Biogeotechnics:

Bio-mediated Processes and Bio-inspired Ideas for Geotechnical Engineering Innovation

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Overview

Introduction

- *Vision, creativity in nature, society's needs*

Sustainability-Driven Approach for Innovation

- *Life Cycle Sustainability Assessment*

Bio-Mediated Processes

- *Biocementation*
- *Biogas*
- *Biofilms*

Bio-Inspired Design

- *Tree root inspired foundations*
- *Invertebrate inspired soil penetration*
- *Snakeskin inspired anisotropic friction*

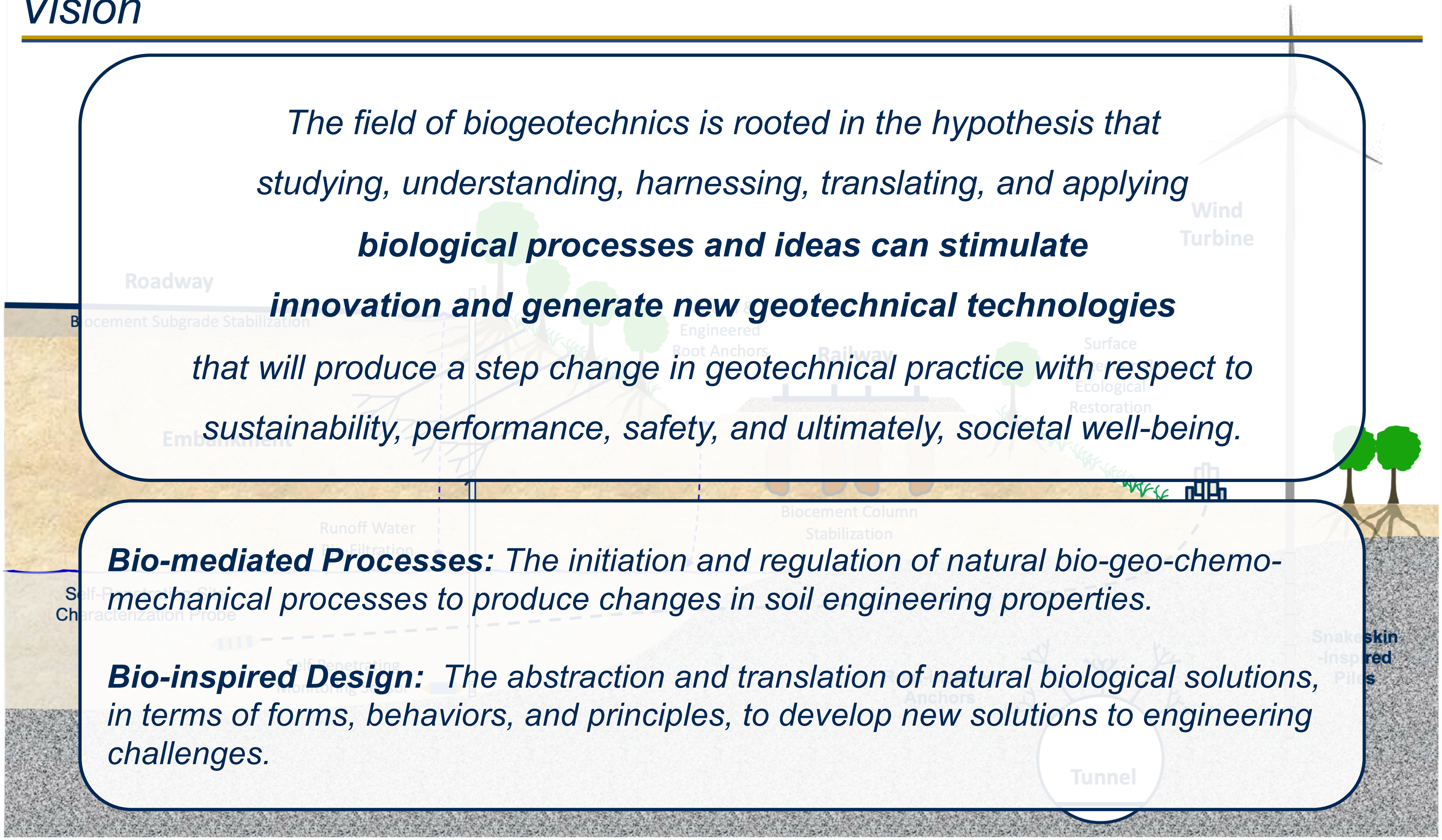
Closure

- *Priorities & Opportunities*

Introduction

Vision, Creativity in Nature, Society’s Needs

Vision



The field of biogeotechnics is rooted in the hypothesis that studying, understanding, harnessing, translating, and applying ***biological processes and ideas can stimulate innovation and generate new geotechnical technologies*** *that will produce a step change in geotechnical practice with respect to sustainability, performance, safety, and ultimately, societal well-being.*

Bio-mediated Processes: *The initiation and regulation of natural bio-geo-chemo-mechanical processes to produce changes in soil engineering properties.*

Bio-inspired Design: *The abstraction and translation of natural biological solutions, in terms of forms, behaviors, and principles, to develop new solutions to engineering challenges.*

Creativity in Nature… Practicing Geotechnical Engineers

Sensing & Penetration

Erosion

Tunneling

Compaction

Foundations & Anchorage

Cementation

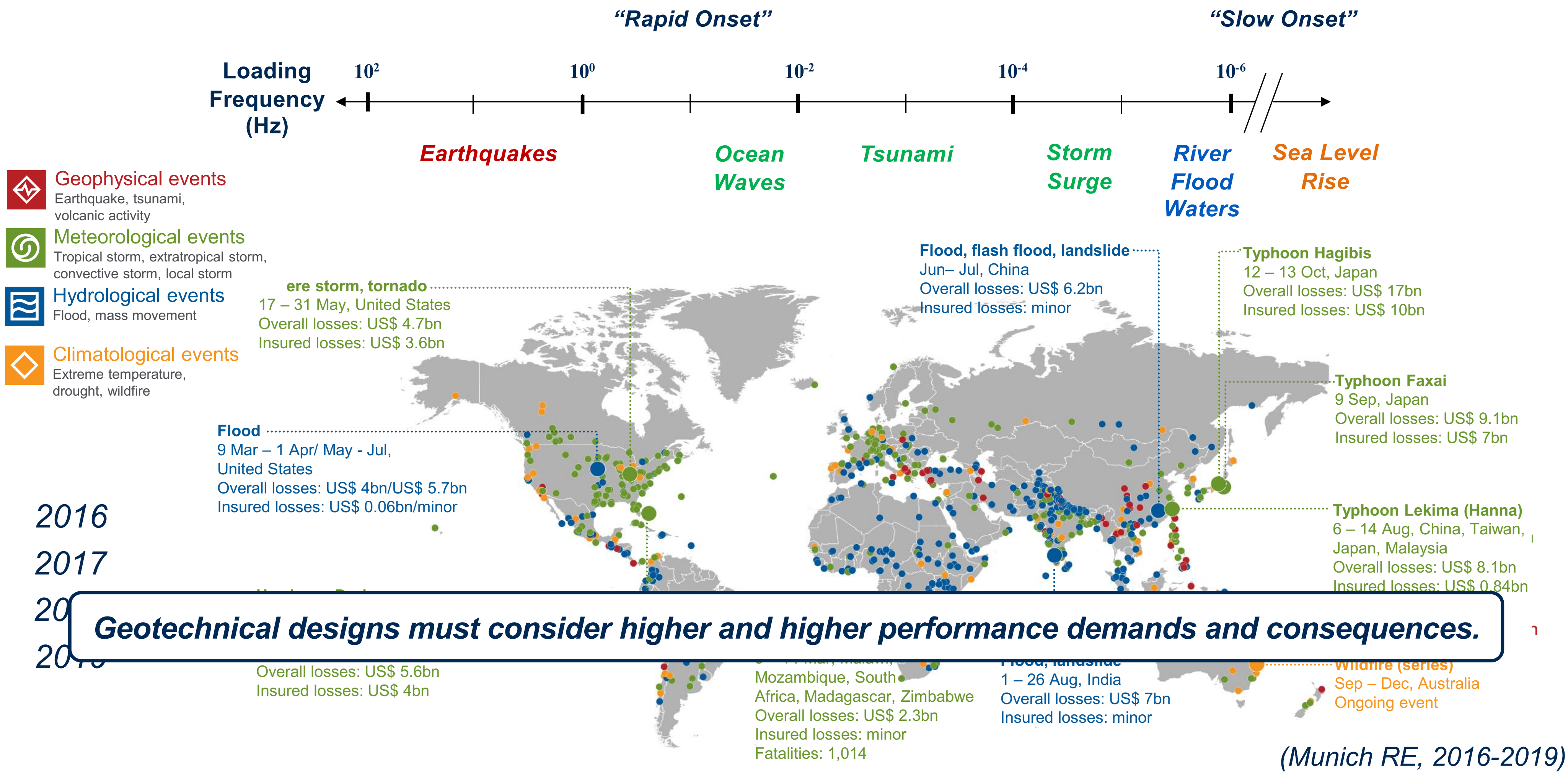
The creativity evident in nature constitutes an alternate source of innovative solutions from which we can gain inspiration.

Creativity in Nature… Nature's Solutions vs. Geotechnical Engineering

Attribute	***Nature's Solutions***	***Geotech. SOP/BAU***
design	*ecosystem specific*	*project site-specific*
objective	*survival, reproduction*	*safety, cost*
currency	*materials, energy*	*capital cost*
functionality	*multi-*	*single, multi-*
sustainability	*reuse, cycling*	*once & done*
adaptability	*growth on demand*	--
healing	*self-repairing*	--

Solutions in nature have similar, and even greater, constraints than geotechnical projects.

Society's Needs – Design Controlled by Natural Hazards



Geotechnical designs must consider higher and higher performance demands and consequences.

(Munich RE, 2016-2019)

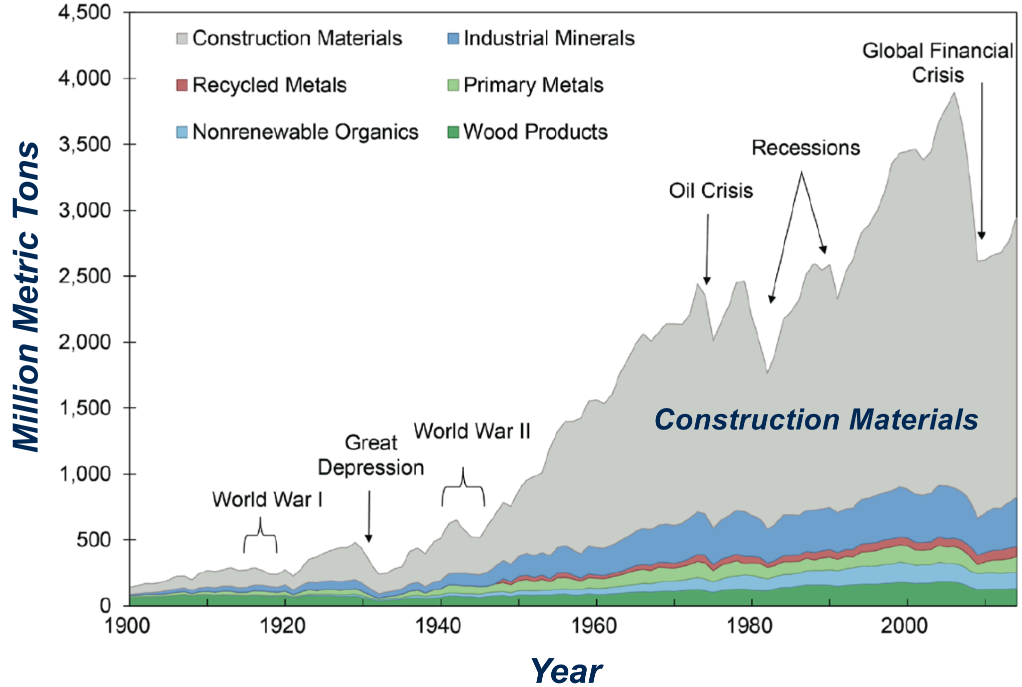
Society's Needs – Environmental Impacts of Construction

- *Construction industry constitutes:*
  - *75% of raw material use*
  - *55% of off-road fuel use*

- *Concrete, steel, and aluminum production generates ~22% of annual green house gas (GHG) emissions.*

- *Use of renewable materials has decreased from 41% to 5% of total materials over the last century.*

U.S. Nonfuel Material Consumption, 1900-2014



Current construction practices used to build geotechnical systems and other infrastructure use materials and processes at rates that cannot be sustained in the future.

