on geo solutions

AUTOMATING FABRICATION
Sewing and welding

Geosynthetics

A PUBLICATION OF IFAI

Geotextile filters for oil sands tailings

Solutions for filtering tailing slurries

2019 GEOSYNTHETICS CONFERENCE
SHOW DETAILS & PRODUCT PREVIEW

USE OF MIDG IN MINING APPLICATIONS

Case Study :
Copper Mountain, BC – 2012

USE OF MIDG IN MINING APPLICATIONS


Dam Expansion

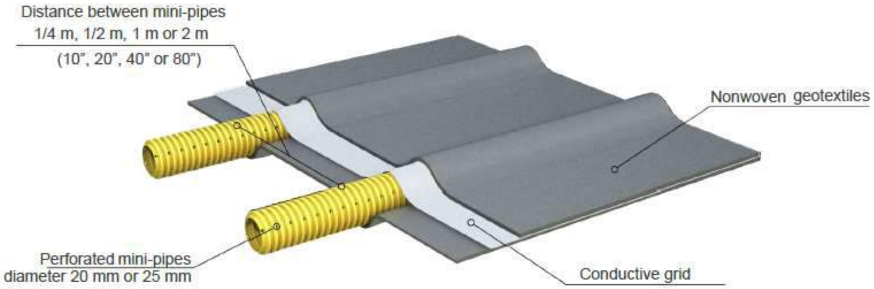
USE OF MIDG IN MINING APPLICATIONS

+ comment on Mount Polley disaster

USE OF MIDG IN MINING APPLICATIONS

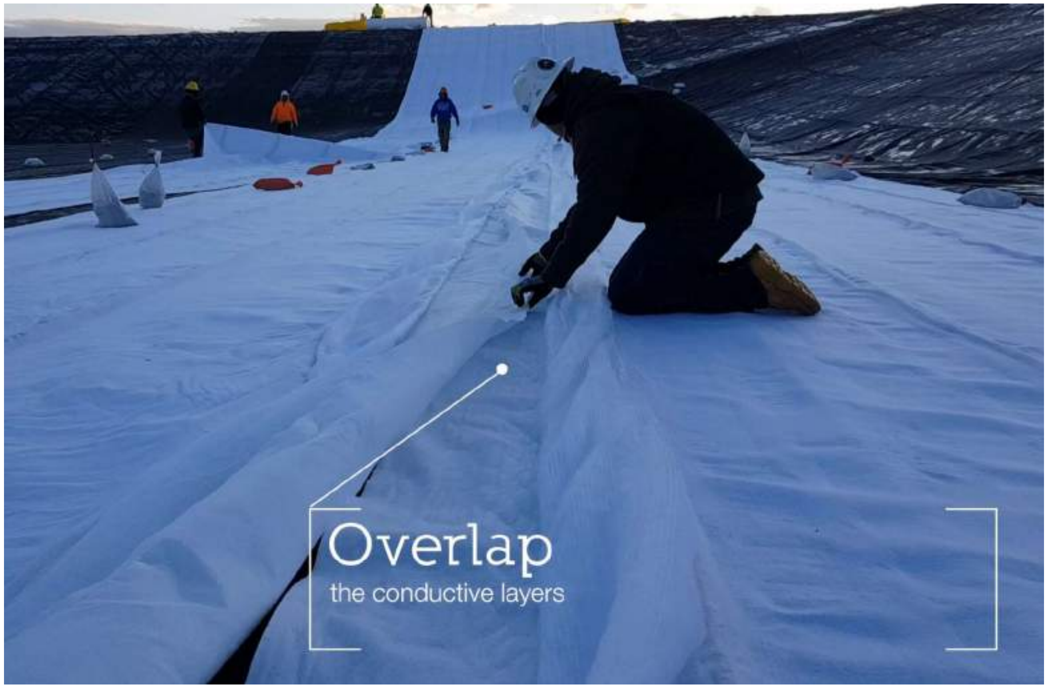
USE OF MIDG IN MINING APPLICATIONS

Double-lined Ponds



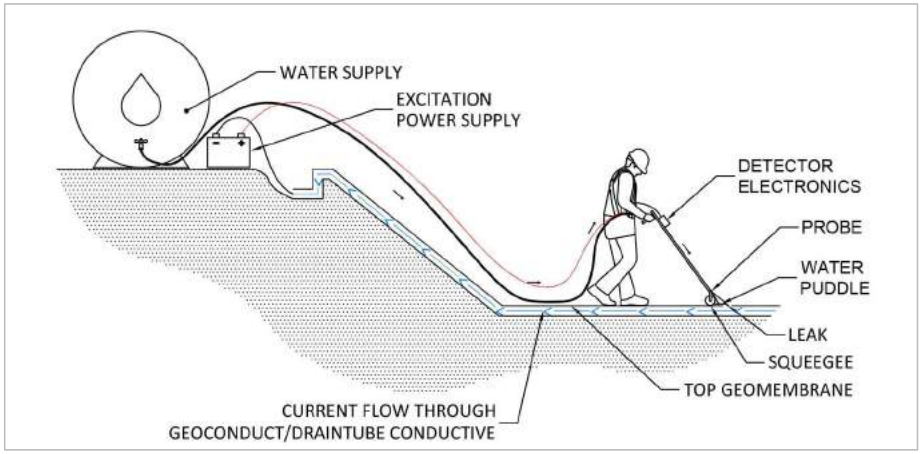
DRAINTUBE Conductive

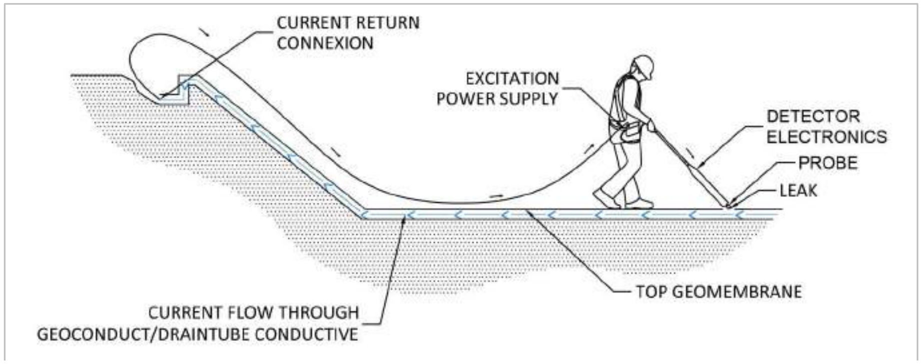
USE OF MIDG IN MINING APPLICATIONS



USE OF MIDG IN MINING APPLICATIONS

Water Lance Method (ASTM D7002)

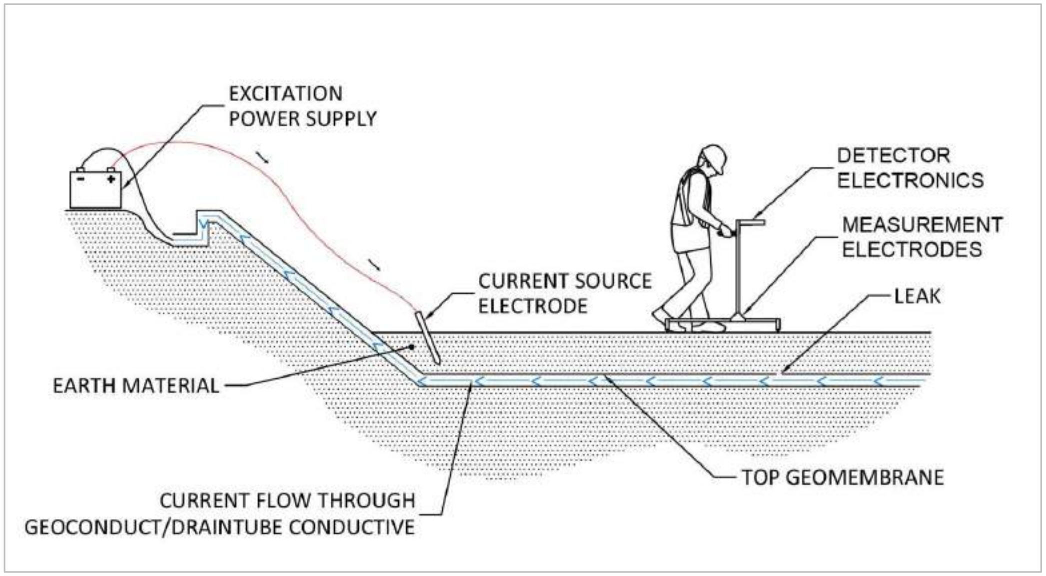




Arctest Method (ASTM D7953)

USE OF MIDG IN MINING APPLICATIONS

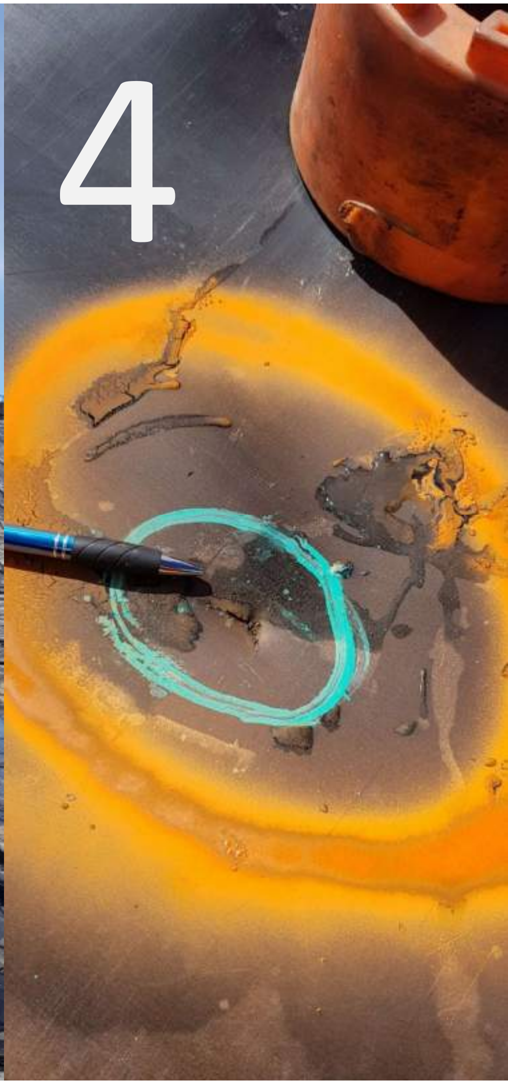
Dipole Method (ASTM D7007)




