Bio-mediated Geotechnics for Hazard Mitigation, Environmental Protection, and Infrastructure Construction

58th Karl Terzaghi Lecture
22 March 2022

Edward Kavazanjian, Jr., Ph.D., P.E., D.GE, NAE, Dist.M.ASCE
Director, Center for Bio-mediated and Bio-inspired Geotechnics
Regents Professor and Ira A. Fulton Professor of Geotechnical Engineering
Arizona State University

CBBG Center for Bio-mediated & Bio-inspired Geotechnics

ASU Ira A. Fulton Schools of Engineering
Arizona State University

What is Bio-mediated Geotechnics?

One component of the emerging sub-discipline of Biogeotechnical Engineering

- Addresses processes managed and controlled through biogeochemistry
- A companion to bio-inspired processes: biological principles employed to develop abiotic solutions

Disparate processes linked by a common premise

What is a Bio-mediated Process?

me·di·ate *verb*

To bring about (a result such as a physiological effect) [Source: Oxford Languages]

Bio-mediated geotechnical process: a biogeochemical reaction that (beneficially) changes the geotechnical behavior of soil or rock

- May involve a living organism (e.g., microbe, fungi) or biological material (e.g., enzyme)
- Broadly interpreted to include abiotic natural processes (interpreting Bio as in Biosphere)

The Biogeotechnical Premise

Nature has developed many elegant and effective biogeotechnical processes

- 3.8 billion years of trial and error

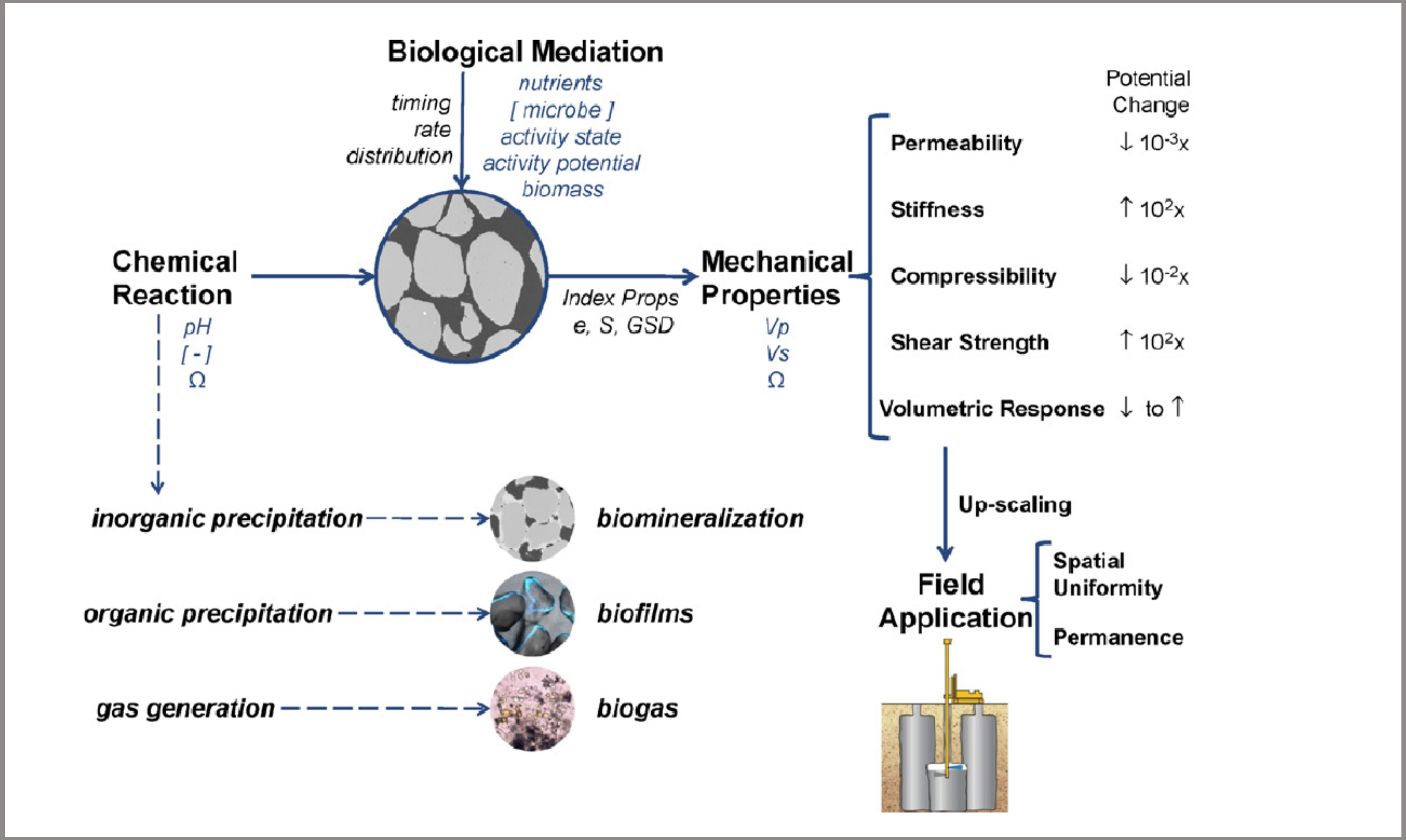
We can learn from nature how to use these processes to address a variety of geotechnical problems

Wikimedia Commons

Graphic courtesy of Carlos Santamarina

Graphic courtesy of Carlos Santamarina

Bio-mediated Soil Improvement (DeJong, et al. 2010)



Beneficial Bio-mediated Geotechnical Processes

Mineral precipitation

- Cementation, sequestration, densification, permeability reduction

Biogas generation

- Permeability reduction, “undrained” behavior change

Biofilms (organic precipitation)

- Permeability reduction, corrosion protection

Transformation of chemical species

- Soil and groundwater remediation

Mineral Precipitation

Most investigated bio-mediated process

Carbonate precipitation most studied (geotechnically)

- MICP (**M**icrobially-**I**nduced **C**arbonate **P**recipitation) most common
- EICP (**E**nzyme-**I**nduced **C**arbonate **P**recipitation) also popular
- MIDP (Microbially-Induced Desaturation and Precipitation) also under investigation (primarily for desaturation)

Many other mineral precipitation processes

- Iron, phosphorus, salt

Calcium Carbonate Precipitation

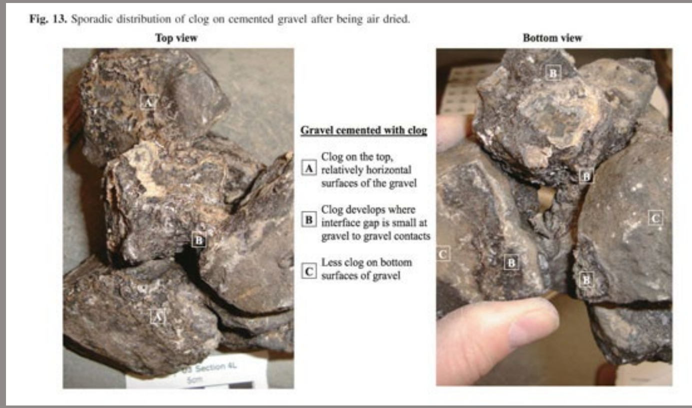
"Biogeo Alchemy" Turning sand into sandstone via precipitation of $CaCO_3$ (Calcite)

- At least 7 different natural processes (Karatas, 2008)

JennBredemeier.deviantart.com

http://top10for.com/top-10-most-iconic-british-landmarks/

https://upload.wikimedia.org/wikipedia/commons/5/59/Cliff_House_from_Ocean_Beach.jpg



McIsaac and Rowe (2008) "Clogging of unsaturated gravel permeated with landfill leachate," Canadian Geotechnical Journal

CBBG Center for Bio-mediated & Bio-inspired Geotechnics

ASU Ira A. Fulton Schools of Engineering Arizona State University

Potential Applications of $CaCO_3$ Precipitation

JennBredemeier.deviantart.com

Foundation support

Fugitive dust control

Liquefaction mitigation

Stabilization of underground openings

Subgrade stabilization

Slope stabilization

Surface water erosion control

Scour protection

“Bio-bricks”

… and more

MICP

Based upon hydrolysis of urea (ureolysis)

- Reaction catalyzed by enzyme urease from microbes
- Creates carbonate ions (CO_3^{2-}) in solution

Calcium ions (Ca^{2+}) in solution (typically from $CaCl_2$) combine with CO_3^{2-} to form $CaCO_3$

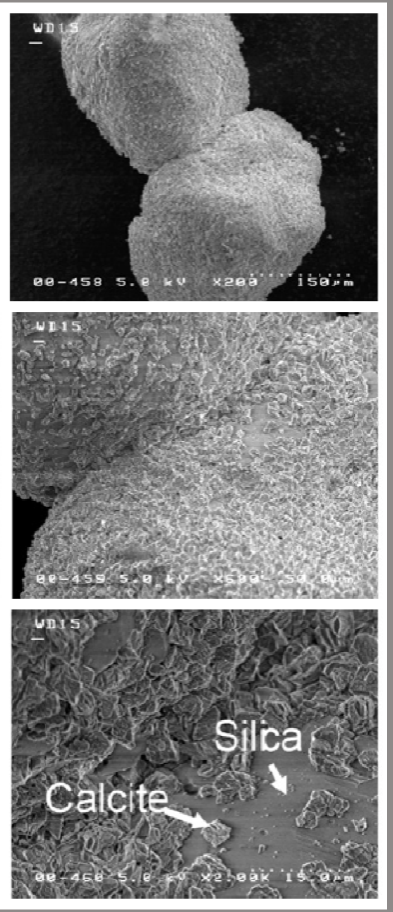
- Ammonium chloride (NH_4Cl) by-product

Most popular bio-mediated process

- 438 Google Scholar citations in Jan, Feb 2022
- 2330 citations since 2021

MICP (via Ureolysis)