(UMCSS CSS05-18 2020, Matos et al. 2017)

Society's Needs – Sustainable Development

Geotechnical engineering has the opportunity to impact and contribute towards achieving several of the United Nations sustainable development goals.

(United Nations 2015)

Sustainability-Driven Approach for Biogeotechnics Innovation

Life Cycle Sustainability Assessment (LCSA) Framework

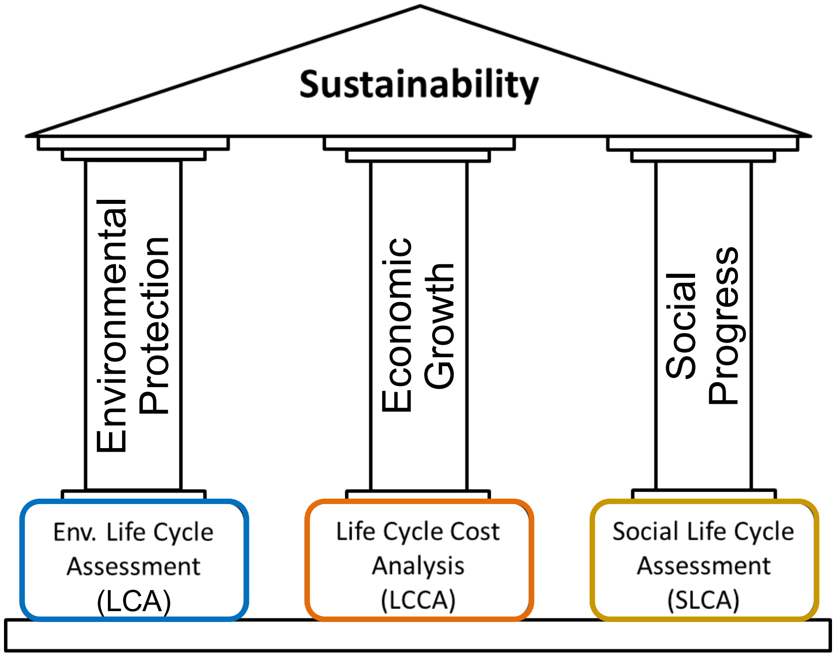
Sustainability-Driven Approach for Biogeotechnics Innovation

Triple Bottom Line:

- ✔ *Engineered safety*
- ✔ *Capital cost*
- *Sustainability and environmental impact*

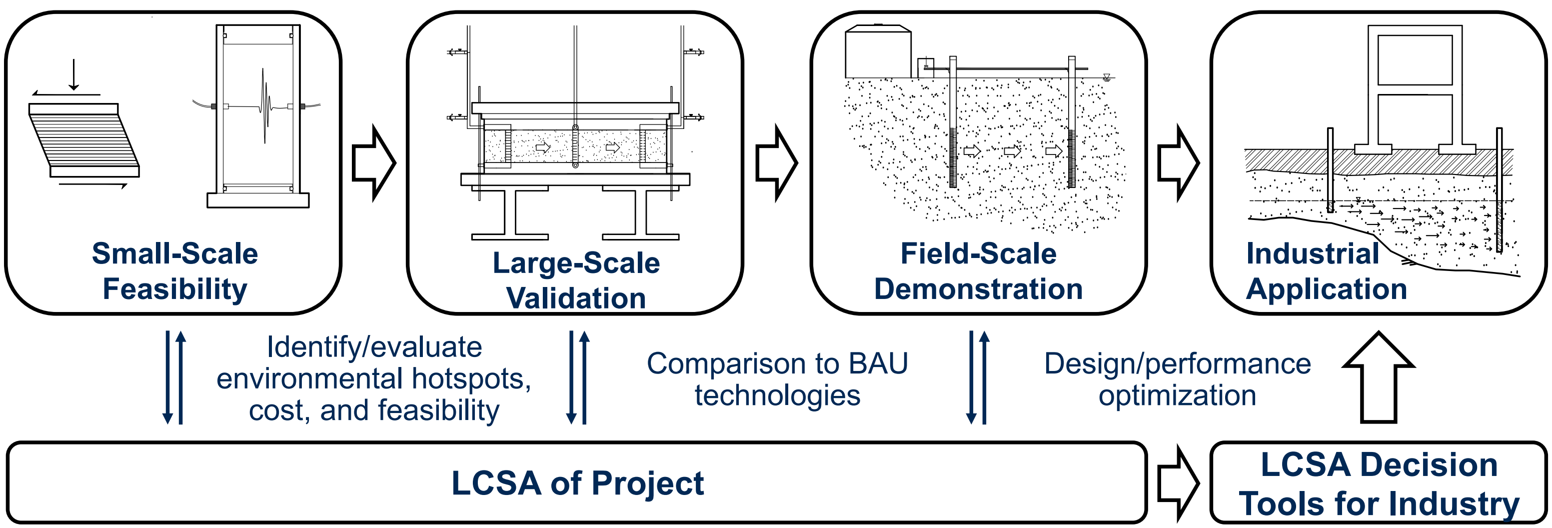
Life Cycle Sustainability Assessment (LCSA):

- *A framework that considers the entire system, from extraction of raw materials, to construction, and through maintenance and end-of-life.*
- *Evaluates project impacts to:*
  - ***Environment*** *– Environmental life cycle assessment (ELCA or LCA)*
  - ***Economy*** *– Life cycle cost analysis (LCCA)*
  - ***Society**** *– Social life cycle assessment (SLCA)*



Sustainability-Driven Approach for Biogeotechnics Innovation

- *Application of the LCSA framework to research projects enables:*
  - *balanced consideration of sustainability-oriented priorities*
  - *identification of sustainability-related research tasks*
  - *comparison against industry Business-As-Usual (BAU) technologies*
  - *evaluation of (future) market competitiveness w.r.t. cost, performance, & sustainability*

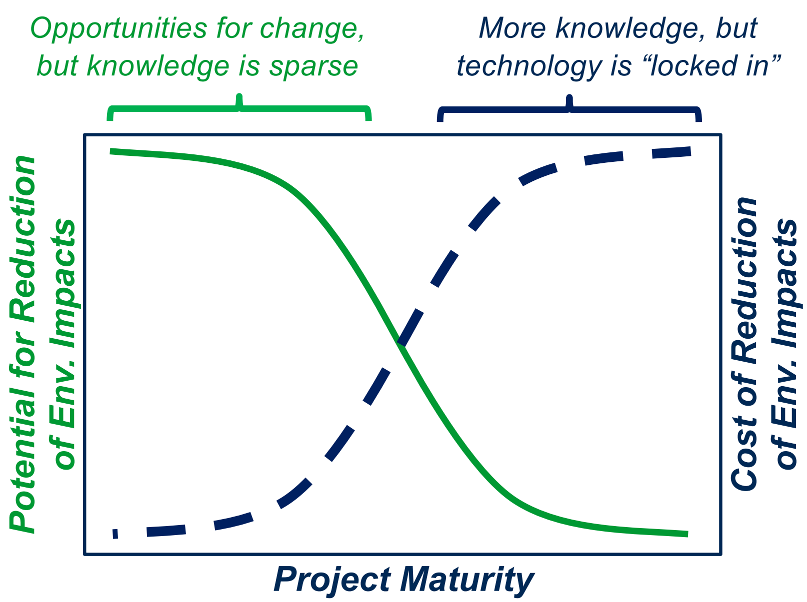


(Raymond et al. 2020)

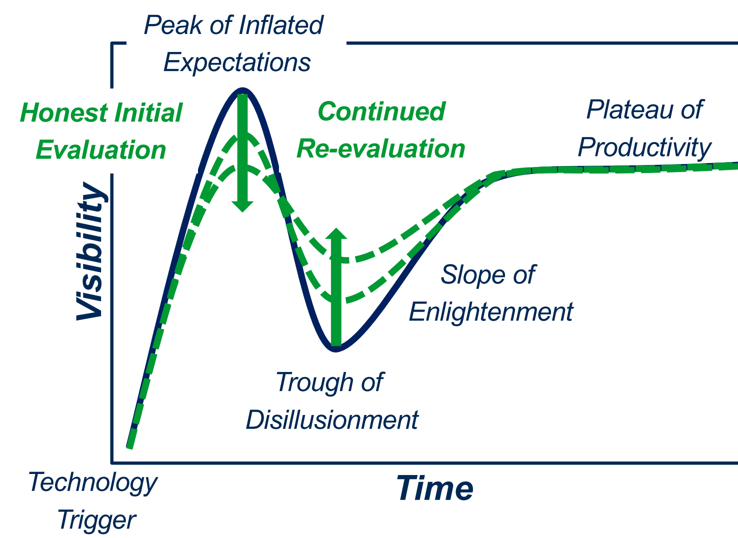
Sustainability Driven Approach for Biogeotechnics Innovation

- *LCSA implementation ideally:*
  - *triggers early R&D changes during development to realize sustainability-related benefits*
  - *provides early and frequent assessment of idea viability relative to BAU technologies*

"Collingridge Dilemma"



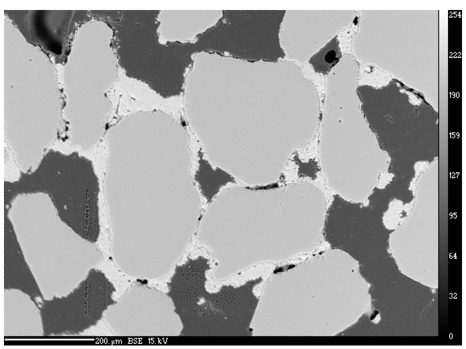
Gartner Hype Cycle

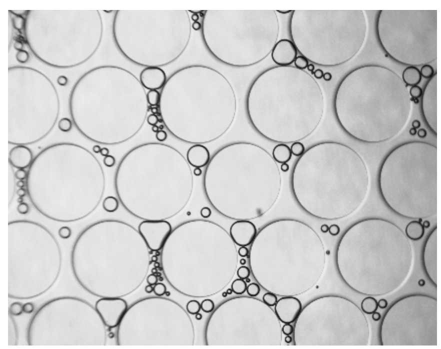


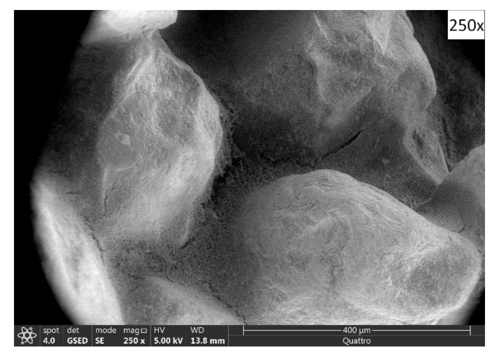
(Raymond 2019, Collingridge1980)