1

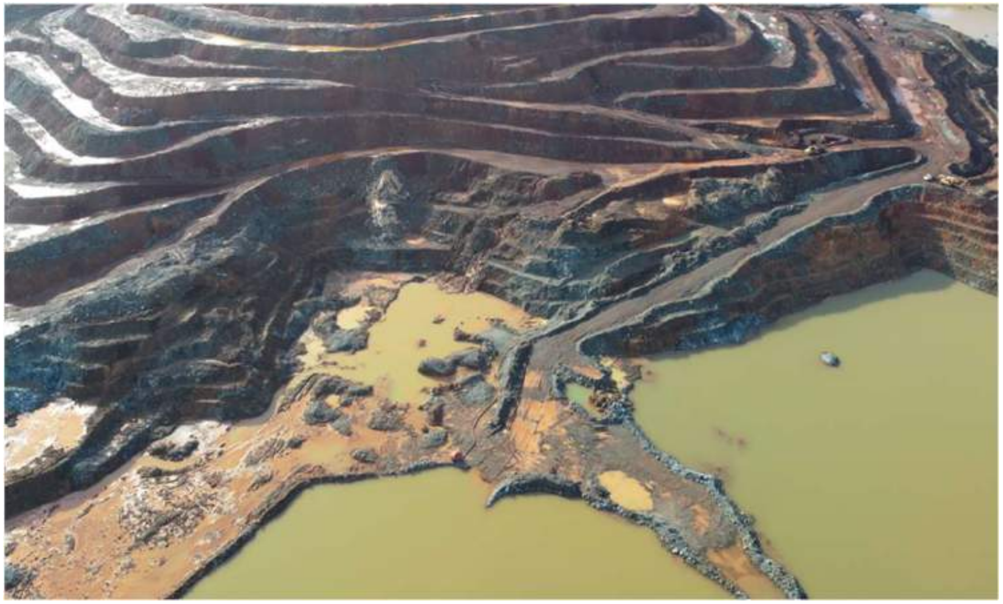

2
Cal.


3

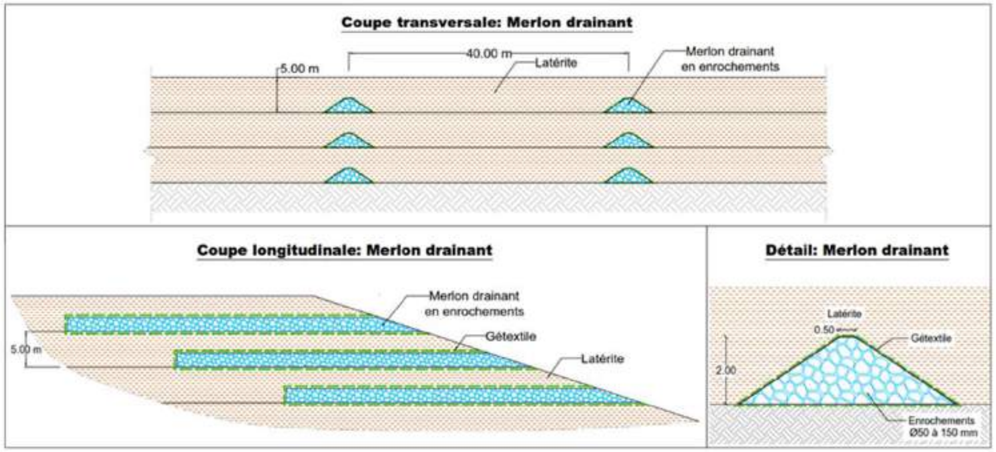

4

USE OF MIDG IN MINING APPLICATIONS

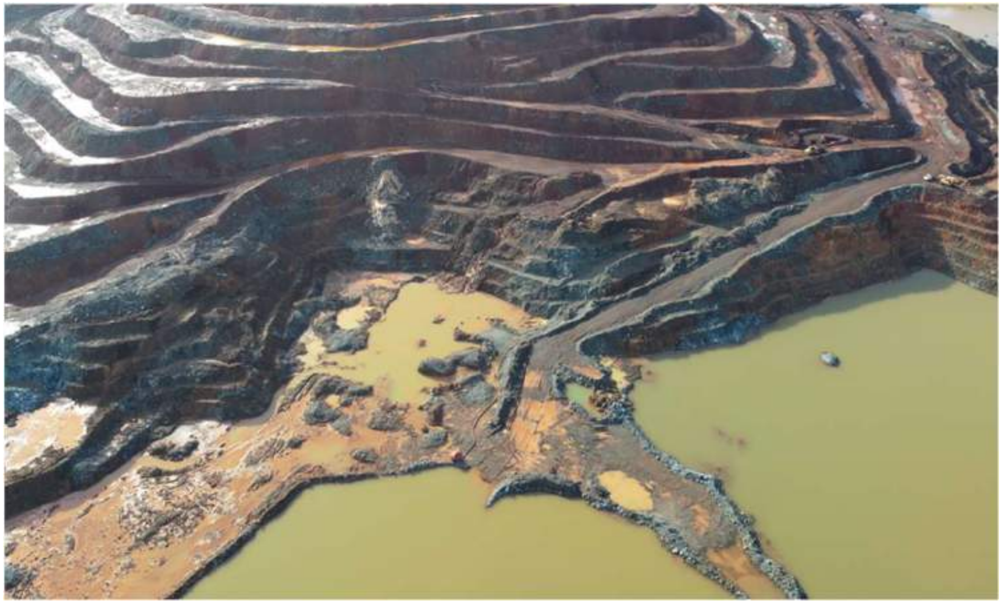
Dry Stack



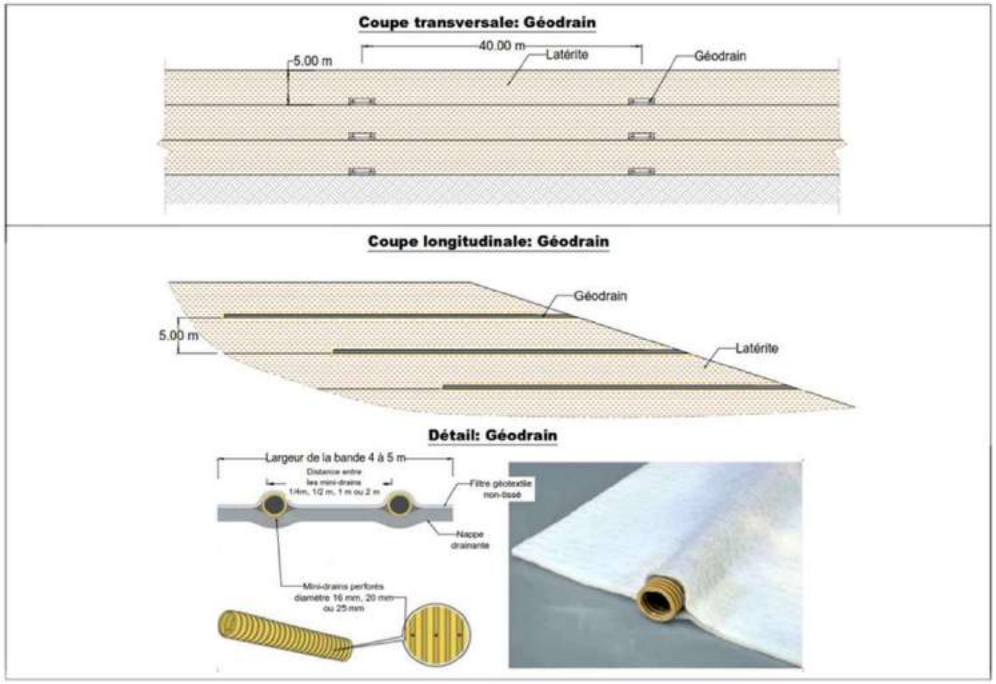
Granular Solution in Fishbones / Fingerdrains



USE OF MIDG IN MINING APPLICATIONS



Optimized Solution



USE OF MIDG IN MINING APPLICATIONS

USE OF MIDG IN MINING APPLICATIONS

+ video pose manuelle

+ video pose pelle

USE OF MIDG IN MINING APPLICATIONS

USE OF MIDG IN MINING APPLICATIONS

USE OF MIDG IN MINING APPLICATIONS

CONCLUSION

- Drainage is a critical path for long term behaviour in mining construction
- Environmental footprint is also an everyday concern
- Lots of great solutions for TSF and minings apps in general
- Multi-linear Drainage Geocomposites are part of them with important advantages :
  - No creep
  - No Intrusion
  - Large adaptability with filters
- Case studies can be found in all sectors/areas of the mining industry

Thank you for your attendance

Pascal Saunier, P.Eng.
AFITEX-Texel inc.
psaunier@afitextexel.com

GEOANZ #1 ADVANCES IN GEOSYNTHETICS

7–9 JUNE 2022 | BRISBANE CONVENTION & EXHIBITION CENTRE

AGENDA

- 01) Aussie Liners and Covers for Mine Waste - Williams
- 02) GCLs for Mine Waste – Benson
- 03) Case Study
- 04) Geosynthetics for Tailings Disposal - Stark
- 05) Tailings Drainage using Geocomposites – Saunier
- 06) Geosynthetics for Evaporation Mining - Stark

Outline

- Evaporation Mining
- Liner System Leakage
- Wrinkle Behavior & Leakage
- Thermal Expansion
- Installation
- Summary

Salar de Atacama

- Elevation ~2,287.5 m (7,500 ft)
- 3,000 km^2
- Ancient seabed
- Underground brine reservoirs
- Recharged by snow melt
- Lithium, K (fertilizer), Boric Acid, and NaCl
- Dry desert – windy & rarely cloudy
- Great evaporation
- One-year yields 1 m of salt

Massive mining evaporation ponds constructed in Chilean desert

| The Salar de Atacama in Chile is the site of the largest PVC geomembrane installation in the world—more than 16 million ft.^{2} utilized in mining operations since 1996.