- Ureolytic microbes from stimulation or augmentation
- Initial work by Kucharski (circa 1990s)
  - "CIPS" (**C**alcite **I**nsitu **P**recipitation System)
- Notable investigators include Whiffin, van Paassen, Santamarina, DeJong, Montoya, Gomez, Chu, Soga



DeJong et al. (2010)

EICP (via ureolysis)

Same biochemical process as MICP

- Hydrolysis of urea catalyzed by urease

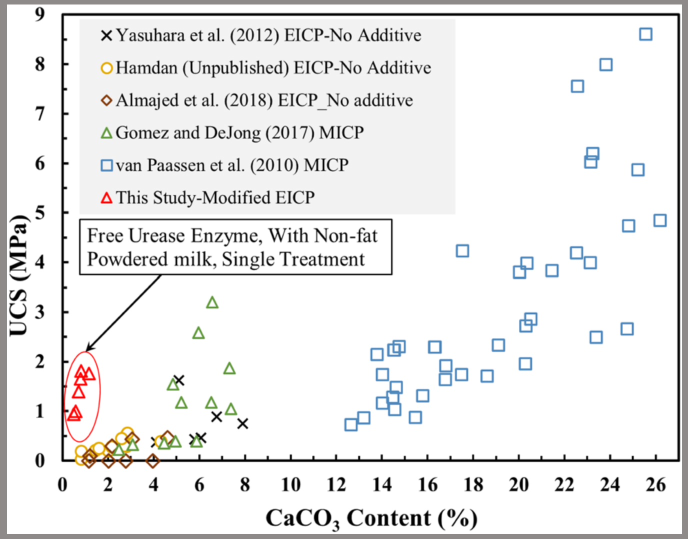
Uses free urease

- Extracted from plants or microbes

Powdered milk additive provides for high strength at low carbonate content in some soils

- Mechanism not well understood

Speed of reaction can be an issue



Almajed et al. (2019) "Enzyme Induced Biocementated Sand with High Strength at Low Carbonate Content", Scientific Reports, Vol. 9: 1135, 6 pages

MICP Advantages & Disadvantages

Advantages:

- Extensively studied process
  - Consistent results in a wide variety of soils
  - May be able to reactivate microbial community
    - Could be self healing

Disadvantages

- Multiple cycles required for significant strength gain
  - Embodied energy (carbon footprint) may be similar to portland cement
  - NH_4Cl by-product can be problematic
    - Some applications require fewer treatments (mitigating the issue), e.g., liquefaction mitigation, dust control
  - Partilce (pore) size limitations due to size of microbes
    - Limit is relatively clean fine sand (10-15% fines)

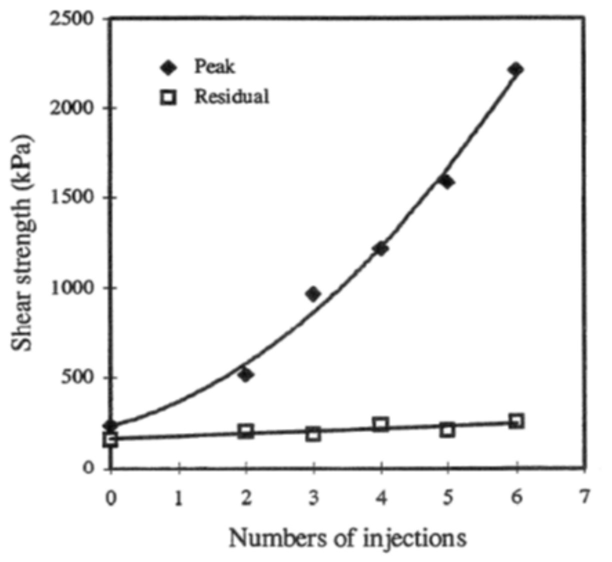


Figure 8. Shear strength (peak and residual) versus number of CIPS injections for Calcareous M sand specimens

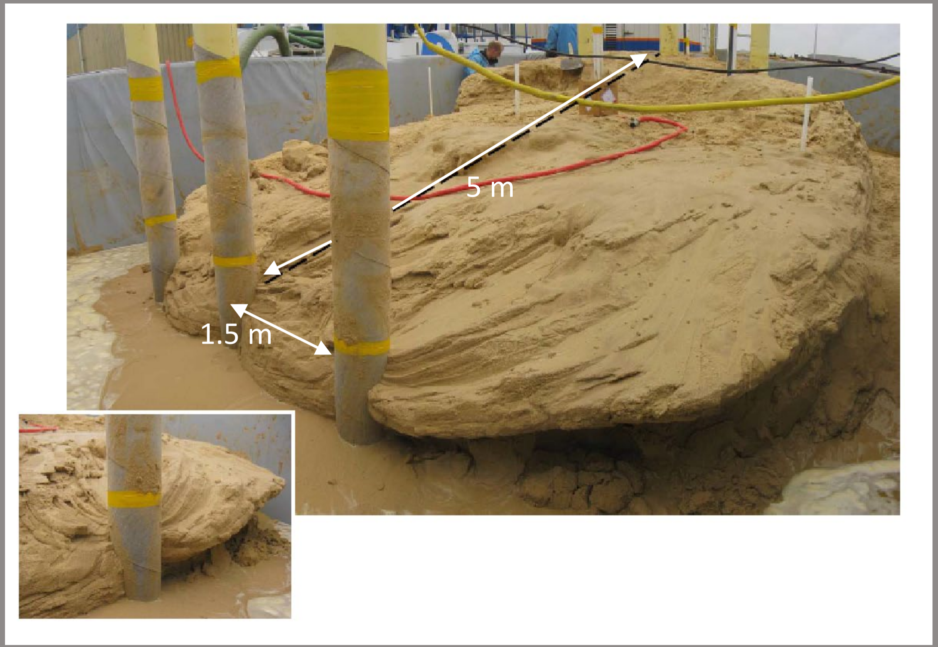
Kucharski et al. (1996) "Laboratory Evaluation of CIPS Cemented Calcareous and Silica Sands" Proc. &th Australia New Zealand Conference on Geomechanics

CBBG Center for Bio-mediated & Bio-inspired Geotechnics

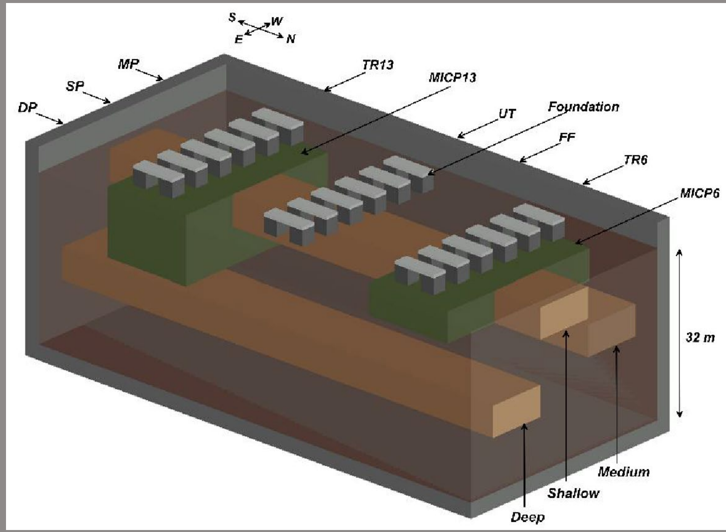
ASU Ira A. Fulton Schools of Engineering Arizona State University

Experience with MICP

Lots of lab testing, some centrifuge and large-scale testing, limited field (or field scale) trials



Van Paassen et al. (2010) "… Large-Scale Biogrout Experiment" ASCE JGGE



Zamani et al. (2021) "MICP Treatment to Mitigate Soil Liquefaction …" GSP 324

CBBG Center for Bio-mediated & Bio-inspired Geotechnics

ASU Ira A. Fulton Schools of Engineering Arizona State University

EICP Advantages and Disadvantages

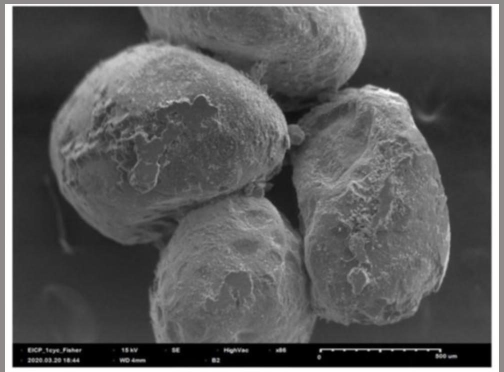
Advantages:

- Less substrate, lower cost, maybe “One and done”
- Less ammonium chloride by-product
- All carbon goes to carbonate formation
- Enzyme is smaller than microbes
  - Can penetrate finer-grained soil

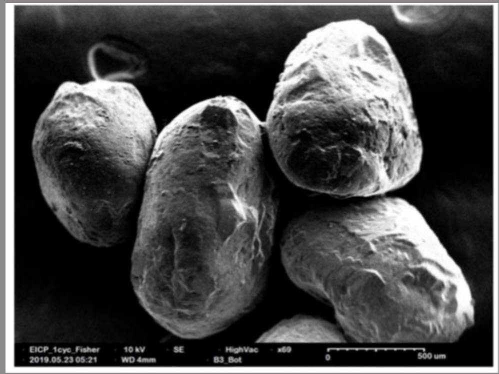
Disadvantages

- Inconsistent biocementation
  - Mechanism not well understood
- Reaction can be too fast
  - May lead to “bio-clogging”