Bio-mediated Geotechnics

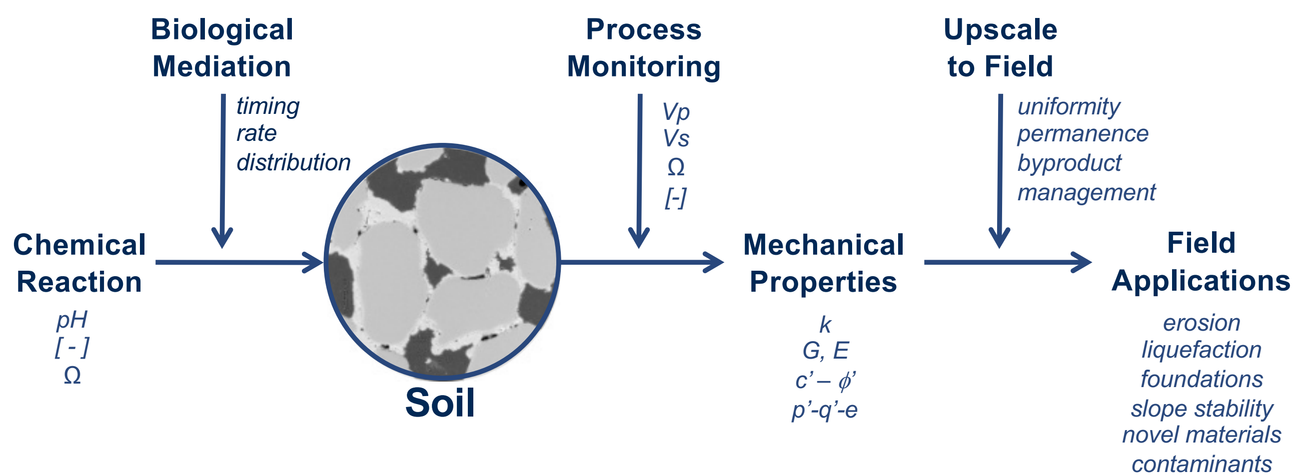
Biocementation, Biogas, & Biofilms







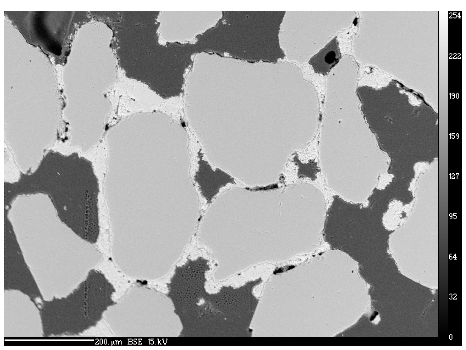
Bio-mediated Geotechnics Approach



- *Key attributes:*
  - *Control and regulation of biology and/or chemistry can accelerate or delay processes*
  - *Process monitoring tracks improvement progress*
  - *Changes in mechanical properties can exceed 10,000%*
  - *Improvement level tunable to performance requirement*
  - *Upscaling challenges are similar to other ground improvement technologies*
  - *Field applications are wide-ranging*

Bio-mediated Geotechnics

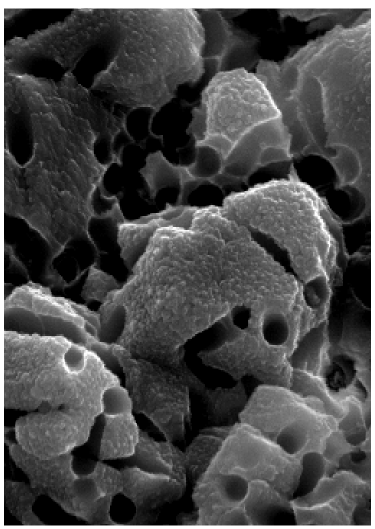
Biocementation

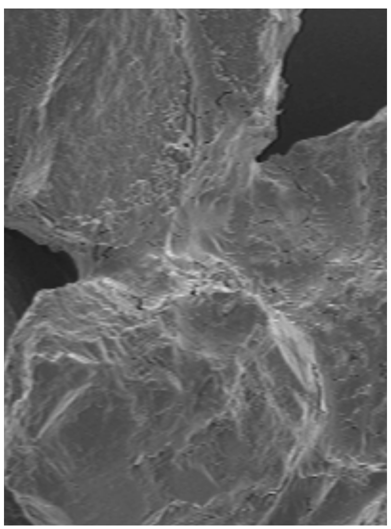


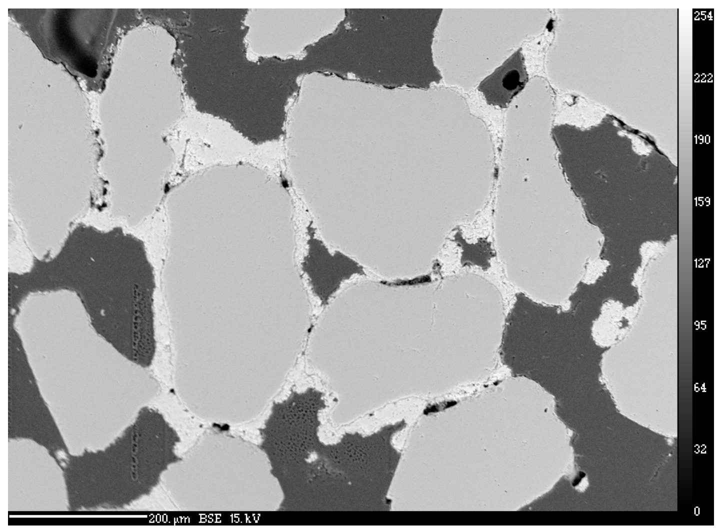
MICP – microbially induced calcite precipitation (ureolysis)
EICP – enzymatically induced calcite precipitation (ureolysis)
MIDP – microbially induced desaturation & precipitation (denitrification)

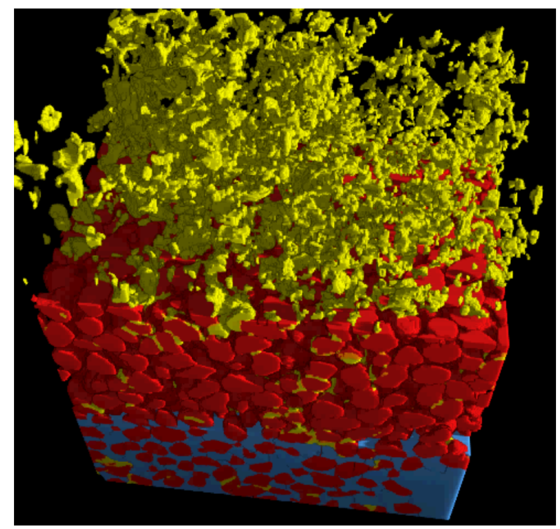
Biocementation – Microstructure

- *Calcium carbonate precipitation driven by microbial processes (e.g. ureolysis, denitrification).*
- *Precipitation occurs primarily at particle-particle contacts and preserves open pore structure.*
- *Three contributors to improvement of engineering properties are:*
  - *generation of cementitious binding at particle contacts*
  - *increase in density through precipitated masses*
  - *increase in particle angularity and interparticle 'frustration'*







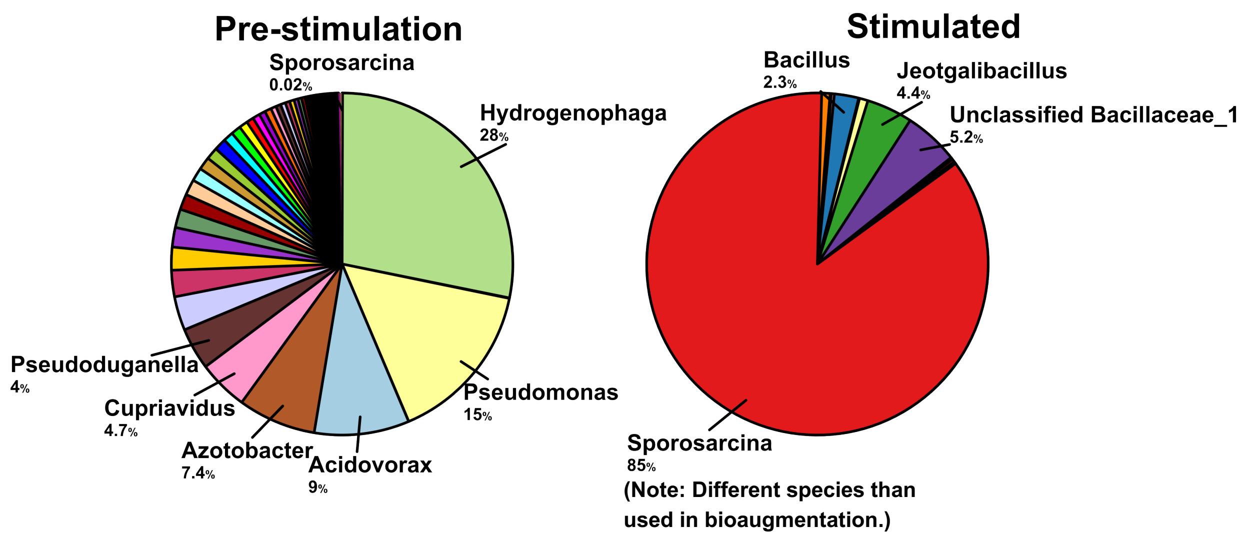


(DeJong et al. 2010, 2013)

Biocementation – Microbiology

- *Microbial activity enables control of timing, rate, and distribution of precipitation.*
- *Transition to biostimulation of native bacteria because they outcompete injected bacteria.*

Microbial Population

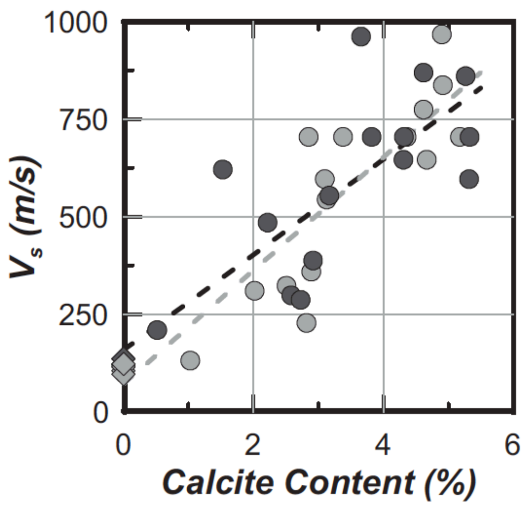


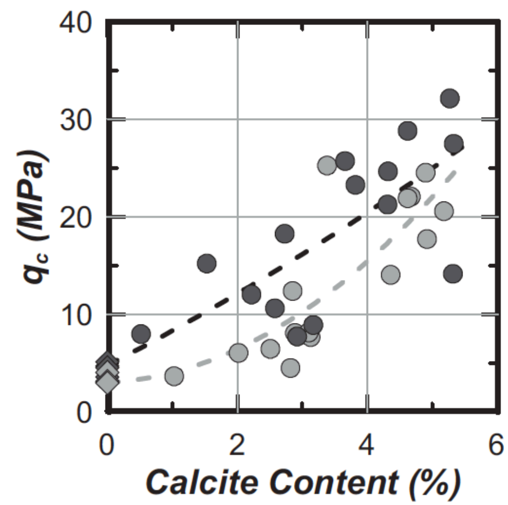
- *Biostimulation technique reduces costs and impacts, improves spatial uniformity, and eases regulatory permitting.*
- *Process effective under anoxic conditions in saturated soils.*