By Dominic Berube,[1] Patrick Diebel,[2] Andre Rollin,[3] and Timothy D. Stark[4]

Photos courtesy of Solmax International unless cited

Photo 1 | In constructing the evaporation ponds, after the PVC liner is deployed, electrical leak-detection tests are done (see page 32).

| [1] International Sales Manager, Solmax International, 2801, Boulevard Marie-Victorin, Varennes, Quebec Canada J3X 1P7, (800) 571-3904 ext. 206, e-mail: dberube@solmax.com

[2] Technical Director, Canadian General Tower, 52 Middleton, P.O. Box 160, Cambridge, Ontario N1R 5T6, Canada, 519-623-1630, e-mail: PDiebel@cgtower.com

[3] Director, Solmers International, 1471, boul. Lionel-Boulet, Bureau 22, Varennes, Quebec Canada J3X 1P7, 514453-6998, e-mail: andre.rollin@sympatico.ca

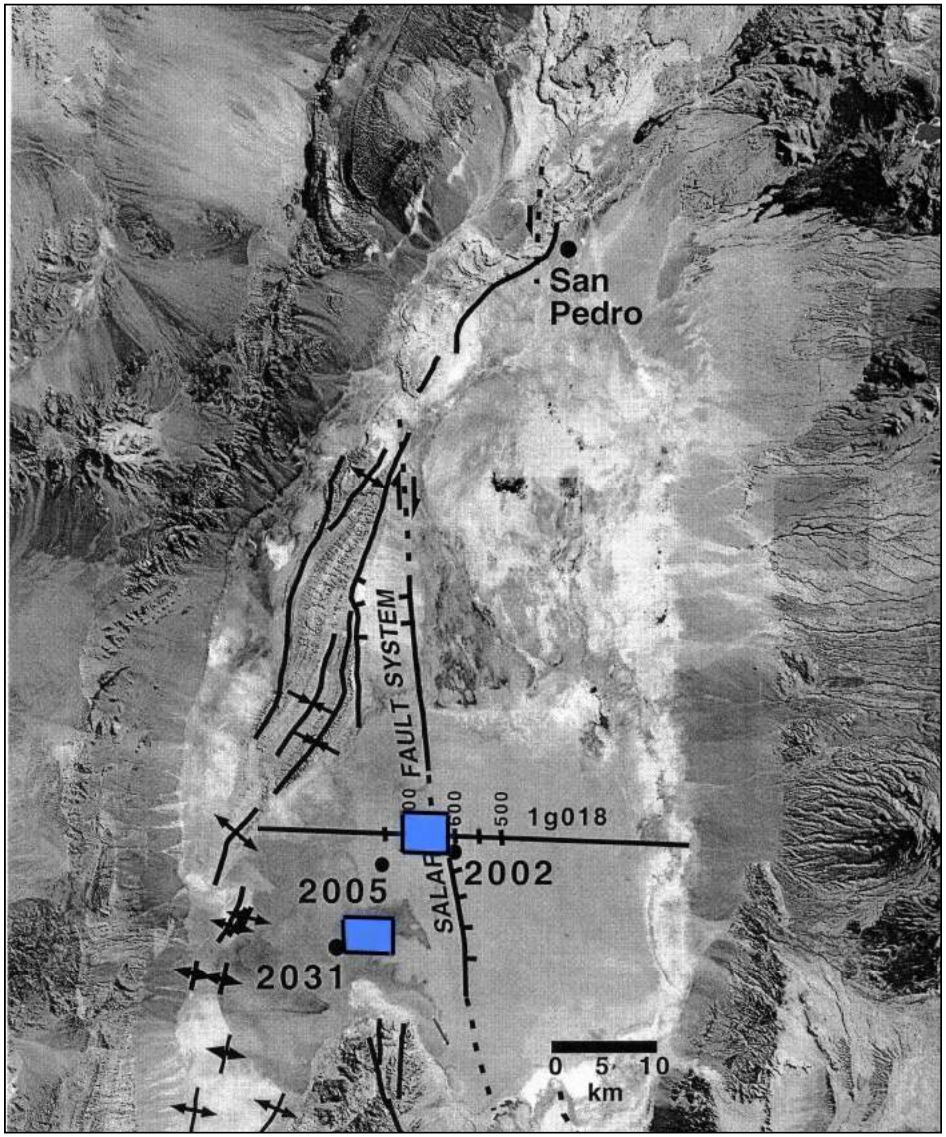
[4] Professor of Civil and Environmental Engineering, University of Illinois, 205 N. Mathews Ave., Urbana, IL 61801, 217-333-7394, e-mail: tstark@uiuc.edu

Geosynthetics February March 2007

26 www.geosyntheticsmagazine.info

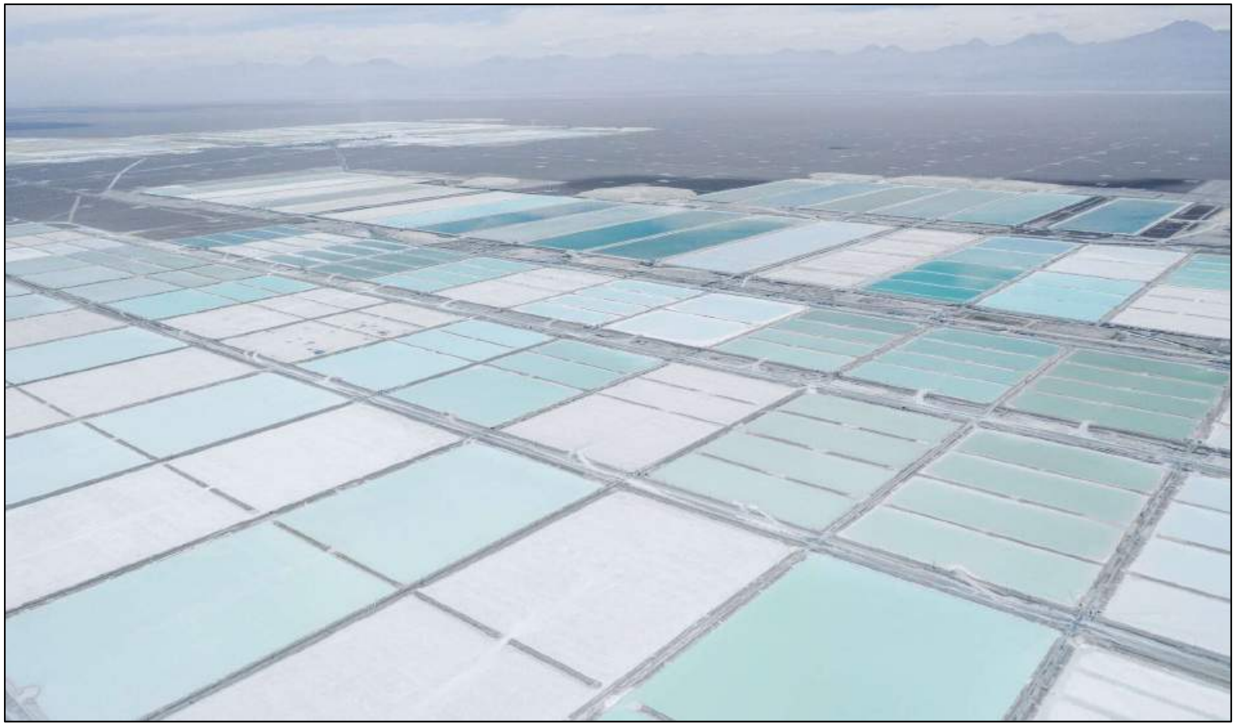
Location


Salar de Llamara
Cerro Palpana
Oyahue
Oficina Rica Aventura
Tocopilla
Toco
Chuquicamata
Aiquina
Rinconada
María Elena
Calama
Pedro de Valdivia
Veragara
Cochinoca
Bahía de Mejillones del Sur
Punta Angamos
Mejillones
Baquedano
Toconao
Susques
Salar de Atacama
Punta Tetas
Antofagasta
Palestina
San Salvador
San Antonio de los Cobres
Aguas Blancas
Augusta Victoria
Socompa
Oficina Dominador
6723
Salar de Arizaro
Bahía Nuestra Señora
Taltal
Catalina
Salar de Antofalla
Altamira
San Carlos
Cafayate
Chañaral
6103
Santa María
Diego de Almagro
Potrerillos
Inca de Oro
San Miguel de Tucumán
Caldera
Algarrobo
6880
Co. Ojos del Salado
Hualfín
Río Copiapó
Copiapó
Tierra Amarilla
Belén
Cerro Bonete
6872
Andalgalá
Los Loros
8064
Tinogasta
Carrizal Bajo
Vallenar
Salar de Pipanaco
Huasco
Chumbicha
Freirina
Chilecito
Cabo Bascuñán
Domeyko
6380
Villa Unión
1798
Cerro del Toro
+4298
Guandacol
Cruz Grande
El Tofo
La Serena
Rivadavia
Rodeo
Coquimbo
Vicuña
Valle Fértil
Tongoy
Monte Patria
Jáchal
Ovalle
San José de Jáchal
Castaño Nuevo
Río Limarí
Punitaqui
Albardón
Combarbalá
Santa Lucía
Illapel
San Juan
Villa Krause
Los Vilos
Salamanca
La Ligua
San Felipe
Los Andes
Cerro Aconcagua
Las Heras
Viña del Mar
Quilpué
6960
Godoy Cruz
Mendoza
Valparaíso
Santiago
La Paz
San Antonio
Peñaflor
Puente Alto
Cord. Domeyko
TRENCH
6000
4000
2000


San Pedro
SALAR FAULT SYSTEM
1g018
600
500
2002
2005
2031
0 5 10
km

Geosynthetics

- Ponds – 3 m (10 ft) deep, 915 m (3000 ft) x 305 m (1000 ft)
- Pond area = 275,000 to 1,000,000 m^2
- ~40 million m^2 of PVC GM



(Acevedo-Soriano and Cortes, 2021)

Geomembranes

- Exposed geomembrane lined ponds
- Ponds hold pumped brine
- 0.5 to 0.75 mm (20 to 30 mil) thick GM panels
- Panel size = 305 m (1000 ft) x 15 m (50 ft)
- Panel area = 4,651 m^2 (50,000 ft^2)

Acevedo-Soriano
and Cortes, 2021)

Geomembrane Importance

- Repair costs
- Lost revenue

Photos from:
de Melo et al. (2021)
GeoStrata March/April

Geosynthetics

- 6-7 panels deployed/day
- Panel area = 4,651 m^2 (50,000 ft^2)
- 30,250 m^2 (325,000 ft^2) of GM deployed/day
- Panels seamed using thermal wedge welders
- Field seams are tested non-destructively