Ottawa 20/30 Sand B1: UCS = 1.6 MPa



Ottawa 20/30 Sand B2: UCS = 0.7 MPa



Ottawa 20/30 Sand B3: UCS = 0.2 MPa

Krishnan et al. (2021) “Variability in the Unconfined Compression Strength of EICP-Treated ‘Standard’ Sand” ASCE JGGE

Experience with EICP

Lab data starting to accumulate

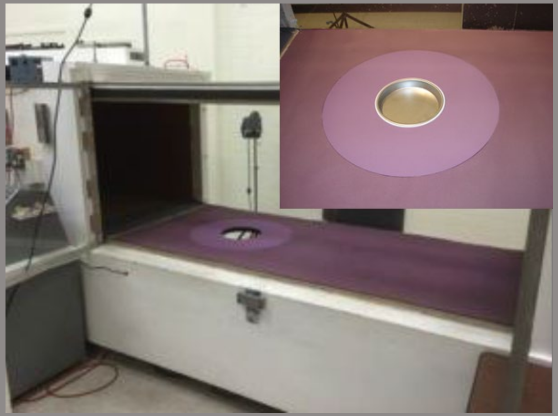
- Several investigators studying ways to control (slow) reaction
  - Reducing pH of solution (Cui et al., 2021)
  - Chilling the EICP solution (Javadi, 2021)

Some studies using fine-grained soils

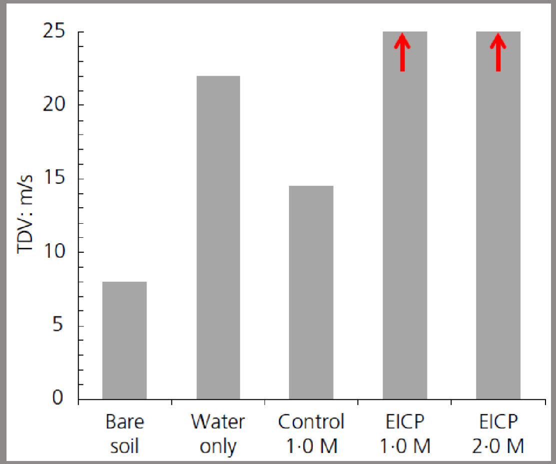
  - Results inconclusive/unconvincing

Wind tunnel testing and field trials on fugitive dust control

Field scale EICP columns



ASU/NASA Planetary Wind Tunnel



Threshold Detachment Velocity of Arizona Silty Sand, from Hamdan and Kavazanjian, Geotechnique (2016)

Fugitive Dust Control

Worldwide air quality problem
- Due primarily to wind-blown soil
    - Not industrial emissions

Plagues many arid/semi arid areas
- Southwest US
- Eastern China
- North Africa

Best available technology: water, salt

Google Scholar Citations
- EICP: 70 in 2021; 14 in 2022
- MICP: 106 in 2021; 21 in 2022

www.Dreamstime.com

Biogeotechnical Fugitive Dust Control (using EICP or MICP)

Concept: Create a wind-erosion resistant carbonate crust using a sprayed-on EICP solution

Advantage:

- "One and done" (but for how long?)

Disadvantages

- Initial cost
- Potential environmental impact

EICP Fugitive Dust Control Test Sections

Work in collaboration with 3 Industry Partners

- Two landfill owners, one mining company

Spray on EICP (or MICP) treatment

- 2 component solution, mixed at the nozzle

First trial in 2021 at an Arizona Landfill

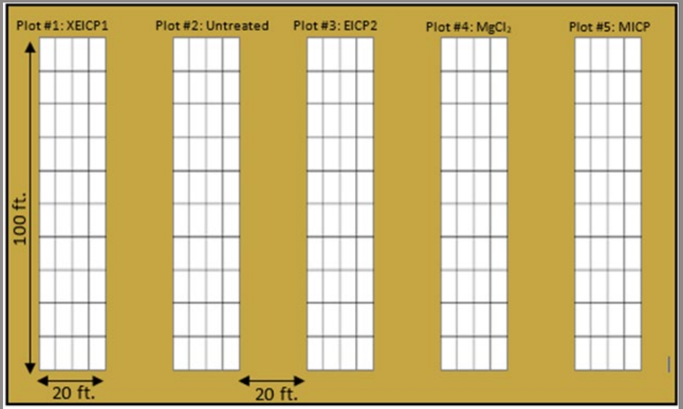
- Developed deployment and monitoring techniques

Second trial deploys next week

- Compare EICP to MICP to $MgCl_2$

Deployment of first trial plot

Dust Generation



Layout of plots for second field trial

CBBG Center for Bio-mediated & Bio-inspired Geotechnics

ASU Ira A. Fulton Schools of Engineering Arizona State University

Enzyme Induced Carbonate Precipitation (EICP) Columns

Concept: Create columns of biocemented sand for ground improvement

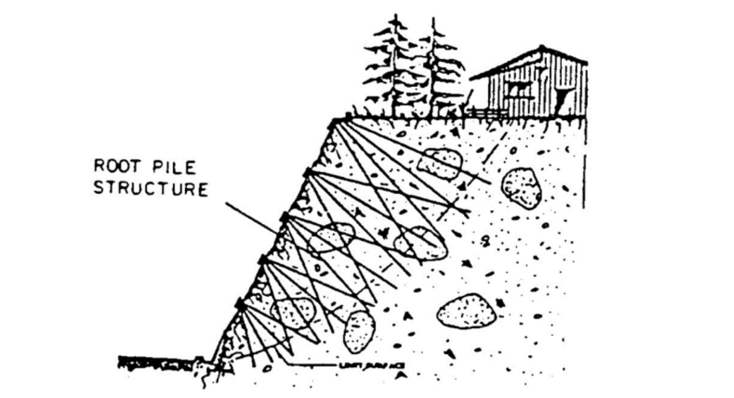
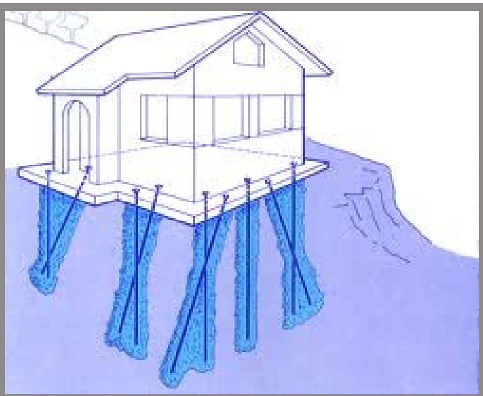
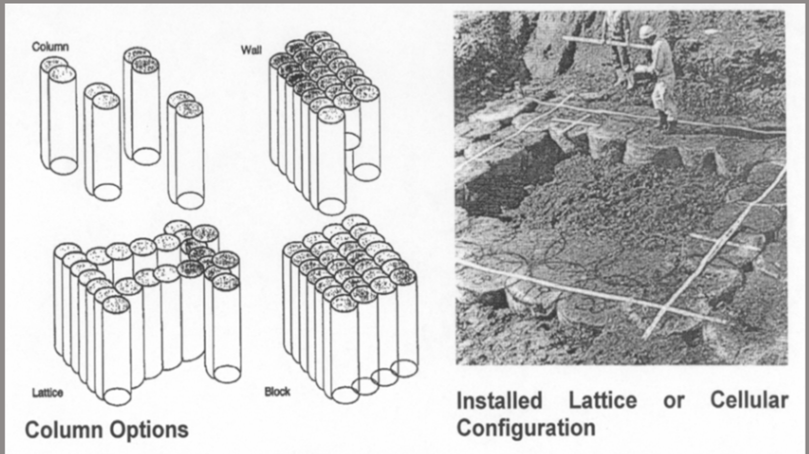
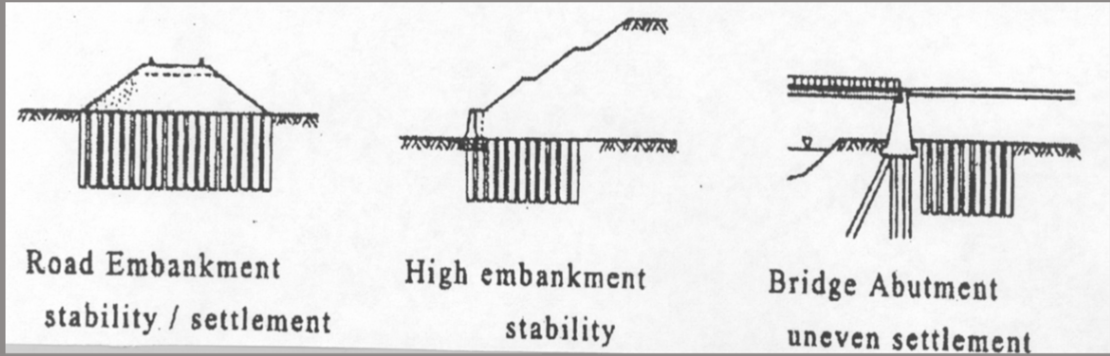


Figure 5-5 Landslide stabilization. (From Mitchell and Villet, 1987.)