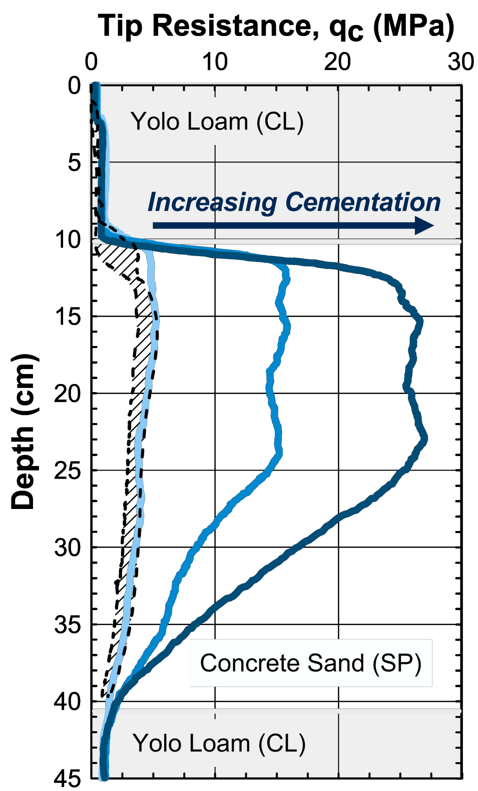
(Graddy et al. 2018, Gomez et al. 2017)

Biocementation – Process Monitoring

- *Biocementation improvement is tunable and can occur in controlled increments.*
- *Chemical and biological monitoring confirms reaction progression but does not confirm mechanical improvement.*
- *Process monitoring of mechanical improvement options:*
  - *Real-time: shear wave velocity*
  - *Post-treatment: CPT q_c, lab tests, direct calcite content*





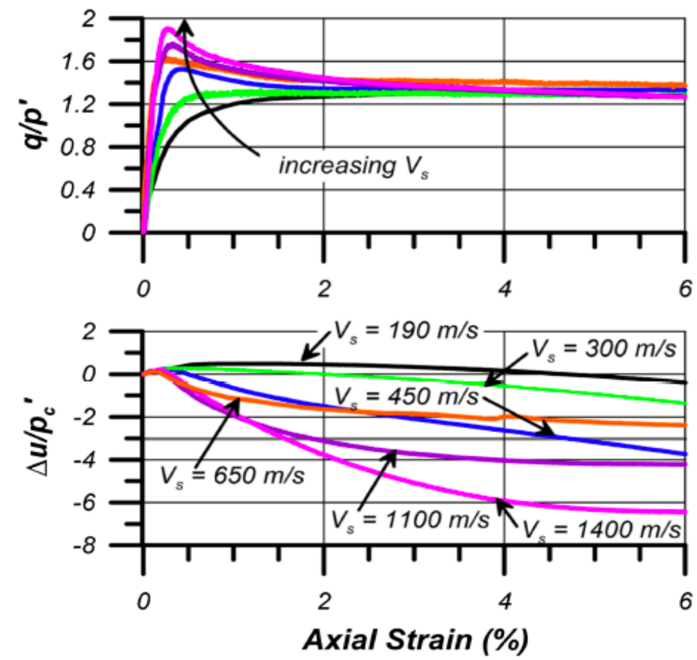


(Gomez et al. 2018)

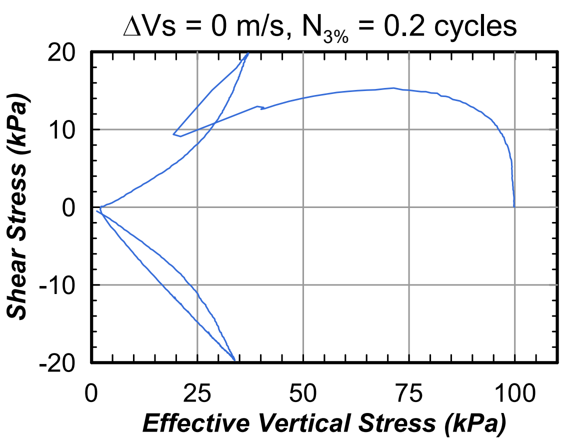
Biocementation – Mechanical Properties

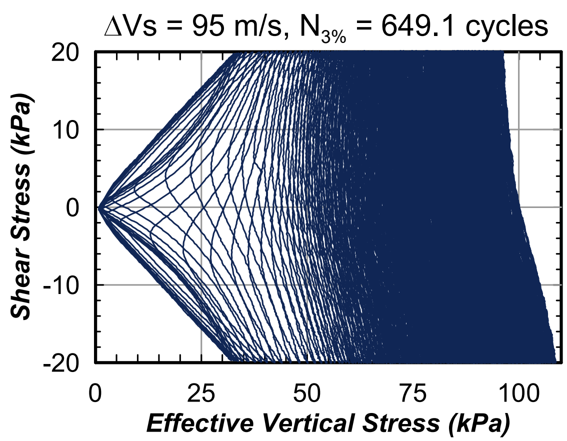
- *Researchers have collectively documented improvements to poorly-graded sands:*
  - *V_s↑ = 100 to 1,500 m/s*
  - *UCS↑ = 0 to 5 MPa*
  - *ϕ'_{peak}↑ = 30º to 45º*
  - *ΔV = contractive to dilative*
  - *CRR (D_R=35%, [$CaCO_3$]=0-1%, γ_{SA}=3%, N=10) = 0.1 to 0.3*
  - *k↓ = 10^{-1} to 10^{-5} cm/s*

CIUC TX Test w/ Vs = 100-1400 m/s



Cyclic DSS Test w/ D_R=35%, CSR =0.2



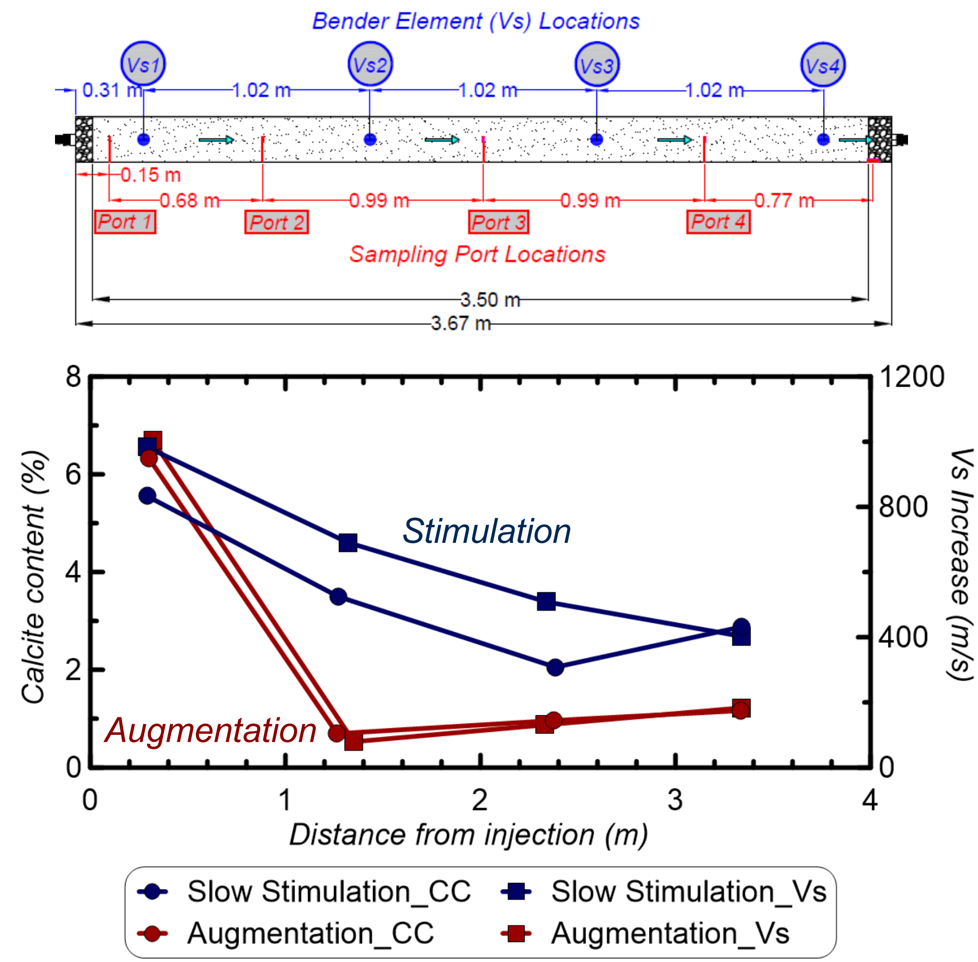


(Lee et al. 2020, Montoya & DeJong 2015, & Others)

Biocementation – Upscaling to Field

- *Upscaled model testing forces focus on field-scale implementation priorities:*
  - *Material efficiency*
  - *Treatment strategies*
  - *QA/QC monitoring*
  - *Byproduct removal*

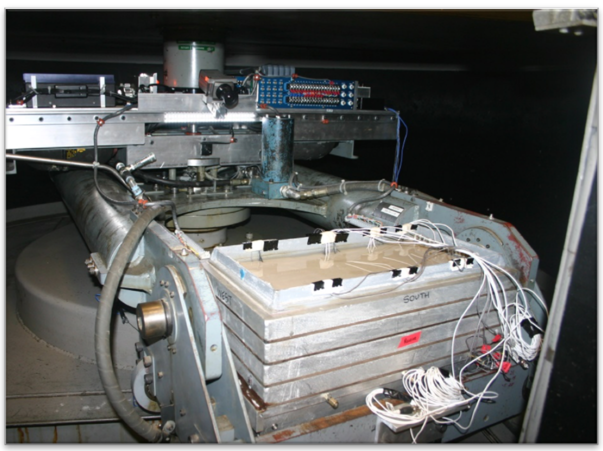
- *Five 3.5 m long 1D columns demonstrated that:*
  - *Biostimulation can enable more uniform cementation than augmentation given the same bulk reactivity.*
  - *1D treatment extent can exceed 4 m in a variety of clean sands.*
  - *Byproducts can be removed effectively with no damage to cementation integrity.*

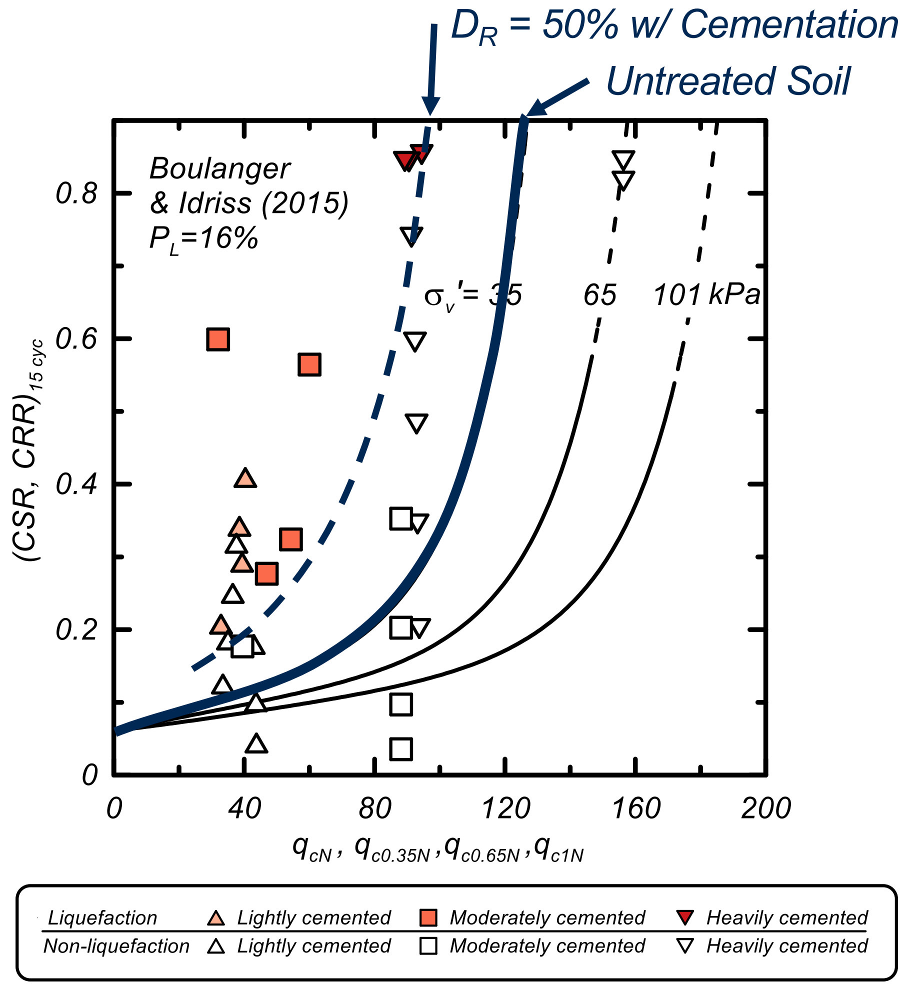


(San Pablo et al. 2020, Lee et al. 2019)

Biocementation – Upscaling to Field – Liquefaction Triggering

- Effect of cementation level on liquefaction triggering resistance examined using the UC Davis CGM 1-m radius centrifuge.
- Models of untreated sand and sands with different cementation levels.
- Measurements of pore pressures, accelerations, V_s, surface settlements, and CPTs.
- Concluded that cementation level increases both CPT q_c and CRR, but has larger effect on CRR which results in upward shift of triggering curve.