Salar de Atacama

- Harsh environment

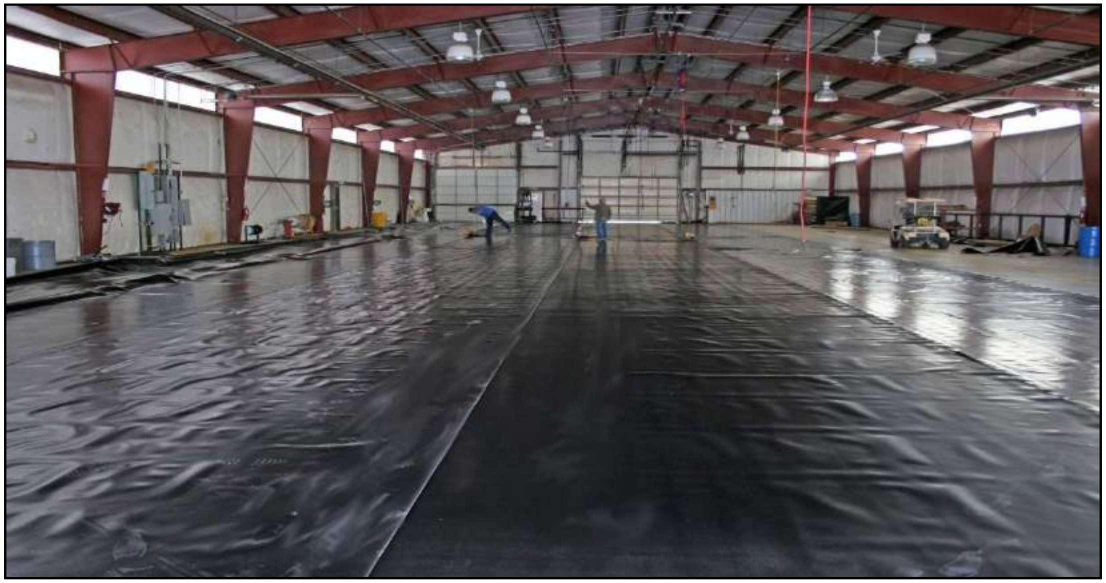
(Berube et al., 2007)

Geomembranes

- Panels weigh 3.2 tons (6,600 lbs)

Factory v. Field Seaming

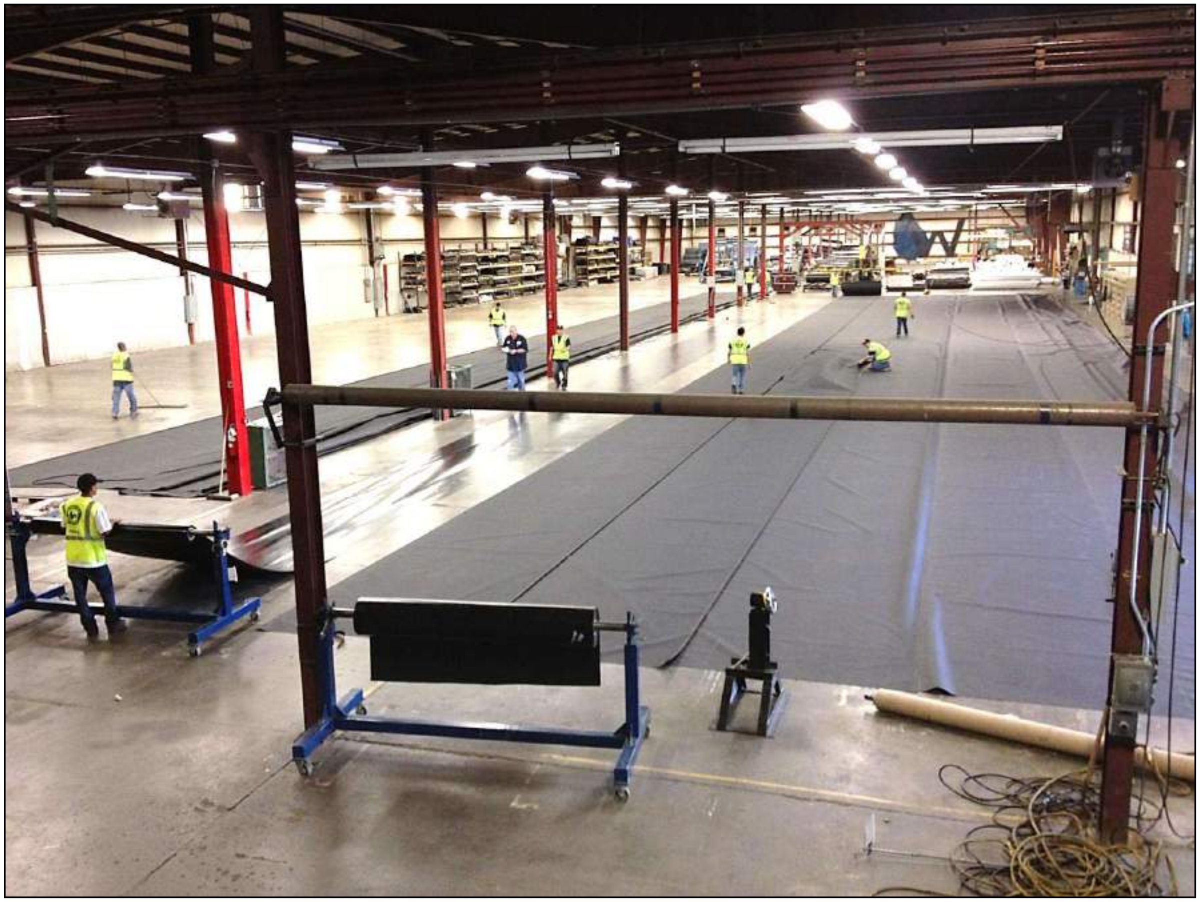
Clean & Controlled



Dirty & Uncontrolled

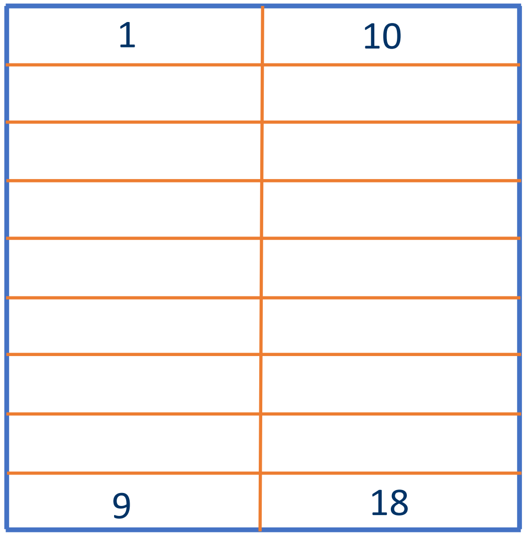
Factory v. Field Seaming

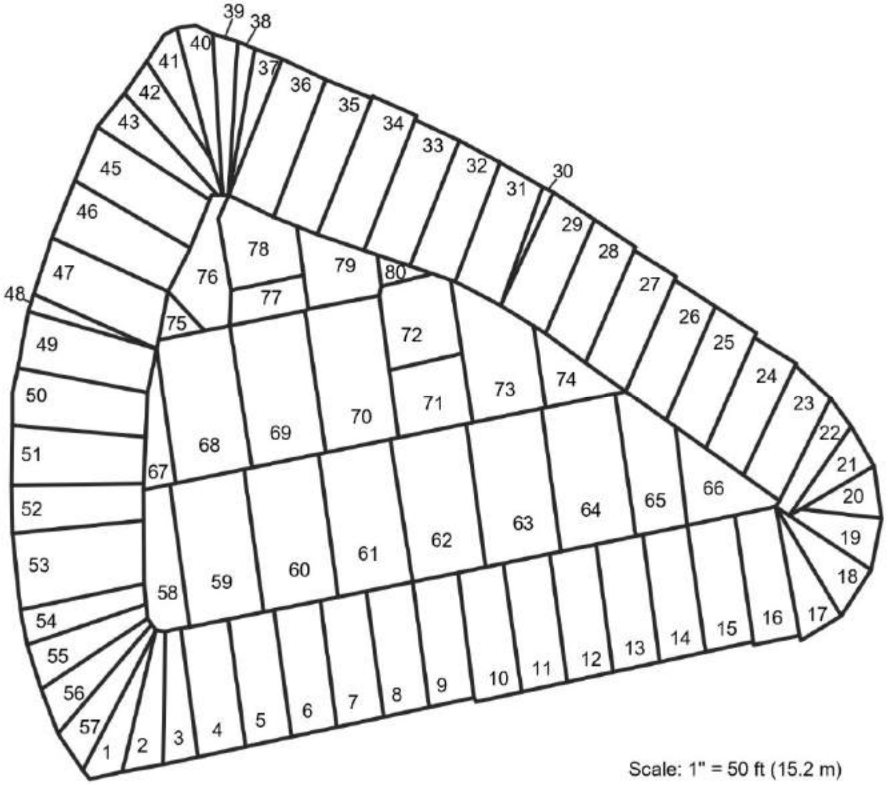
Clean & Controlled




C44
C43
C42

Panel Layout Diagram





Scale: 1" = 50 ft (15.2 m)

Geomembranes

- 410 rolls/panels shipped
- 1,271,738 m^2

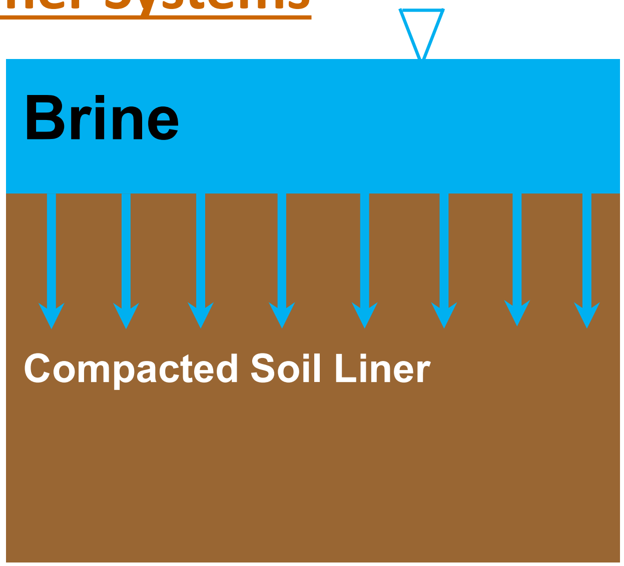
Geosynthetics

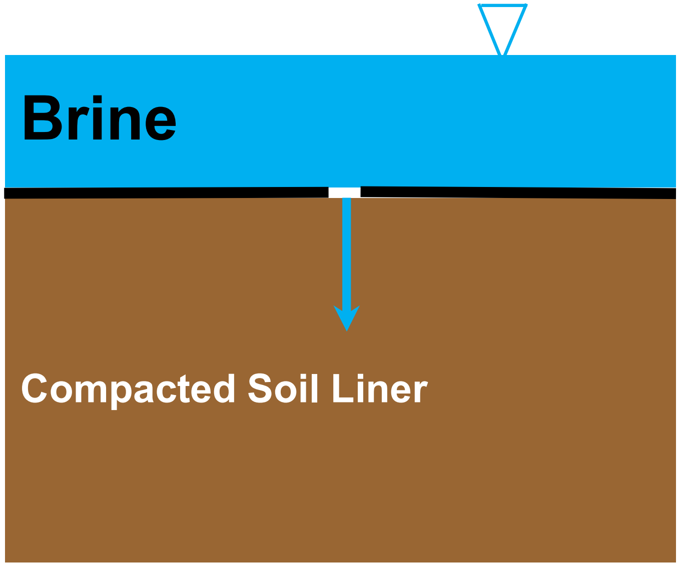
- Over 20 years of exposure

Outline

- Evaporation Mining
- Liner System Leakage
- Wrinkle Behavior & Leakage
- Thermal Expansion
- Installation
- Summary