http://www.sonditalia.it





FHWA Report no. FHWA-NHI-11-032

Field-Scale EICP Columns

Seven 1.5 to 3 ft diameter, 3-8 ft-long columns

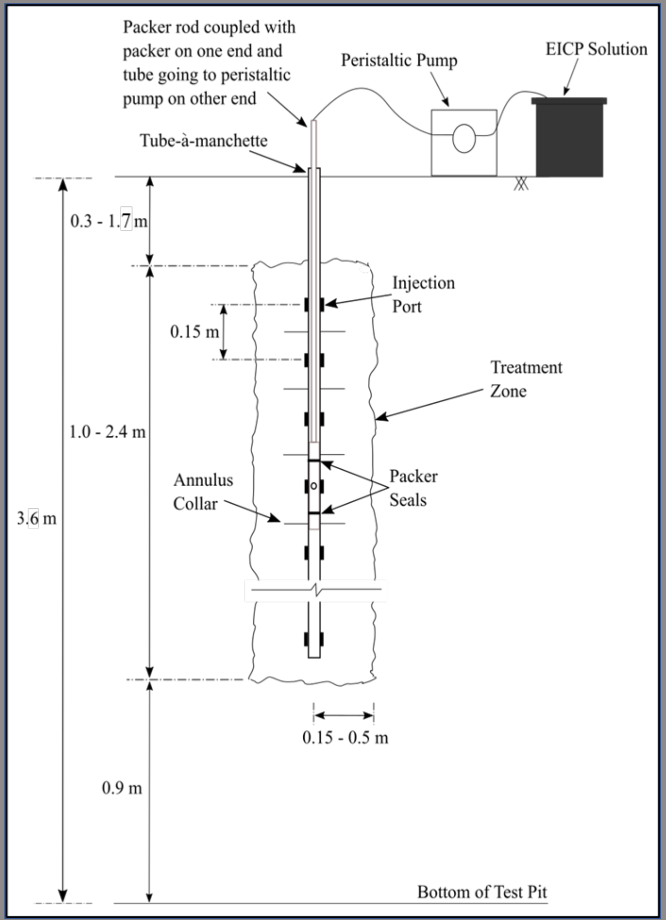
- ASU test pit filled with local quarry sand

Conventional grouting equipment

- Tube-a-Manchette

Three cycles of EICP Treatment

- Injected at 24-hour intervals
- 500 kPa (5 TSF) strength



Martin et al. (2022) “Field Scale Bio-cemented Soil Columns,”
In preparation for ASCE JGGE

Exhumation of EICP Columns

CBBG Center for Bio-mediated & Bio-inspired Geotechnics

ASU Ira A. Fulton Schools of Engineering Arizona State University

MIDP / MID

Microbially-induced desaturation and precipitation

- Alternative carbonate precipitation process (MIDP)
- Also desaturates soil via biogas generation (MID)

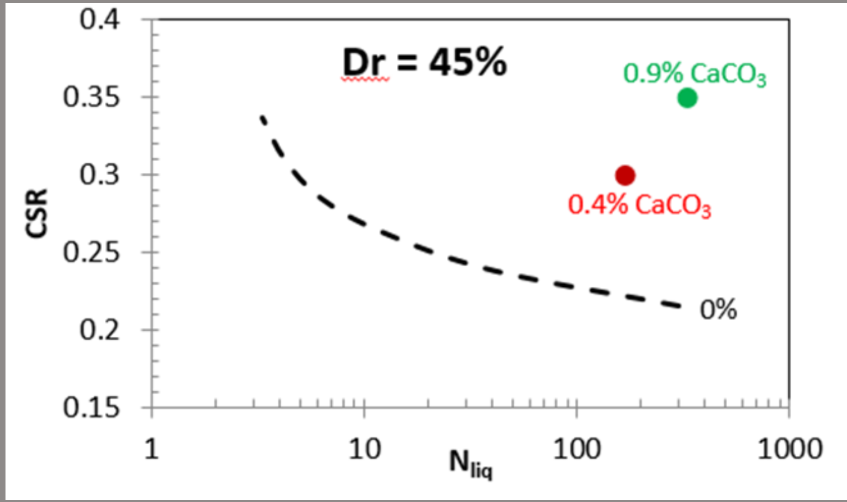
Nitrate reduced to nitrite to nitrogen and carbon dioxide ("denitrification")

- Denitrifying bacteria are "ubiquitous"
- Carbon dioxide goes into solution (creates carbonate ions)
- Insoluble nitrogen desaturates soil

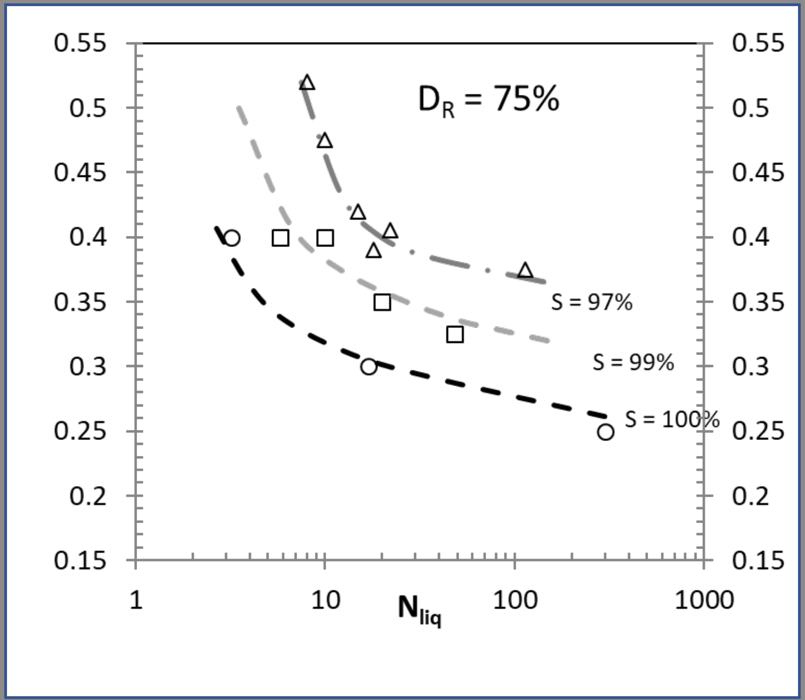
Carbonate precipitation very slow, but desaturation almost immediate

MIDP/MID Lab Testing

O'Donnell et al. (2017) ""Liquefaction Mitigation via Microbial Denitrification as a Two-Stage Process, Stage I: Desaturation" and "…, Stage II MICP," ASCE JGGE



Cyclic Simple Shear Testing, Saturated Biocemented Soil



Cyclic Simple Shear Testing, (Abiotically) Unsaturated Uncemented Soil

CBBG Center for Bio-mediated & Bio-inspired Geotechnics

ASU Ira A. Fulton Schools of Engineering Arizona State University

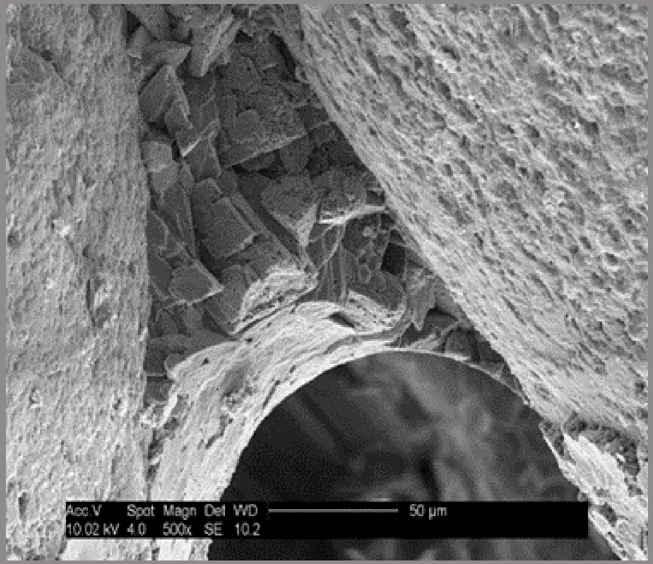
Advantages/Disadvantages of MIDP

Advantages

- Denitrification process well studied, well understood
- Desaturation also mitigates liquefaction
- Benign by-products unless sulfate present
- Precipitation very efficient

Disadvantages

- Precipitation very slow
- Longevity of desaturation unproven
  - Gas may coalesce in lenses, vent
- Potential for H_2S if sulfate present
- N_2 gas can lead to bioclogging

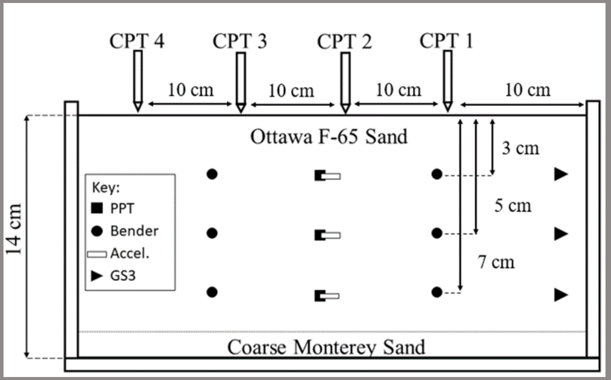


O'Donnell et al. (2017) ""Liquefaction Mitigation via Microbial Denitrification as a Two-Stage Process, Stage I: Desaturation" ASCE JGGE