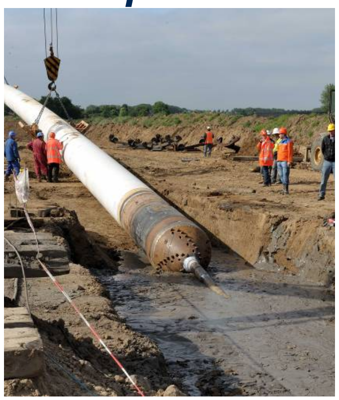




(Darby et al. 2019, Montoya & DeJong 2013)

Biocementation – Field Applications

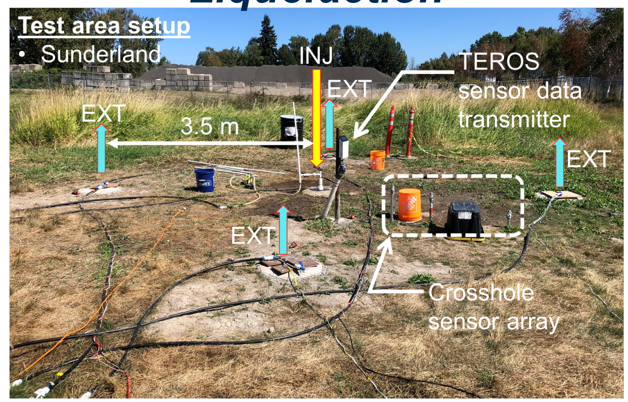
Pipelines



Surface Erosion

Tunnel

Liquefaction



Columns

(2010 van Paassen, TU Delft)

(2013 DeJong, UCD)

(2017 Esnault-Filet, Soletanche-Bachy)

(2018 & 2019 van Paassen, Kavazanjian, ASU)

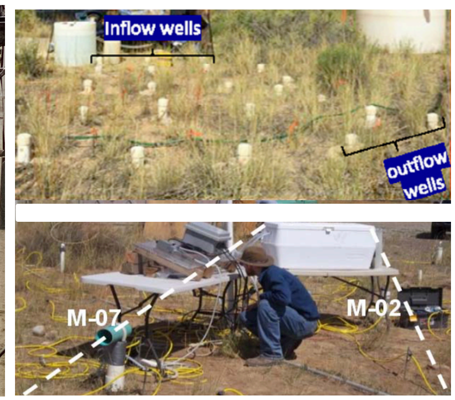
(2019 Kavazanjian, ASU)

Slope Stability

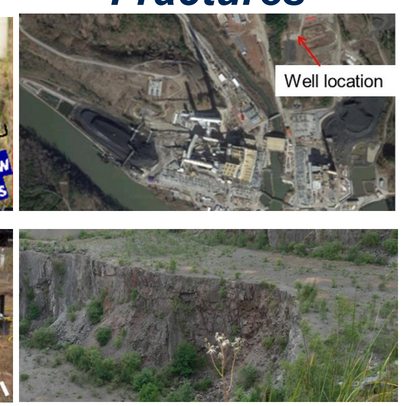
Landslide

Coastal Erosion

Contaminants



Fractures



(2019 Montoya, NCSU)

(2019 Laloui-Terzis, EPFL-Medusoil)

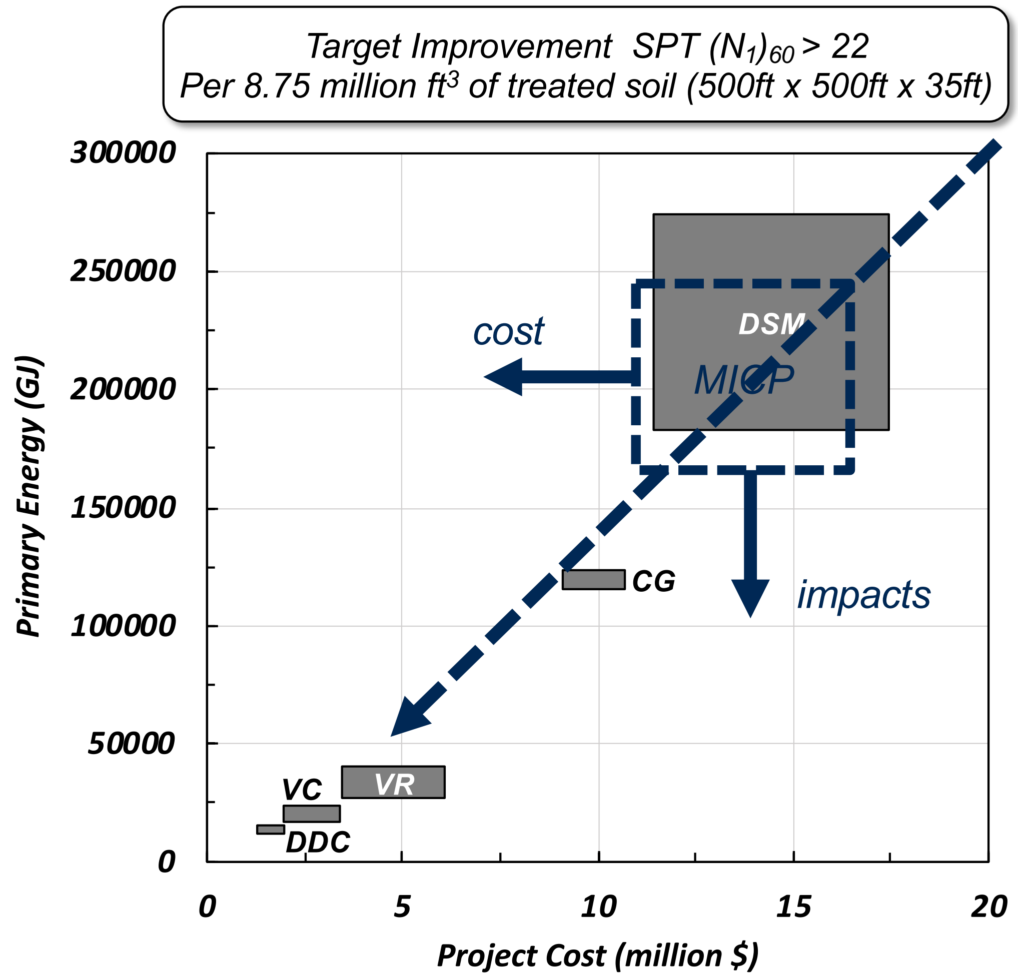
(2019 Montoya, NCSU & Evans, OSU)

(2019 Burns, GT) &
(2012 Smith, DOE)

(2016 Phillips, MSU) &
(2013 Cuthbert, Birmingham)

Biocementation – Comparison Against BAU Technologies

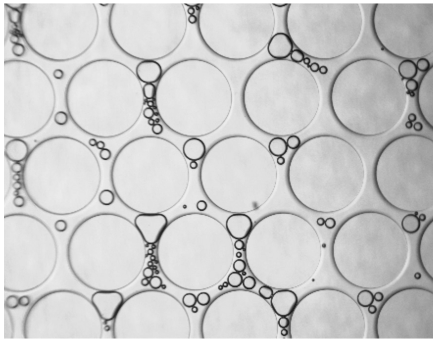
- LCSA of existing BAU methods for ground improvement evaluated with industry partners.
- Idealized level ground site composed of loose, saturated, liquefiable soil to ~10 m depth.
- Continued optimization to reduce cost and impacts
- MICP advantages:
  - does not require Portland Cement
  - provides non-invasive method for improving soils under existing infrastructure



(Raymond et al. 2020)

Bio-mediated Geotechnics

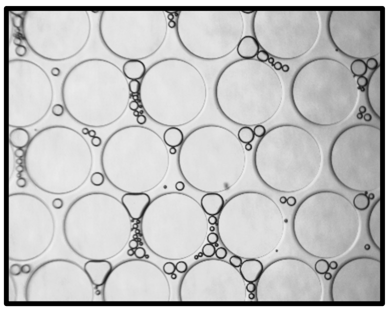
Biogas

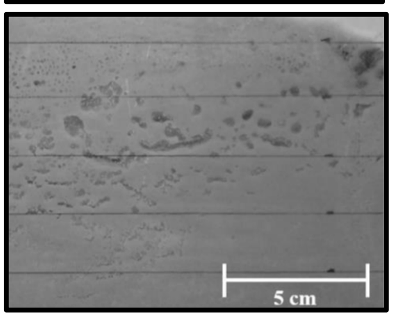


Biogas (desaturation)

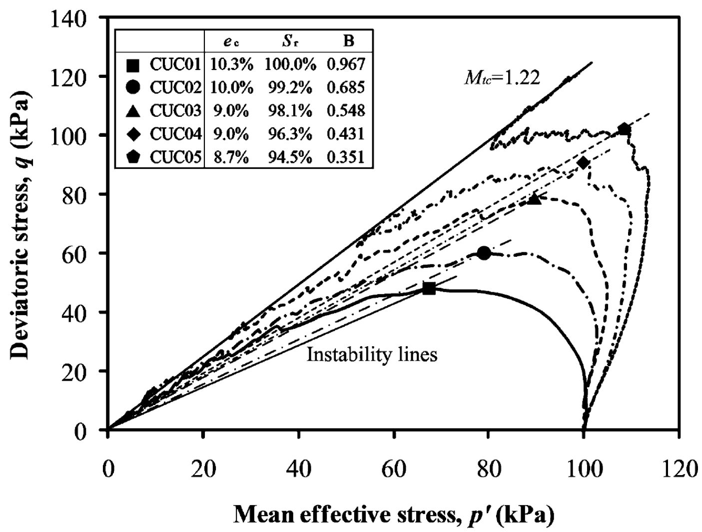
- ***Process:*** *gas bubbles generated in pore space while particle structure is unchanged*
- ***Microbiology:*** *stimulated microbes generate* N_2 *gas bubbles via denitrification*
- ***Microstructure:*** *bubbles decrease saturation and increase pore fluid compressibility*
- ***Process Monitoring:*** *compression waves, permeability*
- ***Mechanical Properties:*** *increase monotonic strength and CRR, permeability reduces*