Various Liner Systems





- ***Darcy's Law:***
- ***Q* = kiA**
- Q = **Seepage/Leakage Rate (m³/sec)**

  k = hydraulic conductivity

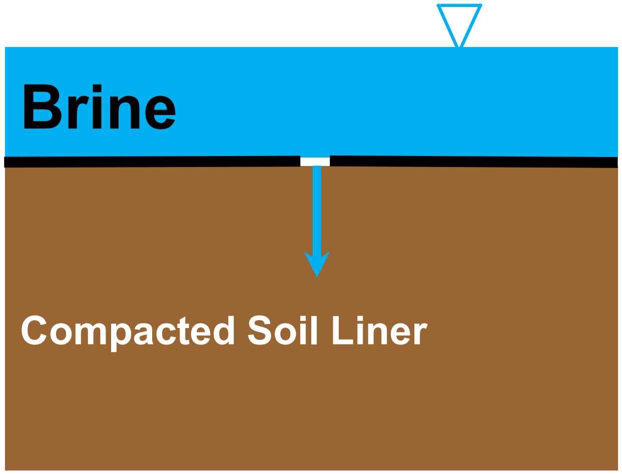
  i = hydraulic gradient

  A = area of seepage

- ***Darcy's Law:***
- ***Q* = kiA**

  A = area of defect if Intimate Contact

Defect Leakage



- **Giroud (2017) – 5th de Melo Lecture - Brazil**

$$Q = 0.21 * \left[1 + 0.1\left(\frac{h_{w-GM}}{t_{soil}}\right)^{0.95}\right] * a^{0.1} * (h_{w-GM})^{0.9} * k^{0.74}$$

Q = Leakage rate through one hole (m^3/sec)
a = hole area (m^2)
t_{soil} = thickness of compacted soil (m)
k_{soil} = hydraulic conductivity of underlying compacted soil (m/sec)
$h_{w\text{-}GM}$ = hydraulic head on geomembrane (m); regulation = 0.3 m

Defect Leakage

Hole Area* (mm²/m²)	Hole diameter (mm/m)	Holes per ha (ha^{-1})	*Int Contact Leakage Q* (m³/sec/ha)	*Int Contact Leakage Q* (lphd)
1.0/1x10^{-6}	1.0/0.001	4	1.56x10^{-8}	1.35
2.0/2x10^{-6}	2.0/0.002	4	1.68x10^{-8}	1.45
3.0/3x10^{-6}	3.0/0.003	4	1.75x10^{-8}	1.51
4.0/4x10^{-6}	2.0/0.002	4	1.80x10^{-8}	1.55

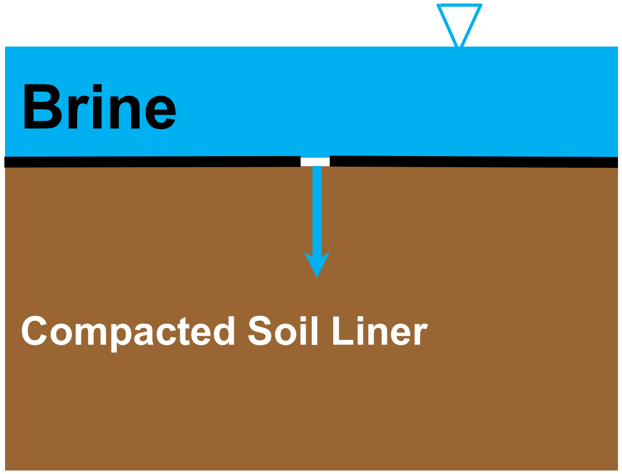
Giroud (2017) – 5th de Melo Lecture – Brazil
- 4 holes per hectare
- hole area of 4 mm²

Other Input Parameters
- h_{GM} = 0.3 m
- k_{soil} = 1x10^{-9} m/sec
- t_{soil} = 0.6 m

Outline

- Evaporation Mining
- Liner System Leakage
- Wrinkle Behavior & Leakage
- Thermal Expansion
- Installation
- Summary

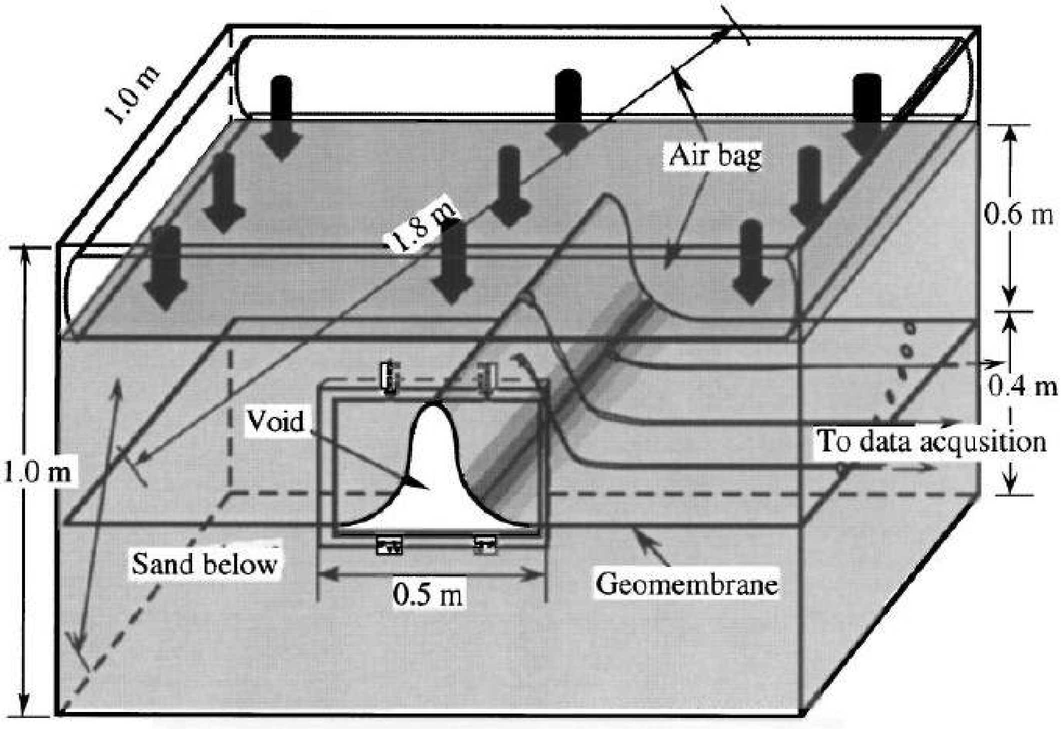
Intimate Contact

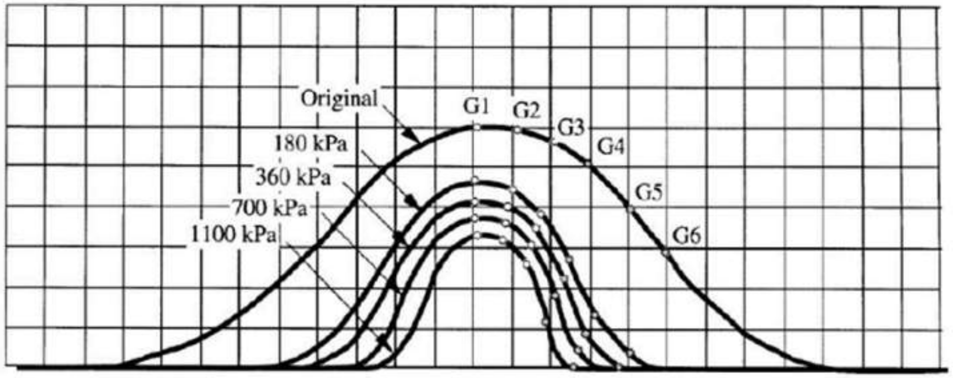


Brine

Compacted Soil Liner

Intimate Contact





Sand below 40 mil HDPE

- Wrinkles as small as 0.5" do not flatten
- Wrinkles fold over and create creases

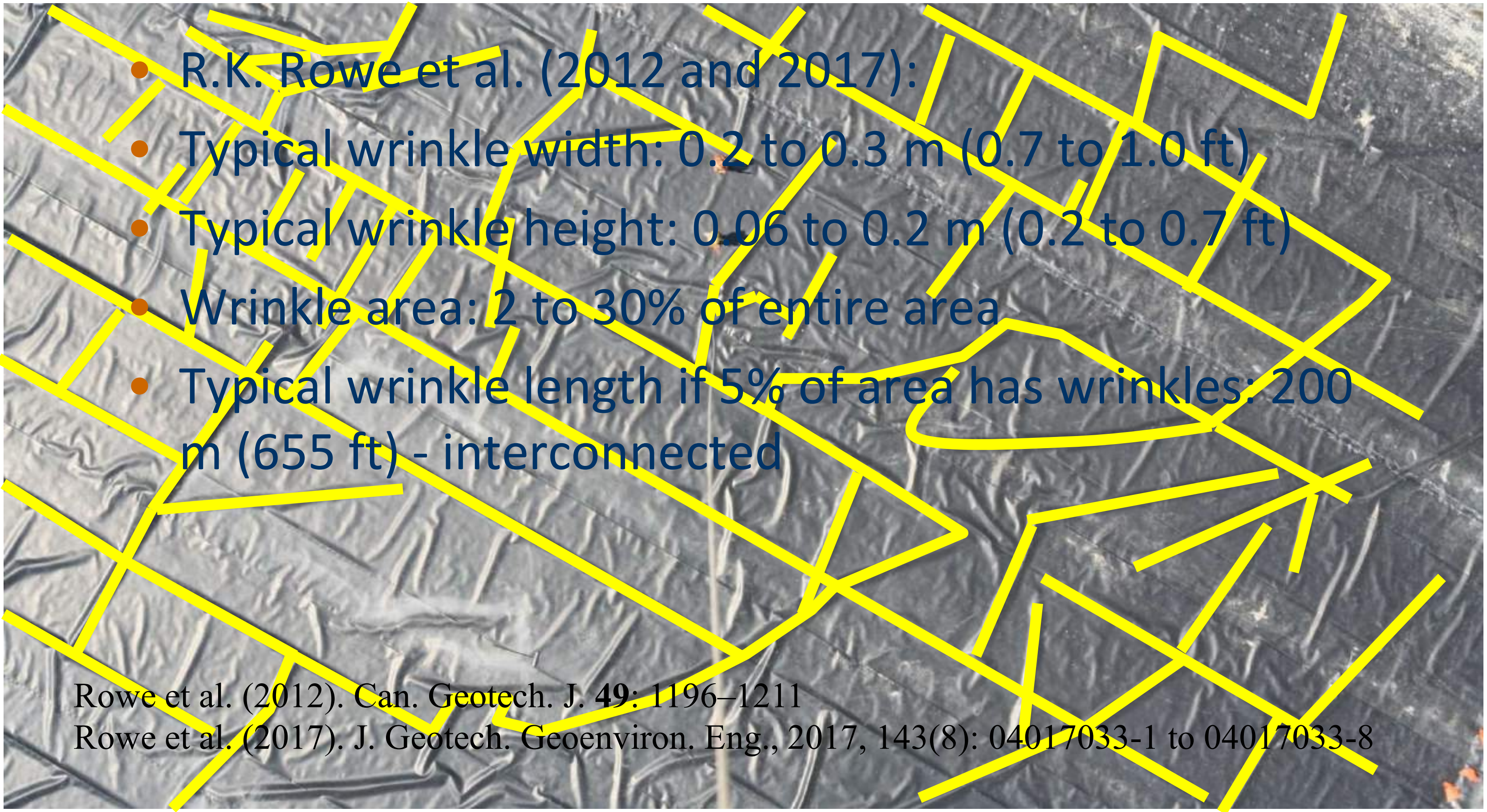
Soong, T.-Y., and Koerner, R. M. 1998. "Laboratory study of high density polyethylene waves." *Proc., 6th Int. Conf. on Industrial Fabrics Association International, Geosynthetics*, St. Paul, Minn., 301–306.