Centrifuge Testing of Liquefction Mitigation via MID

Collaboration between ASU and UC Davis

- 1-m NEHRI centrifuge, 80 g acceleration



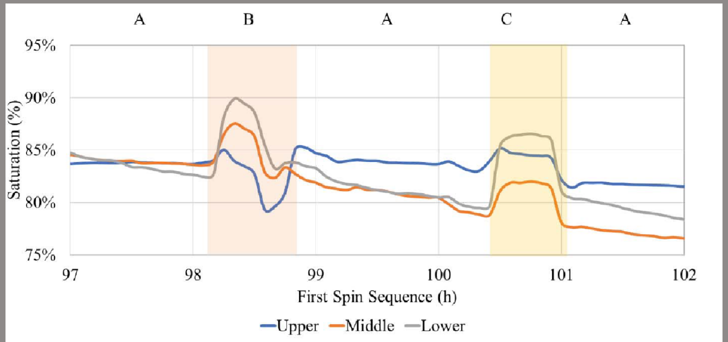
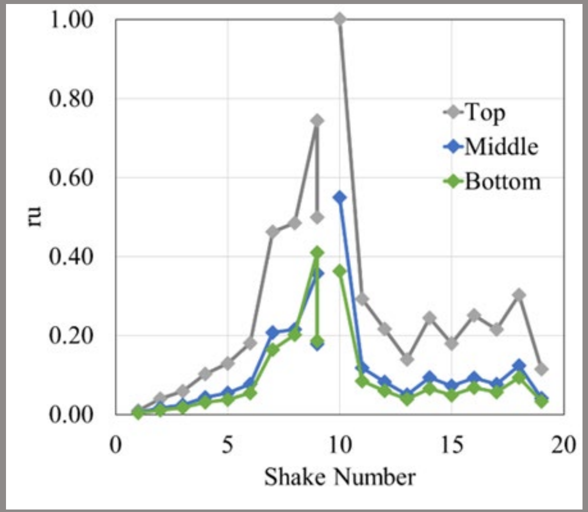


Figure 3. Monitored saturation level: [A] Continued desaturation by biogenic gas generation; [B] first shake sequence; and [C] second cone during first spin sequence

Shake Number	Target Amplitude (g)	Achieved Amplitude at Model Base (g)	Number of Cycles
Spin Sequence 1			
1	0.04	0.025	15
2	0.06	0.044	15
3	0.09	0.054	15
4	0.12	0.074	15
5	0.15	0.10	15
6	0.20	0.14	15
7	0.25	0.20	15
8	0.35	0.26	15
9*	0.40	0.36	15
Spin Sequence 2			
10	0.40	0.34	15
11	0.45	0.34	15
12	0.50	0.38	15
13	0.50	0.35	15
14	0.50	0.41	15
15	0.60	0.40	15
16	0.7	0.44	15
17	0.7	0.44	15
18	0.7	0.45	30
19	0.7	0.41	45



Hall et al. (2018) “"Centrifuge Model Testing of Liquefaction Mitigation via Denitrification-Induced Desaturation,“ ASCE GSP 290

Note: Threshold for liquefaction of unimproved soil ≈ 0.05 - 0.10 g

CBBG Center for Bio-mediated & Bio-inspired Geotechnics

ASU Ira A. Fulton Schools of Engineering Arizona State University

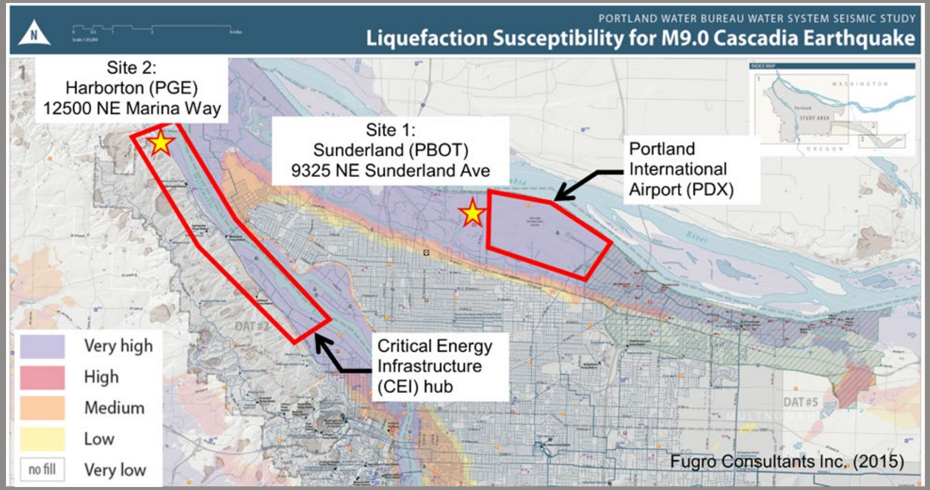
MID Field Testing

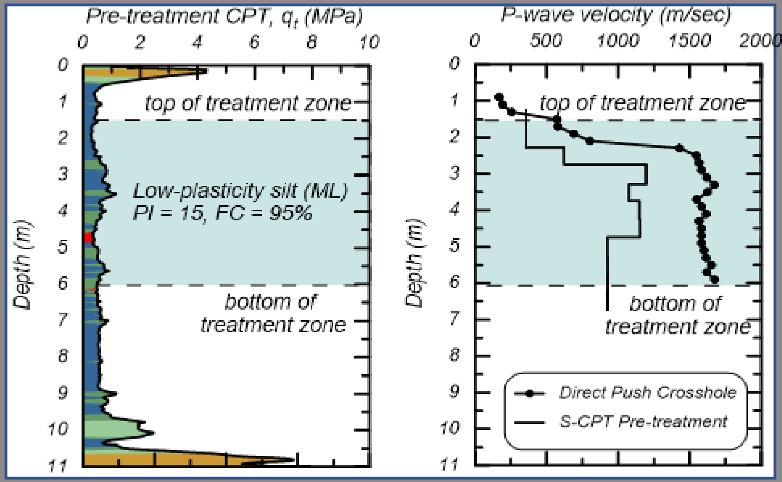
Collaboration with Portland State University, U. Texas, and Oregon Division of Oil, Gas, and Mineral Industries

- Funding from NHERI, CBBG

Successfully desaturated two sites in Port of Portland

- Area of major concern over liquefaction in M 9.0 Cascadia Earthquake
  - 90% of Oregon's Critical Energy Infrastructure on potentially liquefiable soil





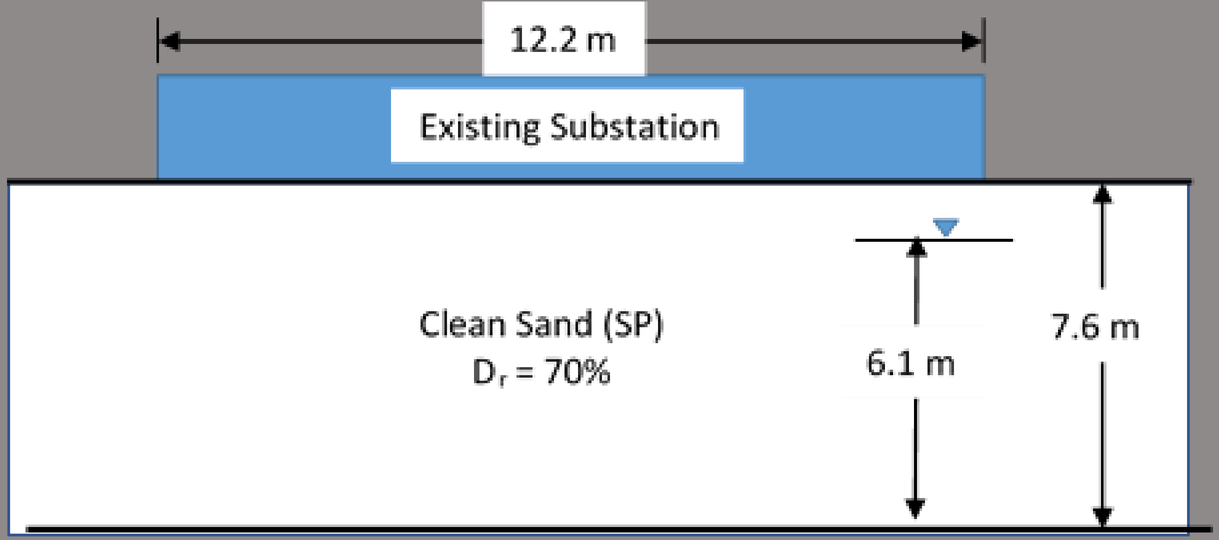
Sunderland Site

Moug, Khosravifar, et al. (2020) "Field Evaluation of Microbially Induced Desaturation for Liquefaction Mitigation of Silty Soils," 17th World Conf. on Earthquake Engineering

Techno-Economic Analysis (TEA) of MID

Existing substation founded upon 7.6 m of liquefiable soil

- 12.2 m x 24 m footprint
- Water table at 1.5 m
- Uniform, clean sand (SP)
- Dr = 70%



Mitigation options

- Permeation grouting
- MID

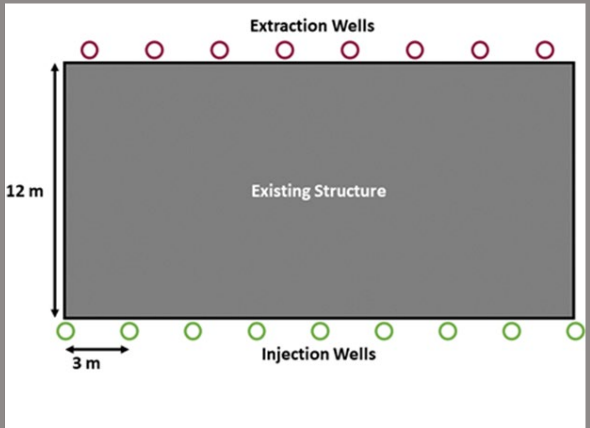
Hall et al. (2022) “Techno-Economic Assessment of Liquefaction Mitigation by Microbially Induced Desaturation” ASCE Lifelines Conference 2021-2022 (in press)