Gas Bubbles

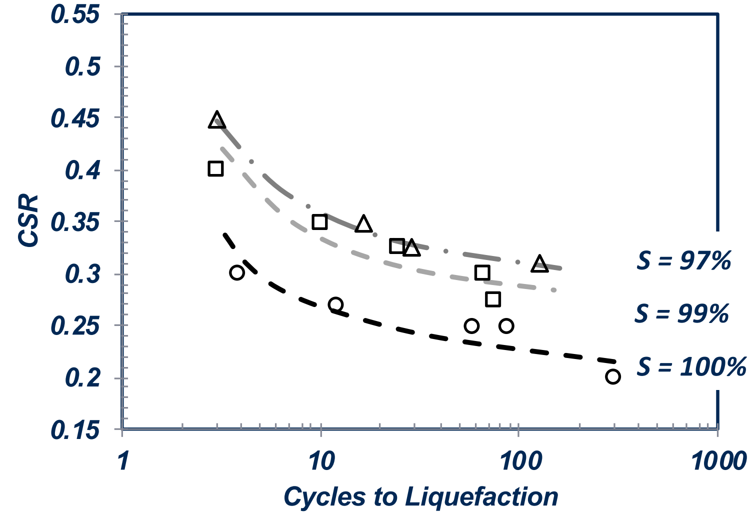




CAUC Triaxial w/ S = 95-100%



Cyclic DSS w/ S = 97-100%

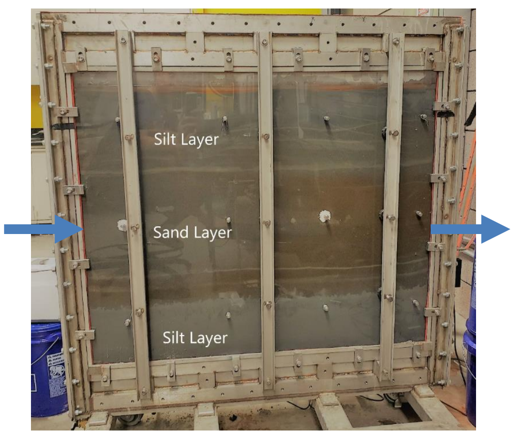


(He and Chu 2014, O'Donnell et al. 2016, Hall et al. 2018, van Paassen et al. 2018)

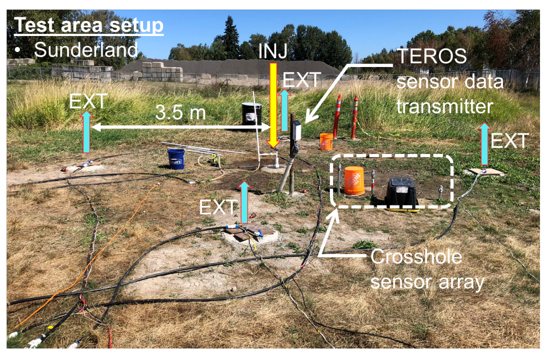
Biogas (desaturation)

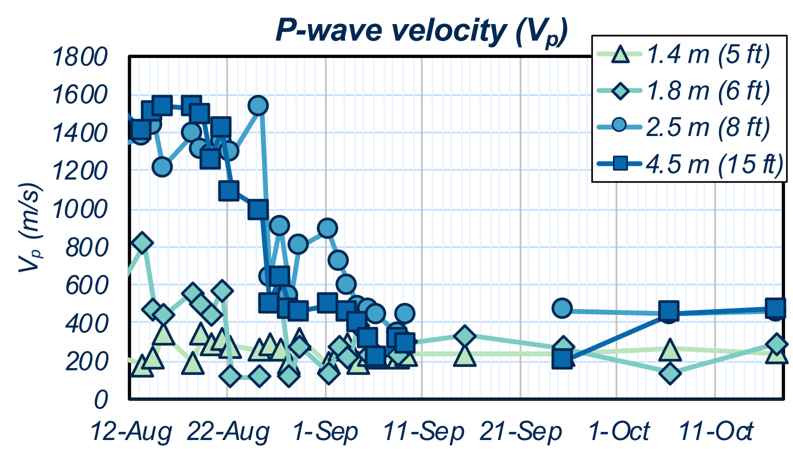
- **Process:** gas bubbles generated in pore space while particle structure is unchanged
- **Microbiology:** stimulated microbes generate N_2 gas bubbles via denitrification
- **Microstructure:** bubbles decrease saturation and increase pore fluid compressibility
- **Process Monitoring:** compression waves, permeability
- **Mechanical Properties:** increase monotonic strength and CRR, permeability reduces
- **Upscaling to Field:** 2D planar models to examine how flow changes with gas generation
- **Field Applications:** liquefaction mitigation by decreasing r_u generation

2D Planar Flow Model



Field Trial

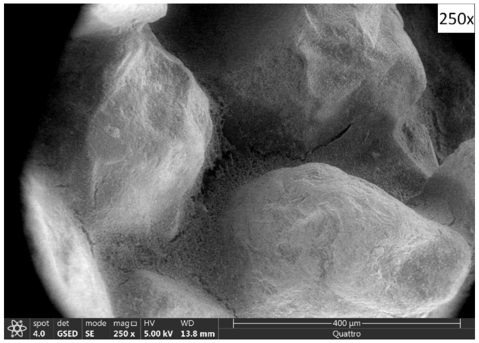




(Young et al. 2020, Moug et al. 2020)

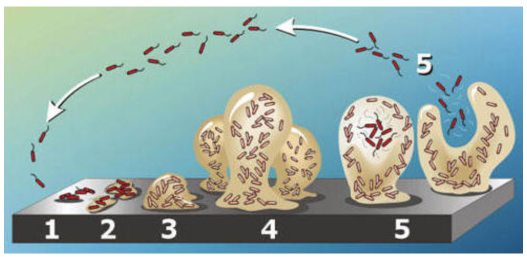
Bio-mediated Geotechnics

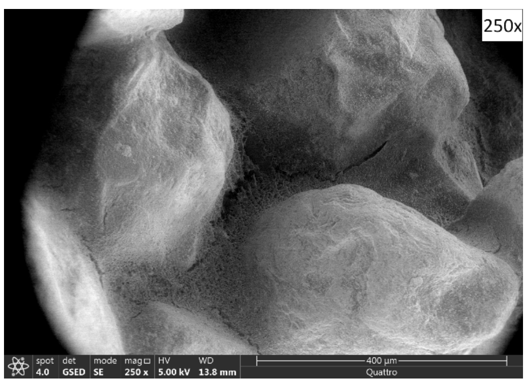
Biofilms

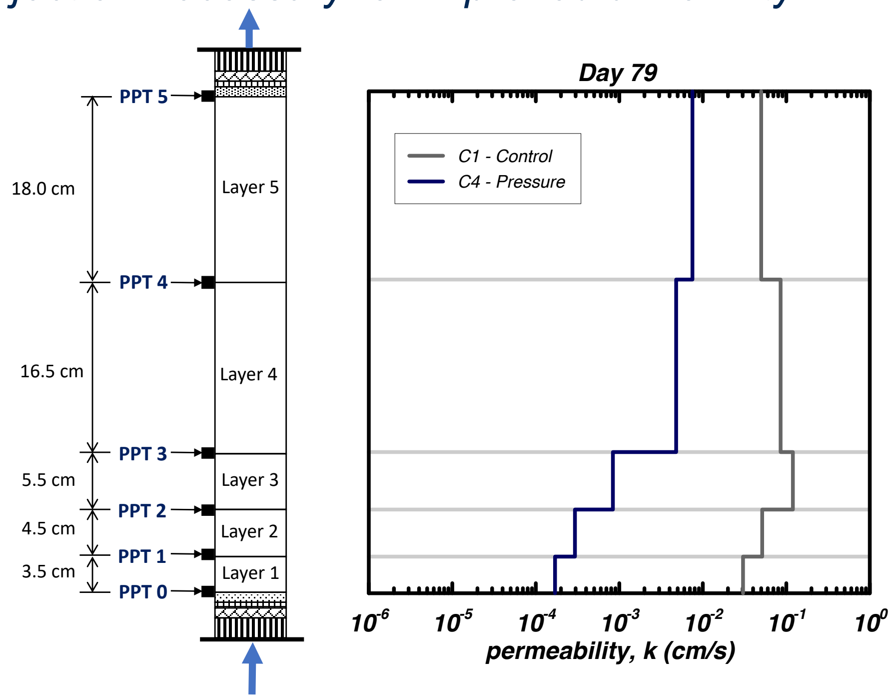


Biofilms

- ***Process:*** *formation of cells, excreted polymers, and solids that attached to particle surfaces*
- ***Microbiology:*** *stimulated microbes induce organic (reversible) precipitate*
- ***Microstructure:*** *biofilm coats and bridges adjacent particles*
- ***Mechanical Properties:*** *permeability reduction up to 1000x*
- ***Upscaling to Field:*** *constant pressure injection necessary for improved uniformity*



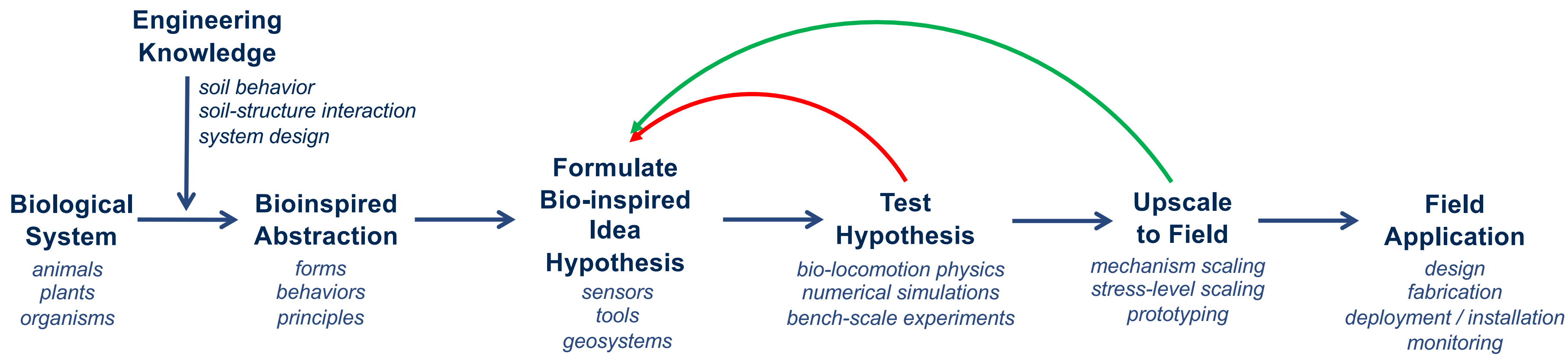




(Zamani et al. 2020, Proto et al. 2017, Stoodley et al., 2002)

Bio-inspired Geotechnics

Bio-inspired Geotechnics Approach



- *Key attributes:*
  - *Idea inspiration triggered by study of biological systems with engineering knowledge*
  - *Abstraction from biological system enables higher-order idea extraction*
  - *Hypothesis testing iterative to refine key principles*
  - *Upscaling challenges across stress and length scales*
  - *Potential to realize >10x improvements relative to BAU technologies*

(Martinez et al. 2020, DeJong et al. 2017, Helms et al. 2009)

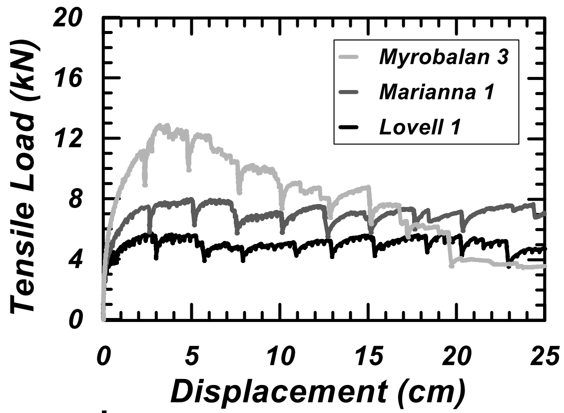
Bio-inspired Geotechnics

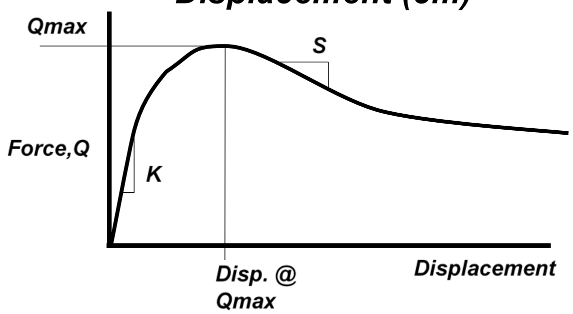
Tree-root Inspired Anchors & Foundations