Wrinkle Behavior

- **R.K. Rowe et al. (2012 & 2017):**

Interconnected Wrinkles

- **R.K. Rowe et al. (2012 & 2017):**



- R.K. Rowe et al. (2012 and 2017):
- Typical wrinkle width: 0.2 to 0.3 m (0.7 to 1.0 ft)
- Typical wrinkle height: 0.06 to 0.2 m (0.2 to 0.7 ft)
- Wrinkle area: 2 to 30% of entire area
- Typical wrinkle length if 5% of area has wrinkles: 200 m (655 ft) - interconnected

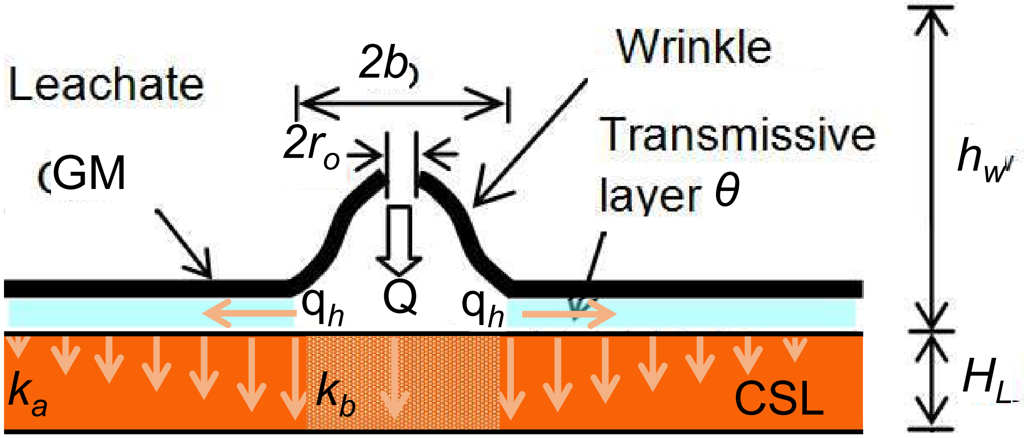
Rowe et al. (2012). Can. Geotech. J. **49**: 1196–1211
Rowe et al. (2017). J. Geotech. Geoenviron. Eng., 2017, 143(8): 04017033-1 to 04017033-8

Interconnected Wrinkles

- **R.K. Rowe et al. (2012 & 2017):**
- Typical wrinkle width: 0.2 to 0.3 m (0.7 to 1.0 ft)
- Typical wrinkle height: 0.06 to 0.2 m (0.2 to 0.7 ft)
- Wrinkle area: 2 to 30% of entire area
- Typical wrinkle length if 5% of area has wrinkles: 200 m (655 ft) – interconnected
- Wrinkles dominate behavior

Rowe et al. (2012). Can. Geotech. J. **49**: 1196–1211
Rowe et al. (2017). J. Geotech. Geoenviron. Eng., 2017, 143(8): 04017033-1 to 04017033-8

Wrinkle Leakage



$$Q = (2b\ L\ k_b\ h_d/H_L) + 2q_h$$

$$q_h = L\ \theta\ i_h$$

$$Q = L\ [2b^{*}k_b + 2(k_a H_L\ \theta)^{0.5}]\ h_d / H_L$$

Rowe (1998):

Q: flow through GM

2b : width of wrinkle

L: wrinkle length

k_b: hyd. conductivity of CSL/GCL below wrinkle

k_a: hyd. conductivity in contact with GM

h_d: Head loss (h_d=h_w+H_L)

h_w: Water/leachate level

H_L: Soil liner thickness

θ: transmissivity b/t GM and compacted soil liner (CSL)/GCL

Wrinkle Leakage

- Giroud (1997)
- **Good Contact is:**
  - GM w/as few wrinkles as possible on smooth compacted soil
  - Rowe (1998) $\theta = 1.6\text{x}10^{-8}\ \text{m}^2/\text{s}$
- **Poor Contact is:**
  - GM w/a number of wrinkles on rough compacted soil
  - Rowe (1998) $\theta = 1.0\text{x}10^{-7}\ \text{m}^2/\text{s}$

Wrinkle Leakage

Wrinkle Length (m/ha)	Wrinkle Width (m)	Holes per Wrinkle	*Leakage Q* (m³/sec/ha)	*Leakage Q* (lphd)
60	0.2	1	4.7×10^{-8}	4.1
230	0.4	1	2.5×10^{-7}	22.0
500	0.6	1	7.1×10^{-7}	60.9
1000	0.8	1	1.7×10^{-6}	149.0

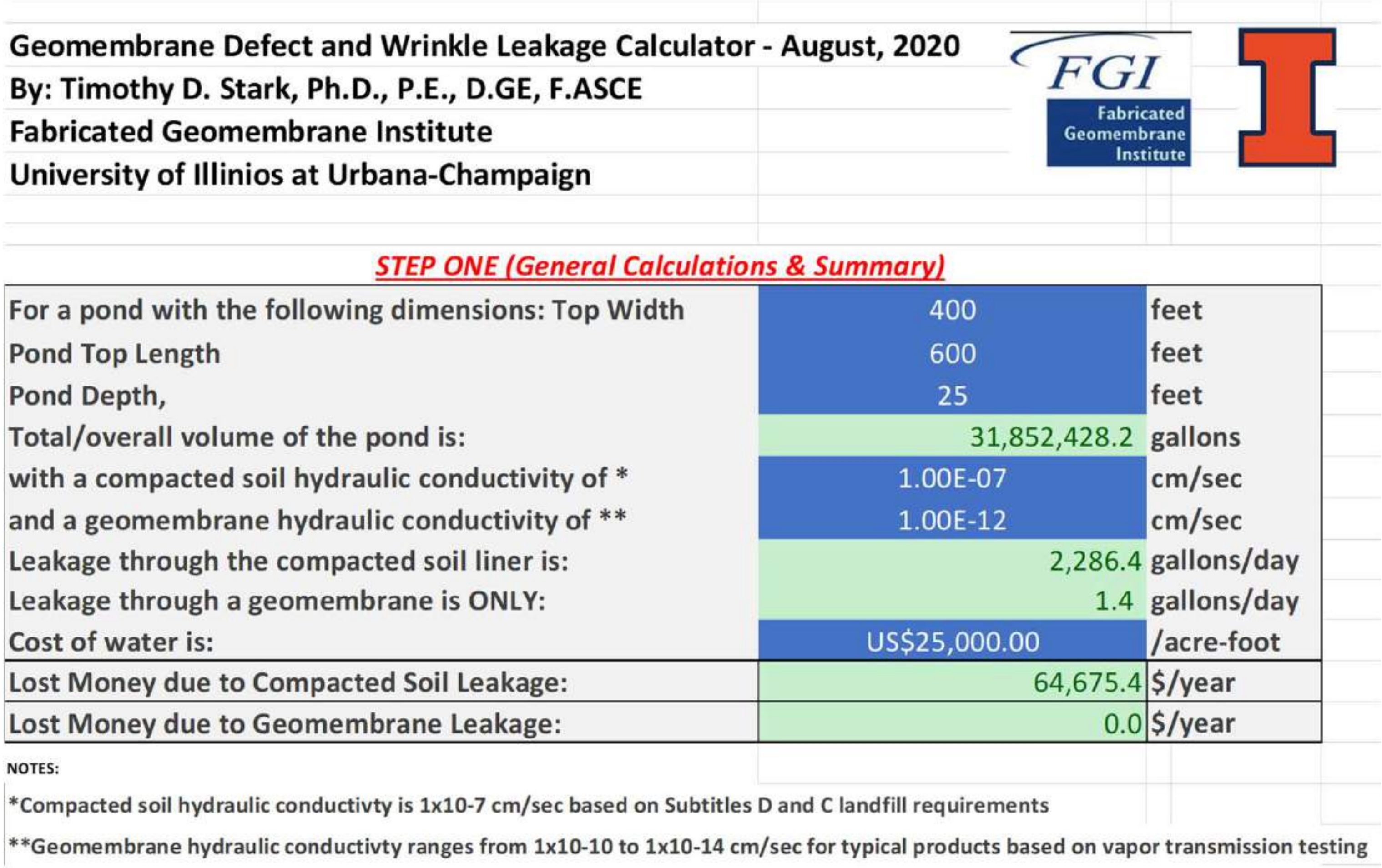
Intimate contact & four holes/hectare ~1.5 lphd
One wrinkle & one hole ~ 100*no wrinkle

Rowe (2012):

GCL $k_b = 5 \times 10^{-11}$m/s, GCL $k_a = 2 \times 10^{-10}$m/s, $H_L = 0.01$m, $\theta = 3 \times 10^{-11}$ m²/s;

CSL $k_b = 1 \times 10^{-9}$ m/s, CSL $k_a = 2 \times 10^{-10}$m/s, $H_L = 0.6$m, $\theta = 1.0 \times 10^{-7}$ m²/s;

Wrinkle Leakage



Geomembrane Defect and Wrinkle Leakage Calculator - August, 2020
By: Timothy D. Stark, Ph.D., P.E., D.GE, F.ASCE
Fabricated Geomembrane Institute
University of Illinios at Urbana-Champaign

STEP ONE (General Calculations & Summary)