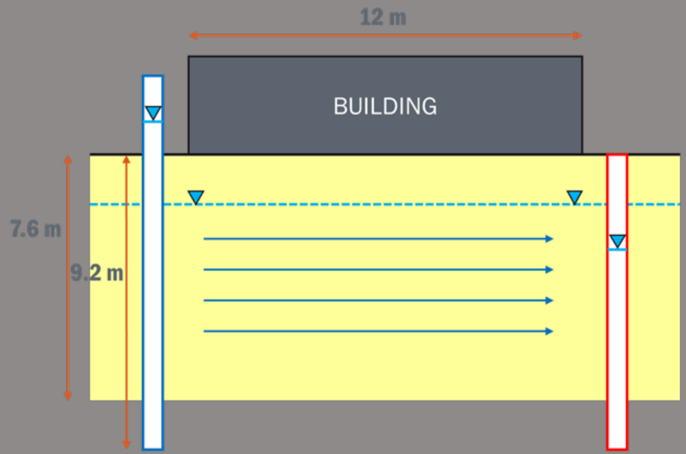
CBBG Center for Bio-mediated & Bio-inspired Geotechnics

ASU Ira A. Fulton Schools of Engineering Arizona State University

Mitigation Treatment Alternatives

MID





Developed in collaboration with Condon Johnson

MID System:

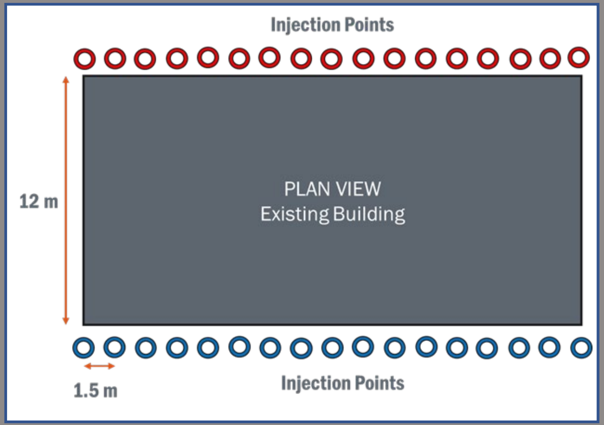
- Vertical wells @ 3 m spacing

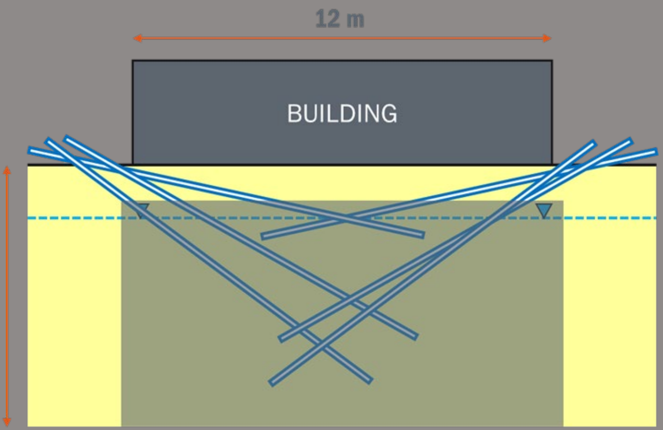
Permeation Grouting System:

- Battered wells @ 1.5 m spacing
- 3 pipes per injection point

Hall et al. (2022) "Techno-Economic Assessment of Liquefaction Mitigation by Microbially Induced Desaturation" ASCE Lifelines Conference 2021-2022

Permeation Grouting





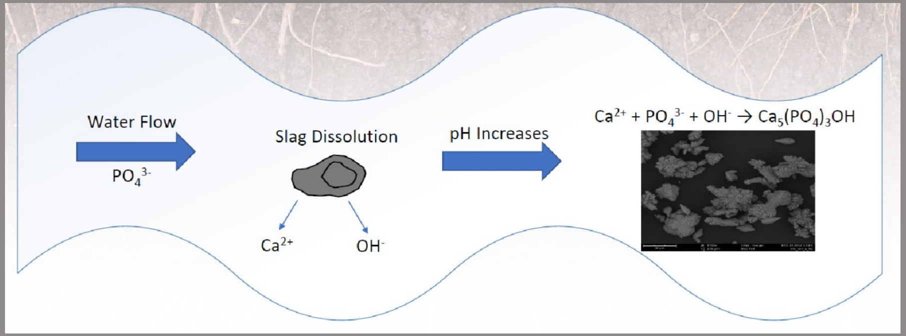
TEA Results

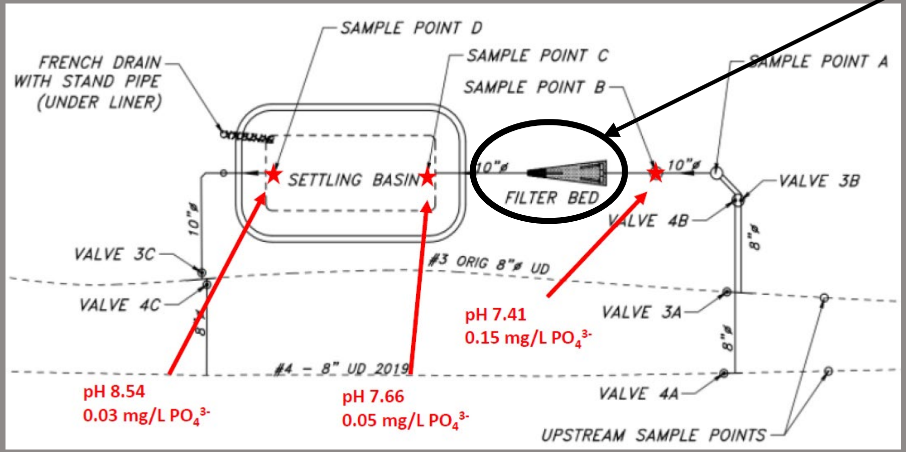
Well Installation	per well	Sleeve Port Pipe Installation	per sleeve port pipe
Installation equipment and labor	$1,500	Installation equipment and labor	$1,036
Construction Materials	$856	Construction Materials	$706
Permitting	$285	Permitting	$145
Overhead and Markup	$660	*Overhead and Markup*	$472
Well Installation Total	$56,111	***Well Installation Total***	$80,225
Treatment Materials	kg/m³ MID solution	**Treatment Materials**	kg/m³ grout injection
Calcium Nitrate	$2.34	Microfine Cement	$290
Calcium Acetate	$4.43		
Overhead and Markup	$1.69	*Overhead and Markup*	$73
Treatment Materials Total	$6,043	***Treatment Materials Total***	$258,625
Injection	per hour	**Injection**	per hour
Equipment and labor	$259	Equipment and labor	$413
Overhead and Markup	$65	*Overhead and Markup*	$103
Injection Total	$84,723	***Injection Total***	$215,923
Mobilization and Demobilization	Project total	**Mobilization and Demobilization**	Project total
Installation	$5,611	Installation	$8,023
Treatment	$9,077	Treatment	$47,455
Decommissioning	$14,500		
Mobilization and Demobilization Total	$17,188	***Mobilization and Demobilization Total***	$55,477
Project Total	$176,064	**Project Total**	$610,250

Hall et al. (2022) "Techno-Economic Assessment of Liquefaction Mitigation by Microbially Induced Desaturation" ASCE Lifelines Conference 2021-2022

Precipitation of Other Minerals, Metalloids

Phosphorus





Edgar (2020) "Removal of Nitrogen and Phosphorus from Impacted Water via Mineral Precipitation and Microbial Transformation," PhD Dissertation, ASU

Precipitation of Other Minerals, Metalloids

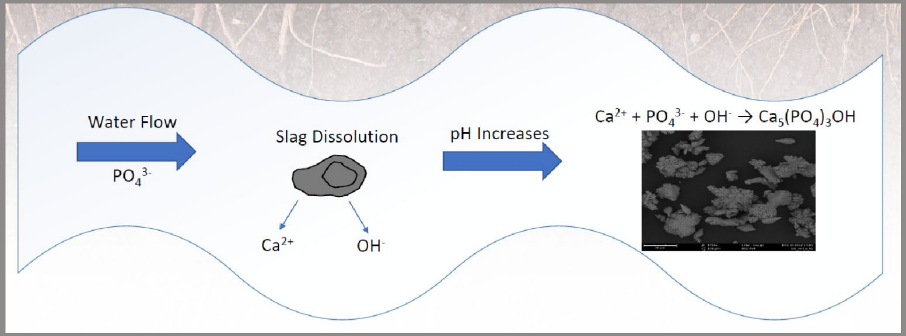
Phosphorus

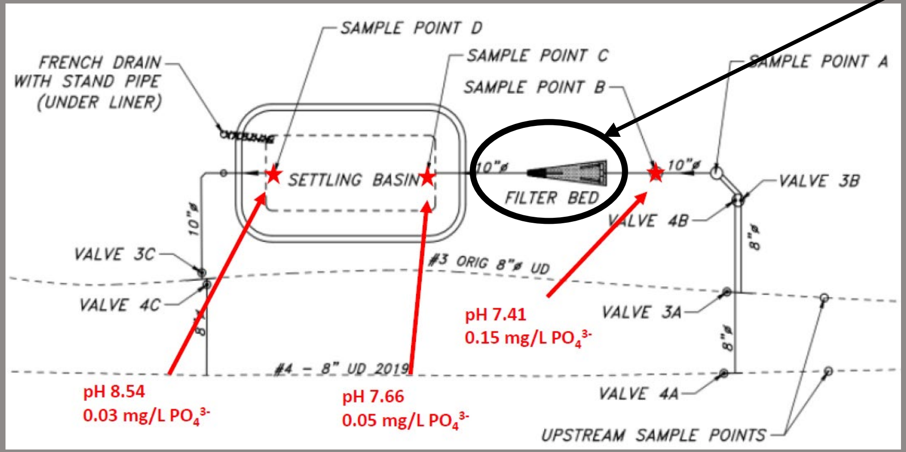
Iron

Salt

Contaminants

- Strontium
- Selenium
- Arsenic
- Chromium





Edgar (2020) "Removal of Nitrogen and Phosphorus from Impacted Water via Mineral Precipitation and Microbial Transformation," PhD Dissertation, ASU