Tree-root Inspired Anchors & Foundations

- ***Biological Systems:*** *multi-functional tree roots for stability, nutrient and water uptake, etc.*
- ***Engineering Knowledge:*** *deformation and capacity of foundation systems*
- ***Bioinspired Abstraction:*** *root architecture governs attributes of tree stability under H-V-M loading*
- ***Hypothesis:*** *non-linear root attributes can enable tunable foundation performance*
- ***Testing & Upscaling:*** *testing of orchard trees, 3D prototyping, CT scans, image analysis*

Lovell (peach) Root System



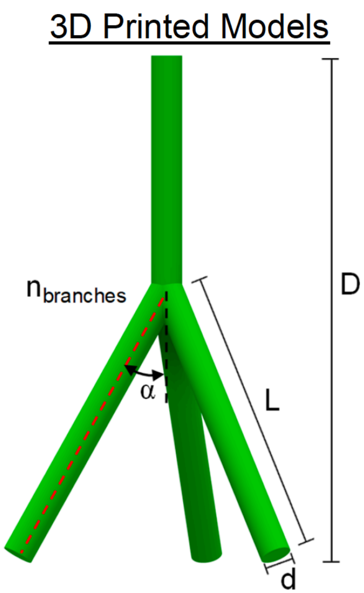


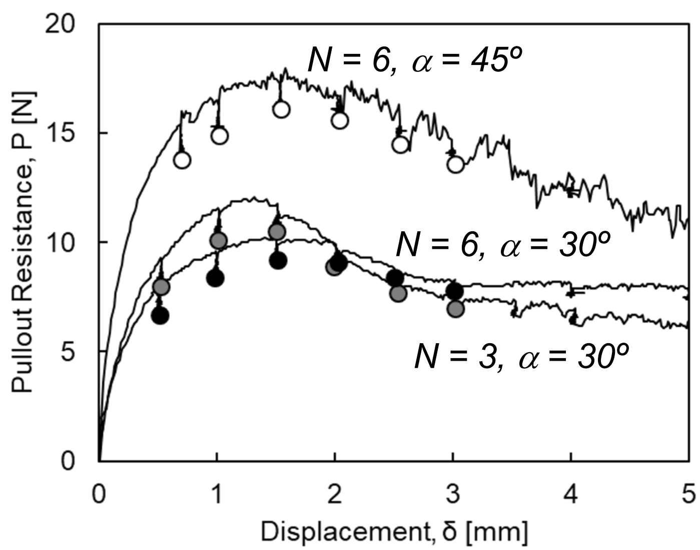
BAU Foundation Element	Mass Basis: $Q_{tree} / Q_{foundation}$	Volume Basis: $Q_{tree} / Q_{foundation}$
Micropile	*12.8*	*8.1*
Shallow Footing	*70.4*	*44.1*

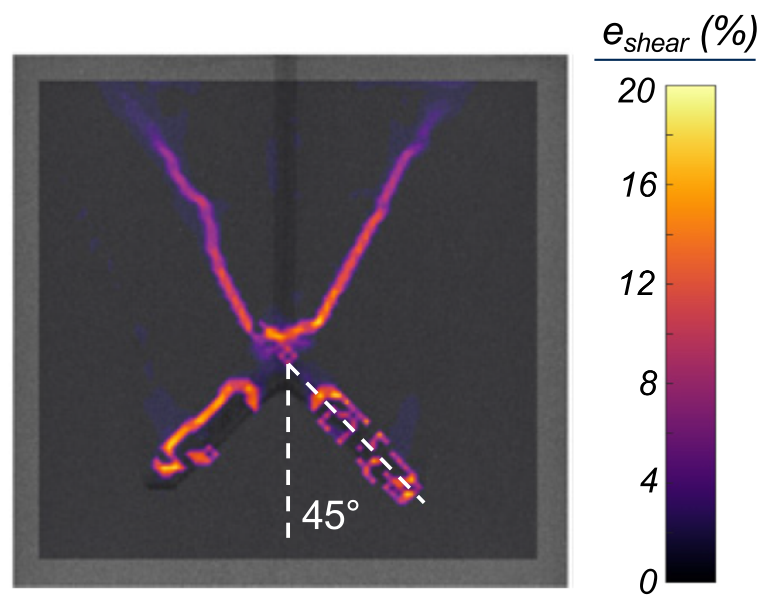
(Burrall et al. 2018, 2020)

Tree-root Inspired Anchors & Foundations

- ***Biological Systems:*** *multi-functional tree roots for stability, nutrient and water uptake, etc.*
- ***Engineering Knowledge:*** *deformation and capacity of foundation systems*
- ***Bioinspired Abstraction:*** *root architecture governs attributes of tree stability under H-V-M loading*
- ***Hypothesis:*** *non-linear root attributes can enable tunable foundation performance*
- ***Testing & Upscaling:*** *testing of orchard trees, 3D prototyping, CT scans, image analysis*







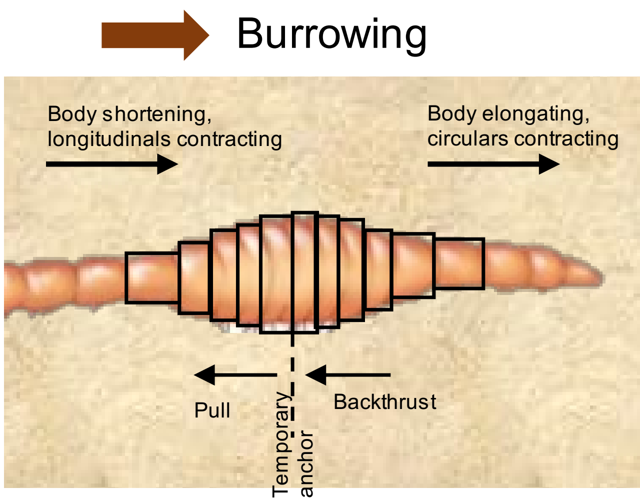
(Mallett et al. 2018, Mallett 2019)

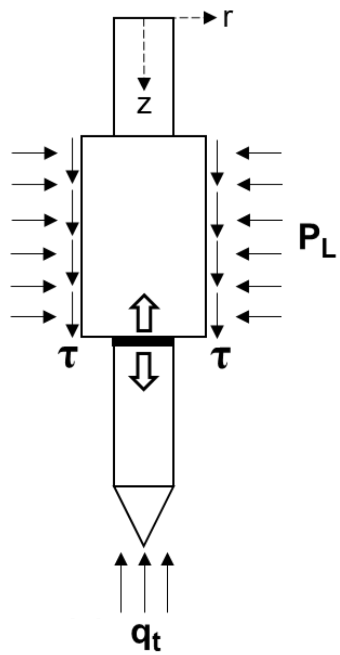
Bio-inspired Geotechnics

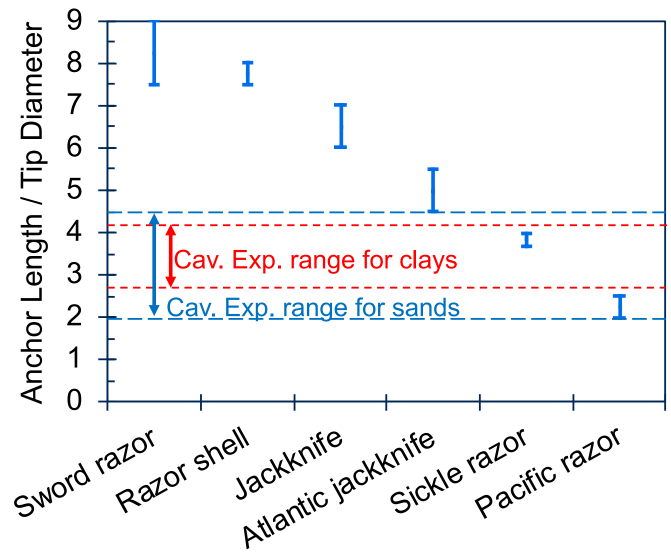
Invertebrate Inspired Soil Penetration

Invertebrate Inspired Soil Penetration

- ***Biological Systems:*** *earth and marine worms, clams, etc.*
- ***Engineering Knowledge:*** *penetration resistance and cavity expansion*
- ***Bioinspired Abstraction:*** *motion sequence and shape of invertebrates govern burrowing ability*
- ***Hypothesis:*** *peristaltic motion that increases anchorage forces and decreases penetration resistance can enable development of self-penetrating sensors and probes*
- ***Testing & Upscaling:*** *cavity expansion analysis, DEM simulations, robot prototyping*







(Khosravi et al. 2020, Saga et al. 2016)

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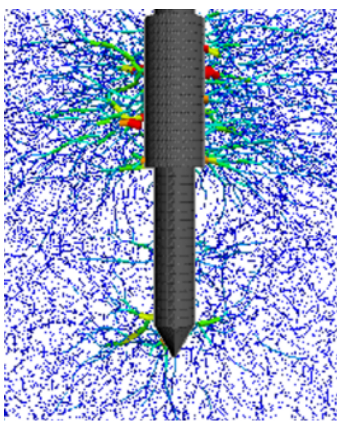
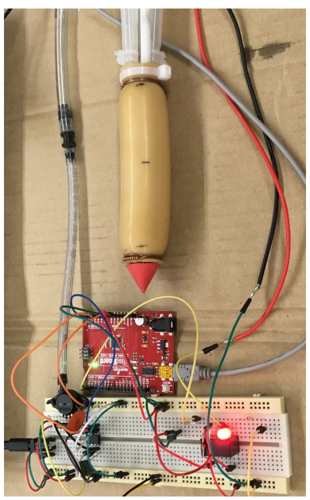
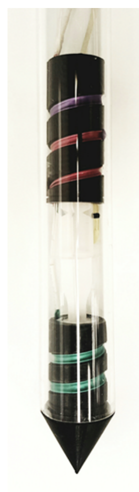


(Martinez)

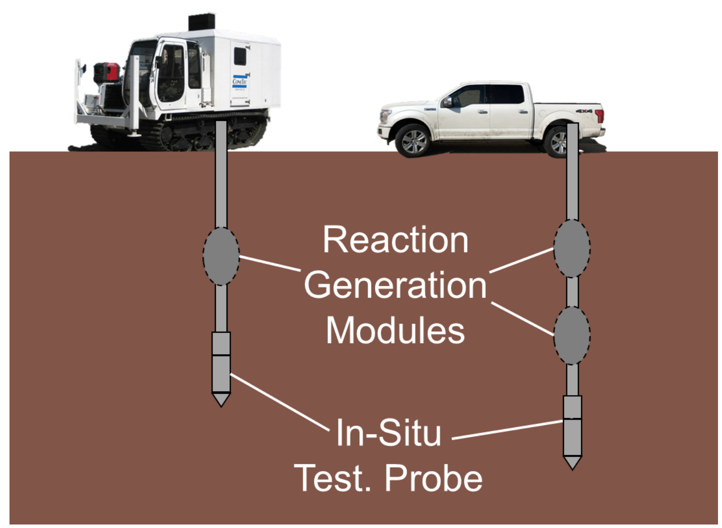


(Tao)