For a pond with the following dimensions: Top Width	400	feet
Pond Top Length	600	feet
Pond Depth,	25	feet
Total/overall volume of the pond is:	31,852,428.2	gallons
with a compacted soil hydraulic conductivity of *	1.00E-07	cm/sec
and a geomembrane hydraulic conductivity of **	1.00E-12	cm/sec
Leakage through the compacted soil liner is:	2,286.4	gallons/day
Leakage through a geomembrane is ONLY:	1.4	gallons/day
Cost of water is:	US$25,000.00	/acre-foot
Lost Money due to Compacted Soil Leakage:	64,675.4	$/year
Lost Money due to Geomembrane Leakage:	0.0	$/year

NOTES:

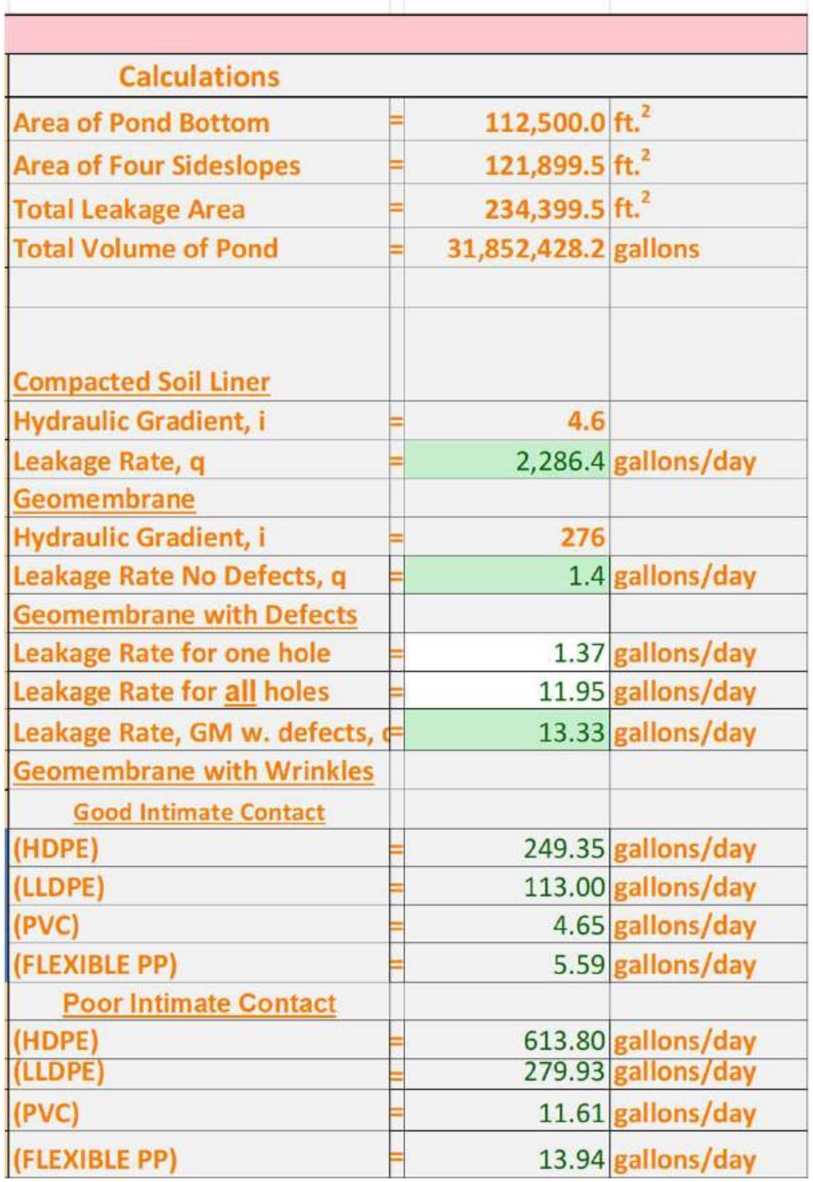
*Compacted soil hydraulic conductivty is 1x10-7 cm/sec based on Subtitles D and C landfill requirements

**Geomembrane hydraulic conductivty ranges from 1x10-10 to 1x10-14 cm/sec for typical products based on vapor transmission testing

Wrinkle Leakage

STEP TWO (Detailed Information)					
Leakage Rate Calculator from a Water Pond					
Input Parameters					
Pond Geometry	Depth	=	25	ft.	
	Pond Freeboard	=	2	ft.	Water Below Pond Surface
	Pond Top Width	=	400	ft.	
	Pond Top Length	=	600	ft.	
	Side Slope Geometry				
	H		V		
	3	:	1		
Material Properties	Compacted Soil	=	5	ft.	Thickness
	Hydraulic Conductivity, k	=	1.00E-07	cm/sec	
	Geomembrane	=	1	in.	Thickness
	Hydraulic Conductivity, k	=	1.00E-12	cm/sec	
	Geomembrane Defects				
	# of holes per hectare	=	4	with "high Inspection"	
	Number of holes	=	9	For the total leakage Area	
	Area of a hole	=	4.00E-06	m^2	
	Hydraulic head on GM	=	0.3	m	
	Wrinkle dimensions		Width (ft.)	Length (ft.)	
	HDPE	=	0.85	655	
	LLDPE	=	0.5	300	
	PVC	=	0.1	12.5	
	Flexible PP	=	0.15	15	
	Head Loss	=	27	ft.	
	Transmissivity	=	1.6E-08	m^2/s	Good Contact
		=	1.00E-07	m^2/s	Poor Contact

Wrinkle Leakage



Calculations			
Area of Pond Bottom	=	112,500.0	ft.^{2}
Area of Four Sideslopes	=	121,899.5	ft.^{2}
Total Leakage Area	=	234,399.5	ft.^{2}
Total Volume of Pond	=	31,852,428.2	gallons
Compacted Soil Liner			
Hydraulic Gradient, i	=	4.6	
Leakage Rate, q	=	2,286.4	gallons/day
Geomembrane			
Hydraulic Gradient, i	=	276	
Leakage Rate No Defects, q	=	1.4	gallons/day
Geomembrane with Defects			
Leakage Rate for one hole	=	1.37	gallons/day
Leakage Rate for all holes	=	11.95	gallons/day
Leakage Rate, GM w. defects,	=	13.33	gallons/day
Geomembrane with Wrinkles			
Good Intimate Contact			
(HDPE)	=	249.35	gallons/day
(LLDPE)	=	113.00	gallons/day
(PVC)	=	4.65	gallons/day
(FLEXIBLE PP)	=	5.59	gallons/day
Poor Intimate Contact			
(HDPE)	=	613.80	gallons/day
(LLDPE)	=	279.93	gallons/day
(PVC)	=	11.61	gallons/day
(FLEXIBLE PP)	=	13.94	gallons/day

Effect of Wrinkles

- Observed leakage 100 to 1,000* greater than calculated
- Causes localized stresses and strains
- Location of stress cracks (Soong and Koerner, 1997)
- Interference with drainage above
- Bentonite migration if GCL present
- Increase mining damage potential
- Leak location surveys = ?

Effect of Wrinkles

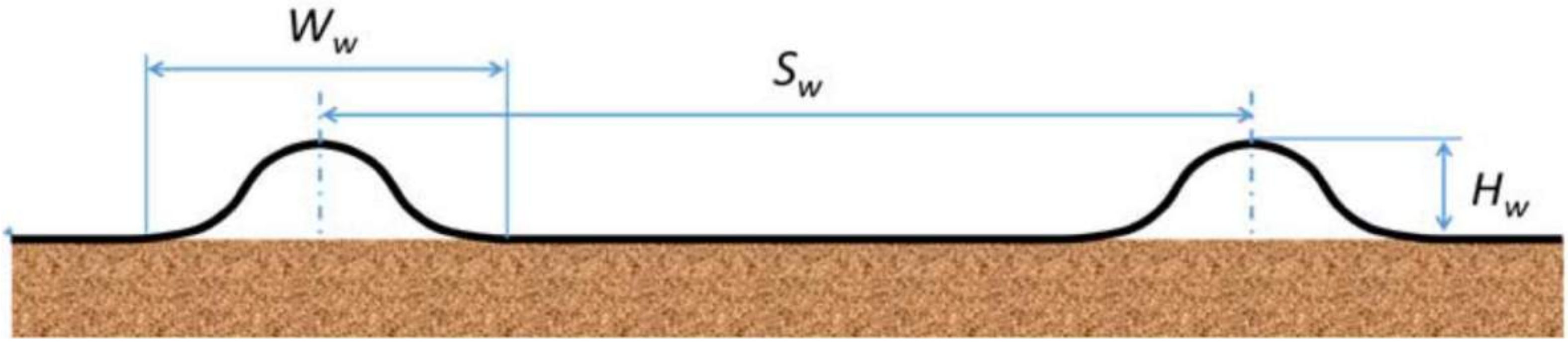
- HDPE
- Large wrinkles ~17.8 to 22.9 cm (7 to 9 inches) tall
- - 3 to 6 m (10 to 20 feet) apart
  - impede flow
  - stress cracking

Effect of Wrinkles

- Low stiffness
- PVC Geomembranes
- Small & Close together wrinkles
- 2.5 to 5 cm (1 to 2 inches) tall
- Not Connected

Effect of Wrinkles

- Giroud & Wallace (2016) – Geo-Americas



- Unreinforced GMs

$$H_w = \frac{1}{2} * \left[\frac{\alpha * \Delta T * E * t_{GM}^2}{\rho * g * \tan(\delta)}\right]$$

$\boldsymbol{H_w = wrinkle\ height\ (m)}$,
$\alpha = \boldsymbol{GM\ coefficient\ of\ thermal\ expansion}\ (^0\boldsymbol{C} - ^1)$,
$\Delta\ \boldsymbol{T} = \boldsymbol{change\ in\ Temperature}\ (^0\boldsymbol{C})$,
$\boldsymbol{E = Young's\ Modulus\ (Pa)}$,
$\mathbf{t}_{\boldsymbol{m}} = \boldsymbol{GM\ thickness\ (m)}$,
$\boldsymbol{g = 9.81\ m/s^2}$,
$\rho = \boldsymbol{GM\ density\ (kg/m^3)}$, and
$\delta = \boldsymbol{CSL\ or\ \frac{GCL}{GM}\ interface\ friction\ angle}\ (^0)$.