Challenges with Precipitation

Fines content

- Number of inter-particle contact points (for biocementation)
- Permeability (for delivery of substrates)

Bio-clogging

- Due to mineral precipitation
- Due to growth of organic matter
- Due to gas generation

Saturation of media

Permanence / Reversibility

By-product management

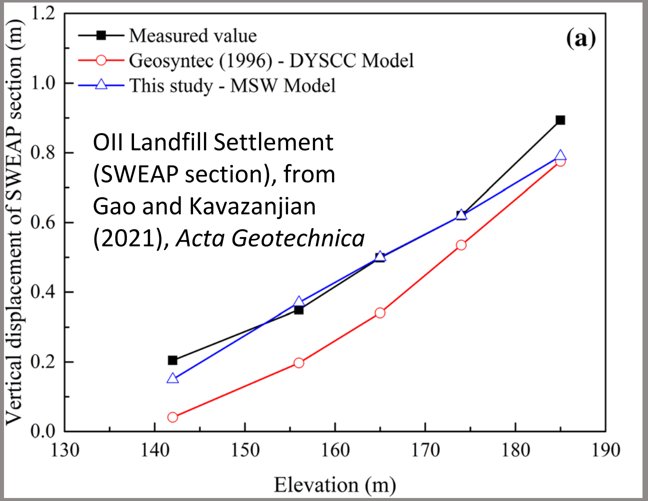
Transformation of Organic Chemicals

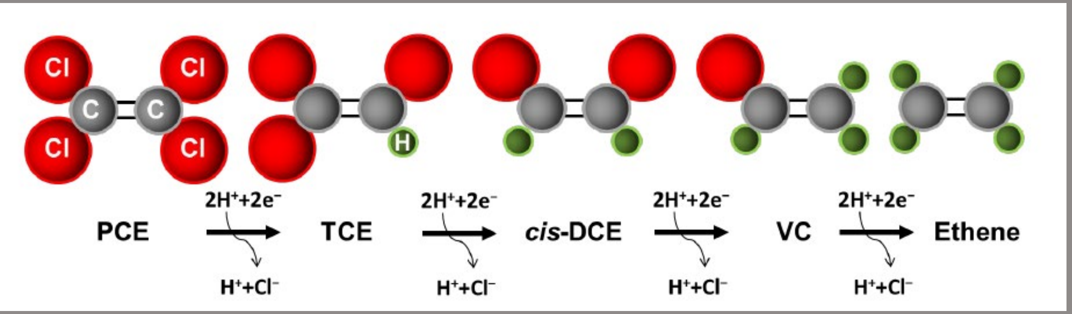
Perhaps the most advanced biogeotechnical process

- For environmental remediation

Processes of interest include:

- Aerobic and anaerobic degradation
- Denitrification
- Ureolysis
- Reductive dechlorination





Sustainability

Just because it's bio-mediated doesn't mean it's sustainable! (or environmentally friendly!)

Embodied energy

- 22.2 GJ per ton (22 MJ/kg) urea (Baboo, 2015)
- 4.5 MJ/kg for Portland cement (U. Bath, 2013)

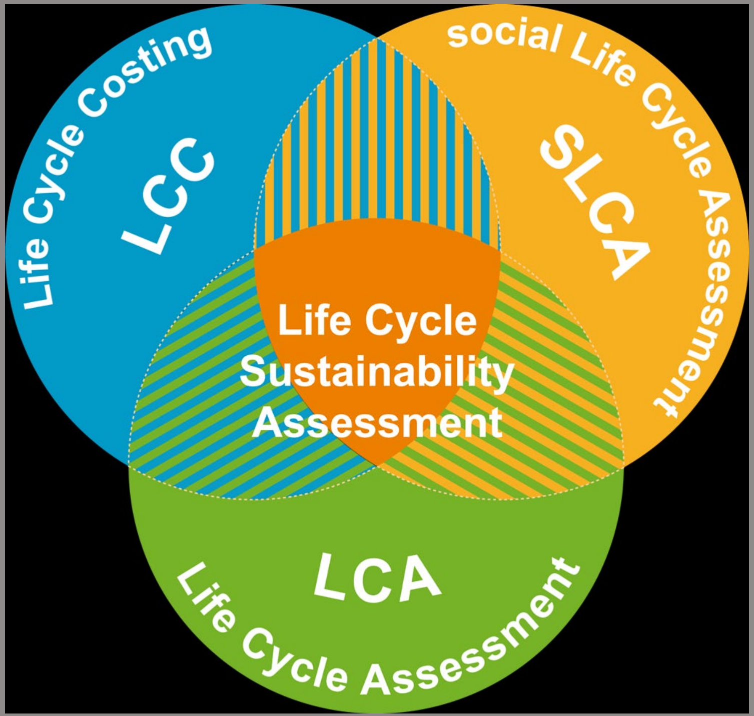
Embodied carbon

- 0.91 kg CO_2/kg for urea (VegaAlga, 2017)
- 0.73 kg CO_2/kg for Portland cement (U. Bath, 2013)

Sustainability Assessment

Issues to consider (when comparing technologies):

- Cost
- Permanence/reversibility
  - Reversibility may be beneficial
- Energy consumption
- Environmental impacts



industrialece.wixsite.com

Evaluate all biogeotechnologies using Life Cycle Sustainability Assessment (LCSA)

Life Cycle Sustainability Assessment of EICP for Fugitive Dust Control

Raymond, A.J., Kendall, A. DeJong, J.T., Kavazanjian, E., Woolley, M. and Martin, K. (2021) “Life Cycle Sustainability Assessment of Fugitive Dust Control Methods,” ASCE J. Construction Eng. & Management

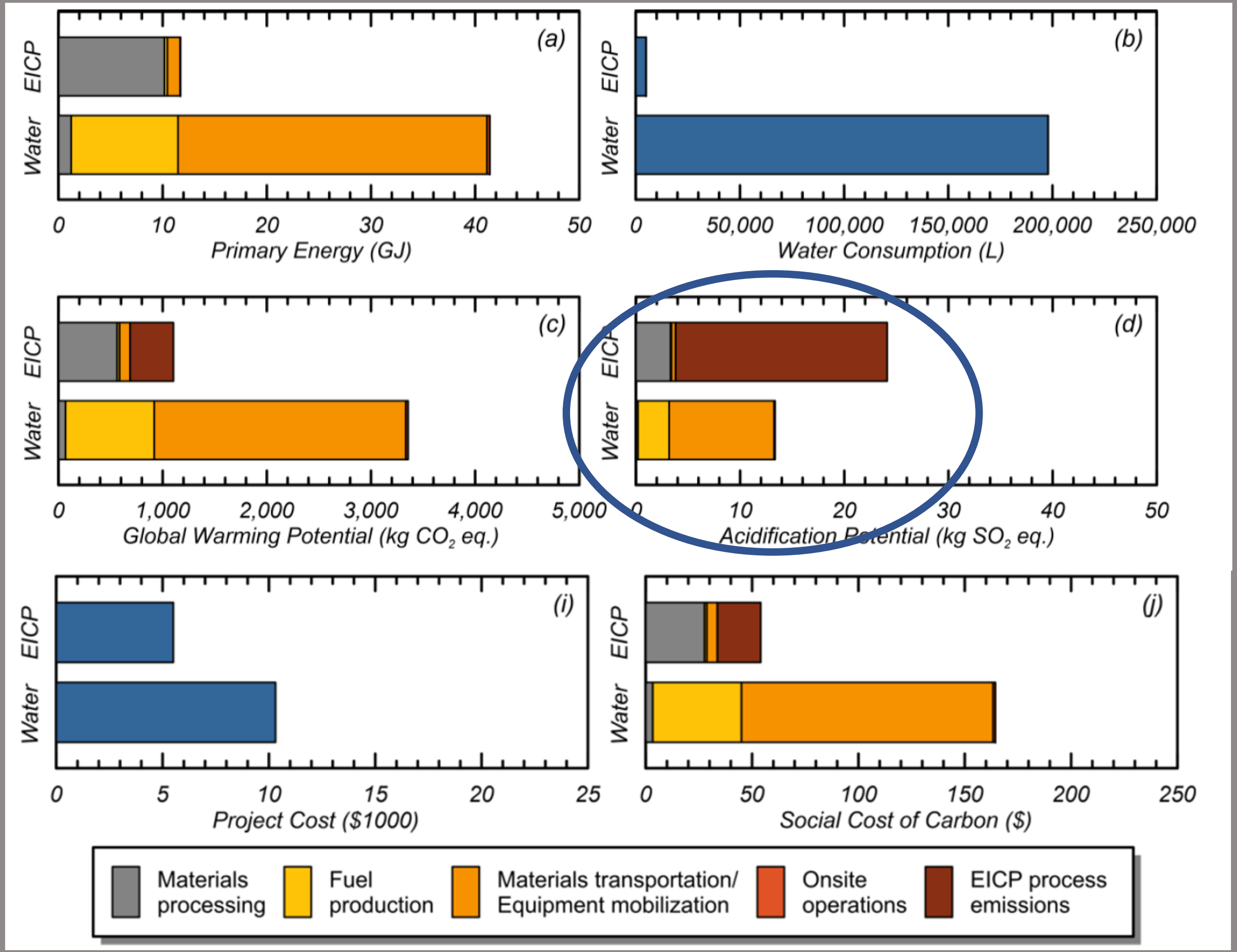
Higher initial cost for EICP, but cheaper if durability is > 1 week