(Cortes)

(Frost)



(Borela et al. 2020, Chen et al. 2020, Cortes 2020, Huang & Tao 2020, Martinez et al. 2019)

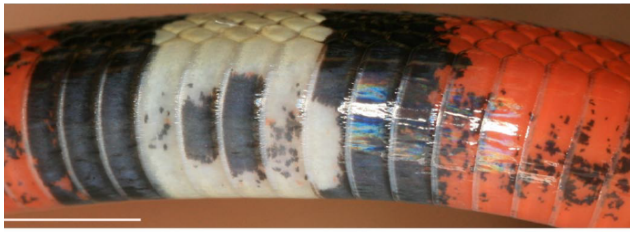
Bio-inspired Geotechnics

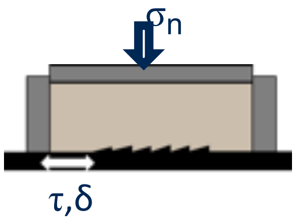
Snakeskin Inspired Anisotropic Friction for Piles

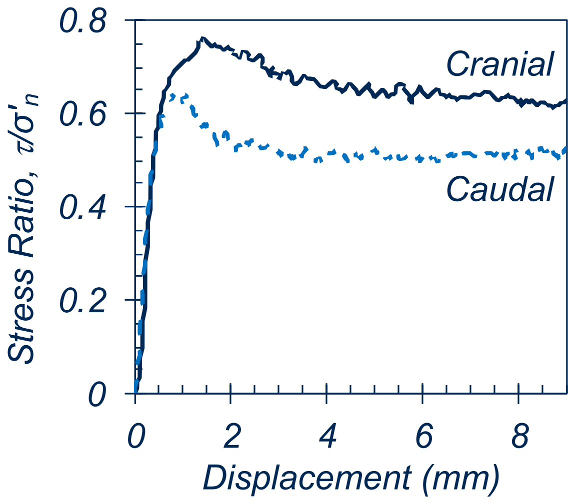
Snakeskin Inspired Anisotropic Friction for Piles

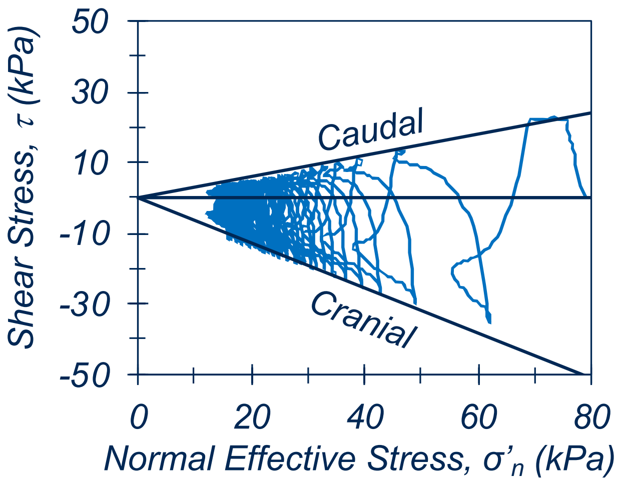
- ***Biological System:*** *interaction of snake scales against different surfaces*
- ***Engineering Knowledge:*** *soil-structure interface behavior*
- ***Bioinspired Abstraction:*** *anisotropic scale shape enables bias load transfer*
- ***Hypothesis:*** *anisotropic soil-structure interfaces can reduce installation resistance and increase pullout capacity*
- ***Testing & Upscaling:*** *3D printed surfaces tested in interface direct shear w/ GeoPIV image analysis, centrifuge modeling*

(O'Hara and Martinez 2020, Hu et al. 2009)









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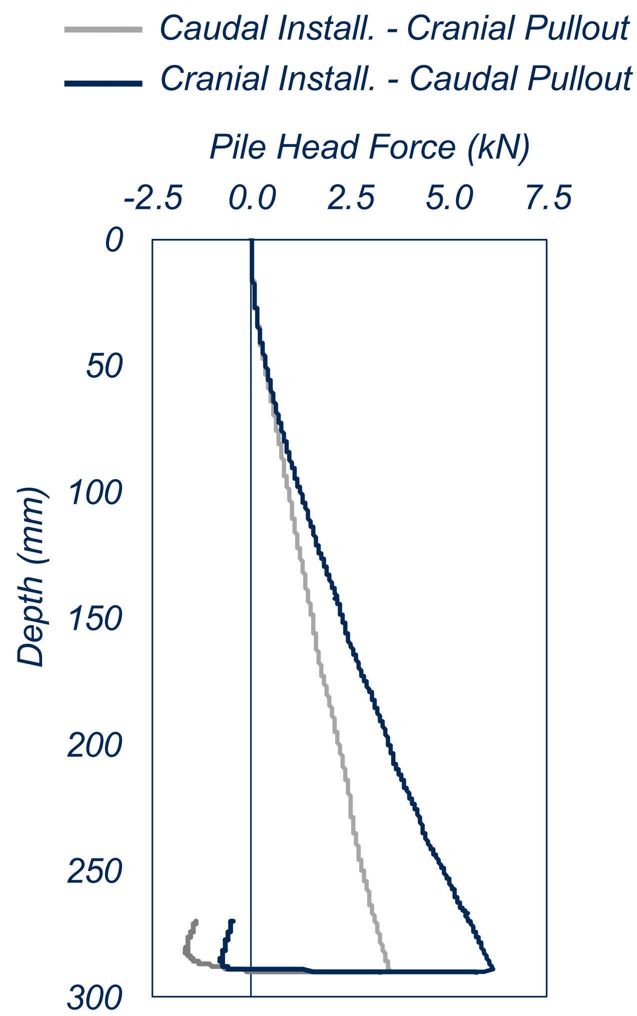
UCD 9 m Centrifuge



Closure

Priorities & Opportunities

Closure

- *The creative solutions in nature are site-specific, efficient, multi-functional, and sustainable. Collectively they can be a great source of inspiration.*
- *The LCSA tool can provide a quantitative framework to make project decisions informed by environmental indicators alongside performance and cost metrics. The future competitiveness against BAU technologies can also be systematically evaluated.*
- *Bio-mediated geotechnical solutions harness natural, tunable, bio-geo-chemo-mechanical processes that can produce 10% to 10,000% changes in soil engineering properties (e.g. strength, stiffness, permeability). Biocementation and biogas technologies have been deployed in the field, and emphasis is shifting towards optimization and competitiveness.*
- *Bio-inspired geotechnical ideas are based on biological solutions that can be 1,000% more efficient than BAU technologies and provide new opportunities to develop more sustainable solutions. Ideas currently being explored could revolutionize different industry sectors.*
- *The field of biogeotechnics is still young, and only a small fraction of processes and ideas are being explored (and even fewer have been presented herein). It is likely, if not certain, that some of the most impactful solutions are yet to be discovered.*

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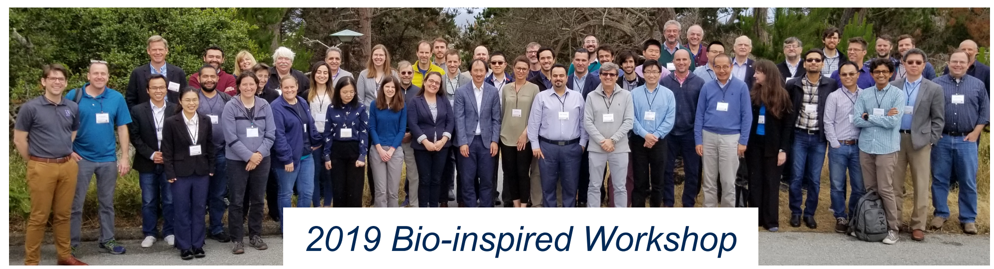
Arizona State University

Georgia Institute of Technology

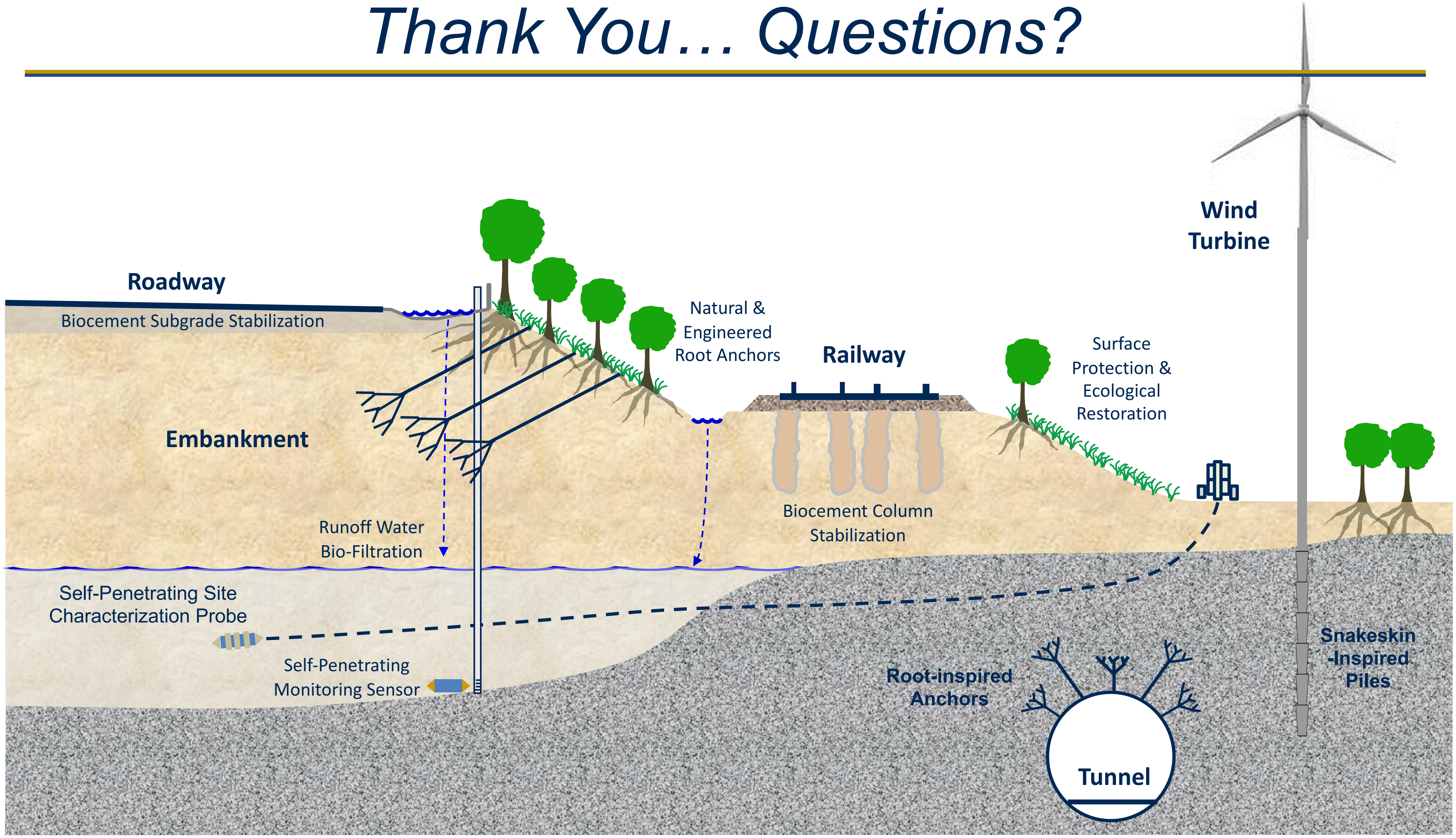
NM STATE



2019 Bio-inspired Workshop

2007 & 2011 Bio-mediated Workshops

Thank You… Questions?



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