Effect of Wrinkles

- Giroud & Wallace (2016) – Geo-Americas

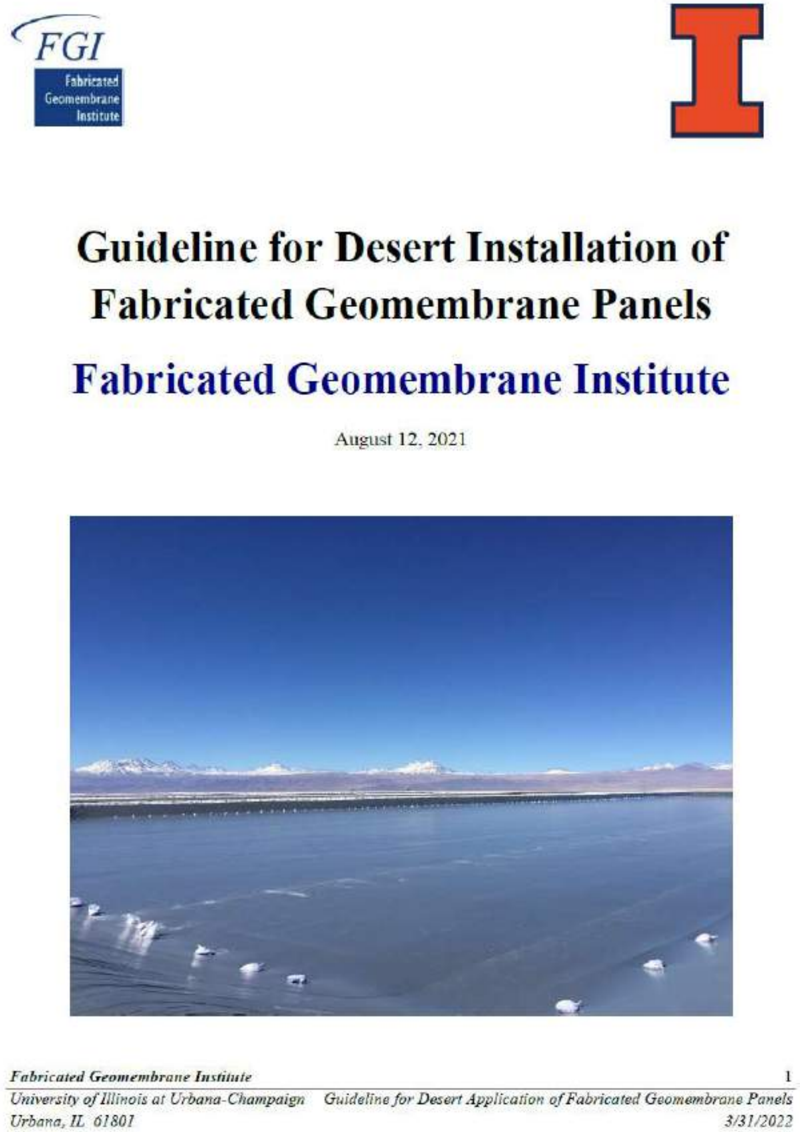
Unreinforced GM Polymer (Black)	Coeff. Thermal Exp. ($^0C^{-1}$)	GM Bending Modulus (MPa)	GM Density (kg/cm^3)	GM Thick-ness (mm)	GM Inter-face friction (deg)	*Wrinkle Height,* H_w (mm)
HDPE-S	1.9×10^{-4}	250	940	1.5	10	92
LLDPE-S	1.9×10^{-4}	200	850	1.0	10	58
fPP	8.9×10^{-5}	150	750	1.0	22	27
PVC#1-Grey	1.3×10^{-4}	125	700	0.75	20	12

$$g = 9.81\ m/s^2$$
$$\Delta T = 45^0 C$$

HDPE ~ 8* higher wrinkle than PVC

Outline

- Evaporation Mining
- Liner System Leakage
- Wrinkle Behavior & Leakage
- Thermal Expansion
- Installation
- Summary



FGI
Fabricated Geomembrane Institute

Guideline for Desert Installation of Fabricated Geomembrane Panels

Fabricated Geomembrane Institute

August 12, 2021

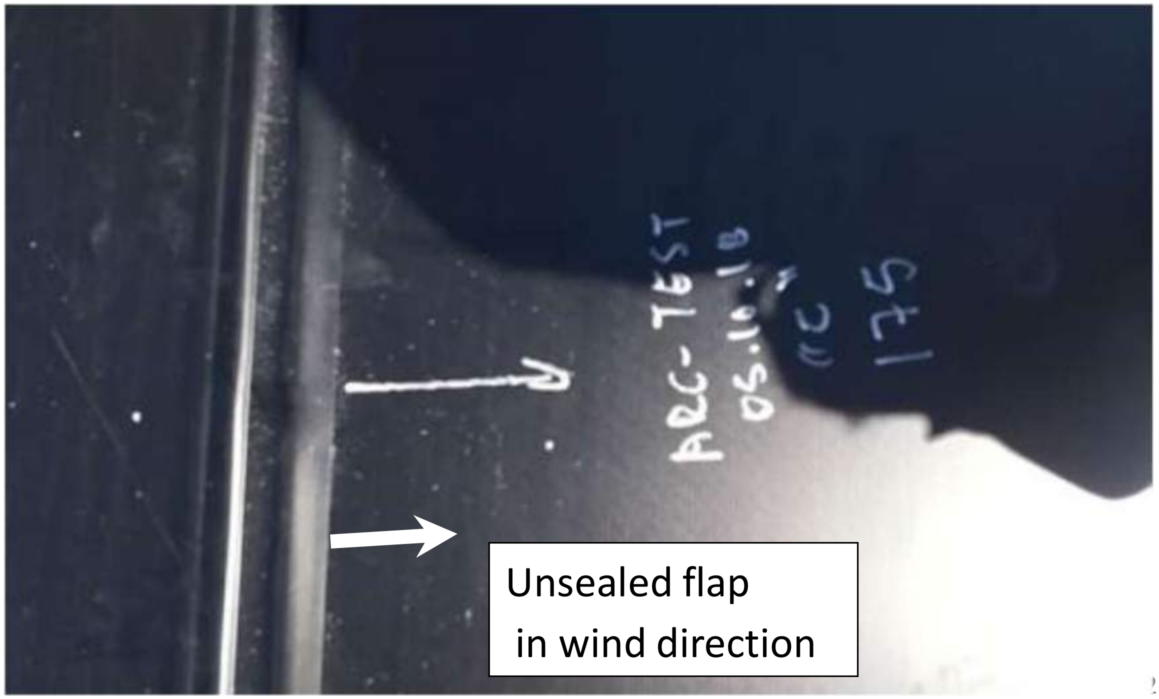
Fabricated Geomembrane Institute 1
University of Illinois at Urbana-Champaign *Guideline for Desert Application of Fabricated Geomembrane Panels*
Urbana, IL 61801 *3/31/2022*

Rolling, Packaging, and Shipping

- Pallet should extend past finished dimensions
- Even panels
- Strap cushions
- Good labeling
- Pallet should extend past finished dimensions
- No protruding objects or nails
- Weather resistant covering
- Store in shade (10°C (50^{0}F) and 40°C (105^{0}F))

GM Deployment

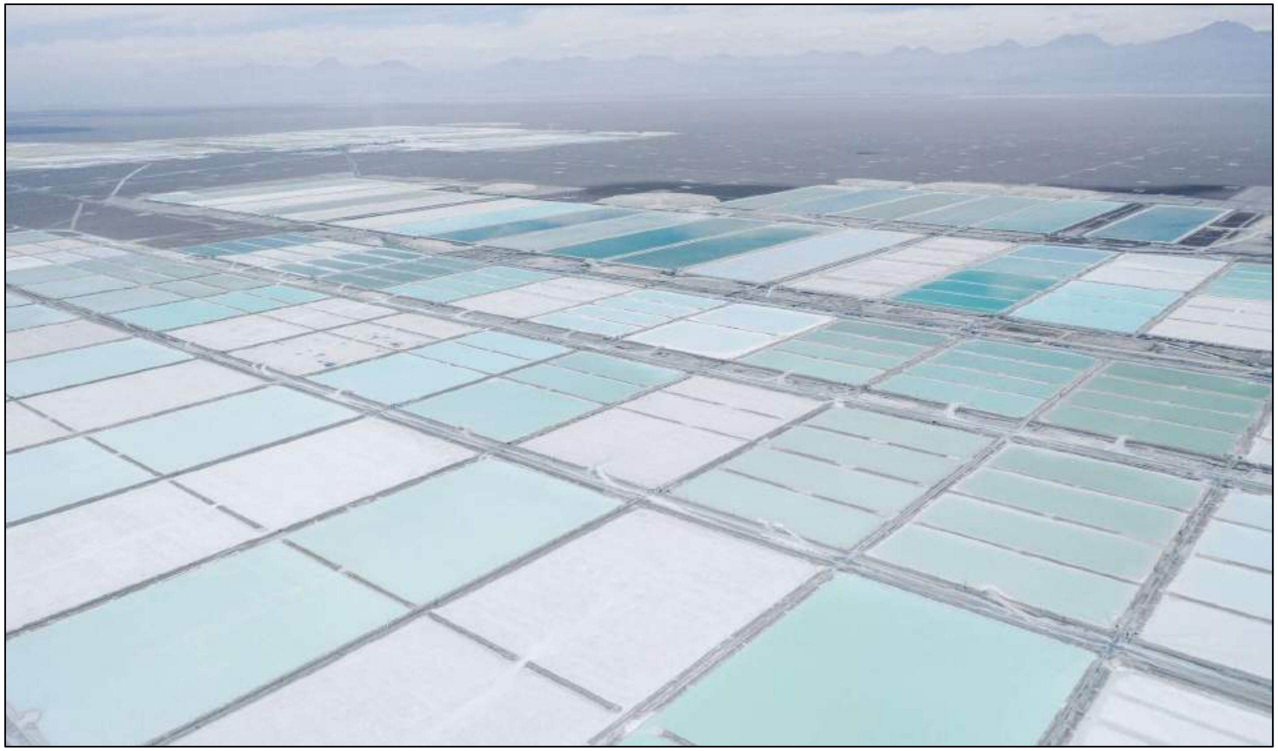
- No rocks or salt crystals larger than 9.5 mm (3/8”)
- No water or mud
- Wind speed ~ 5 km/hour (3 mph) & not > 30 km/hour (18 mph)
- Deploy when ambient and GM temperatures are 10°C (50^0F) to 40°C (105^0F)
- Unroll or unfold 1/3 (100 m) & allow acclimation – 3 pauses if 300 m
- Embossed/textured side in contact with subgrade
- Unsealed flap in wind direction
- Ballast GM quickly



Unsealed flap
in wind direction

Summary

- Evaporation mining increasing
- Minimum GM
- No defects
- Leak location
- Wrinkles:
    - Remain
    - No intimate contact
    - Pond liquid
    - Increase leakage
    - Impact leak location surveys



(Acevedo-Soriano and Cortes, 2021)

GEOANZ #1 ADVANCES IN GEOSYNTHETICS

7–9 JUNE 2022 | BRISBANE CONVENTION & EXHIBITION CENTRE