- Uses less water
- Consumes less fuel, generates less emissions

Ammonium chloride by-product can lead to acidification/eutrophication

- Requires receiving body of water for run-off
- Also a fertilizer can stimulate vegetation

Fugitive Dust LCSA Results: 2 week Durability



Raymond, A.J., Kendall, A. DeJong, J.T., Kavazanjian, E., Woolley, M. and Martin, K. (2021) "Life Cycle Sustainability Assessment of Fugitive Dust Control Methods," ASCE Journal of Construction Engineering and Management,

Center for Bio-mediated and Bio-Inspired Geotechnics (CBBG)

Funding provided by NSF

- $36 million for 10 years (plus cost share)
- Research and workforce development

Four leading public Universities

- ASU, Georgia Tech, New Mexico State, UC Davis

Education and Outreach programs

- REU, RET, K-12 and public outreach

Industrial Partners program

- Consultants, Contractors, Owners, Agencies

CBBG Industry Partners

Freeport McMoRan Copper & Gold

Salt River Landfill
An Enterprise of the Salt River Pima-Maricopa Indian Community

Cosanti Foundation

Geosyntec consultants
engineers | scientists | innovators

Schnabel Foundation Company

Republic Services

United States Environmental Protection Agency

NMDOT

Keller

ConeTec

Haley Aldrich

Geopier®

Nicholson

Groundwater Technology

Menard

City of Phoenix

Golder

Geo-Logic Associates

ADOT

ADEQ
Arizona Department of Environmental Quality

Arizona Department of Water Resources
Est. 1980

~~CBGB~~

www.cbgb.com

Home of Underground Rock

CBBG √

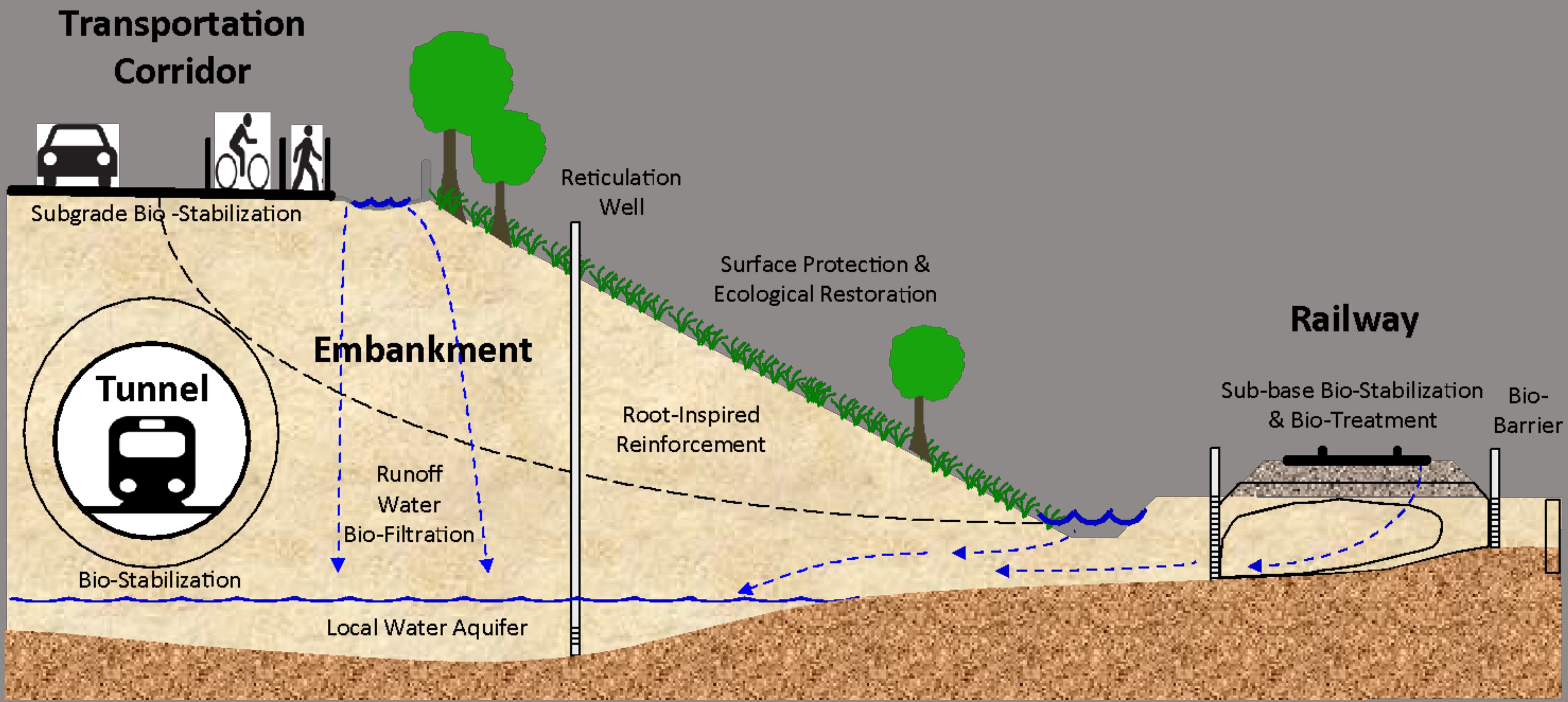
www.biogeotechnics.tech

Home of Underground Microbes

The Biogeotechnical Future

Only a few processes/methods explored to date

Opportunities to do much more

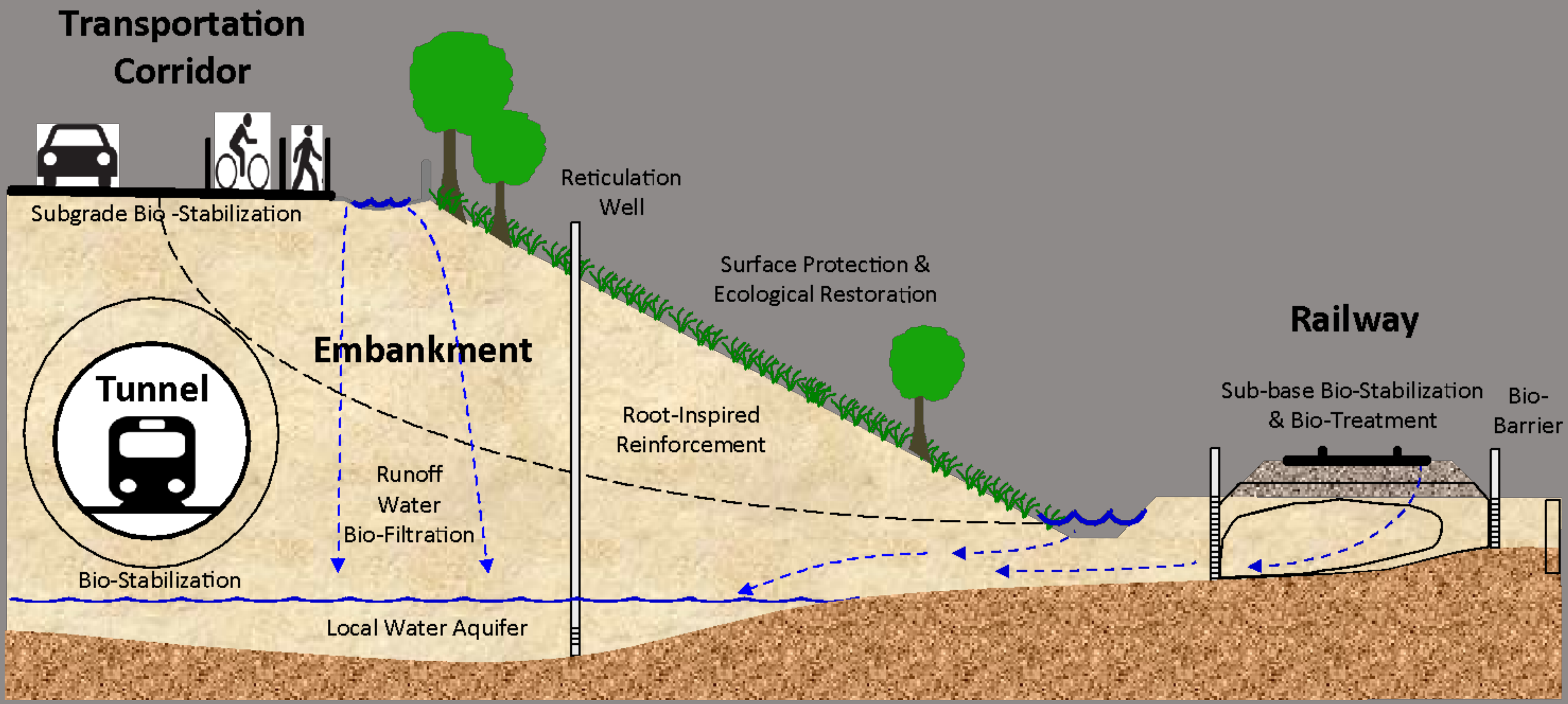


CBBG Center for Bio-mediated & Bio-inspired Geotechnics

(DeJong 2015)

Ira A. Fulton Schools of Engineering Arizona State University

Thank You for Listening



(DeJong 2015)

CBBG Center for Bio-mediated & Bio-inspired Geotechnics

ASU Ira A. Fulton Schools of Engineering Arizona State University