CBBG Center for Bio-mediated & Bio-inspired Geotechnics

Biogeotechnical Mitigation of Earthquake-Induced Soil Liquefaction

By

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Biogeotechnical Engineering

An emerging sub-discipline in geotechnical engineering that includes:

- Bio-mediated Processes: managed and controlled through biological activity (living organisms)
- Bio-inspired Processes: biological principles employed to develop new, abiotic solutions (no living organisms)
    - Includes Nature-inspired abiotic processes

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

Four leading academic institutions

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

Seed funding provided by NSF

- Gen-3 ERC
- Research and education
- $18.5 million for 5 years

Industry Partnership program

- 23 Consultants, Contractors, Owners, Agencies

CBBG Vision

Learn from nature

- Nature has had 3.8 billion years of trial and error (evolution) to get it right

Develop nature-compatible solutions for resilient, sustainable infrastructure development

- Solutions of first resort
- Minimize “carbon footprint” (e.g., greenhouse gas generation) and use of non-renewable resources
- Mitigate natural and man-made geotechnical hazards

Bio-Geo-Chemo-Mechanical Natural Processes

Mineral precipitation

Chemical transformation

Biopolymer generation

Motile (self propelled) organisms

Root support/reinforcement systems

Biogeotechnical challenge: Mobilize these processes for beneficial use

CBBG Technologies (Thrusts)

Hazard Mitigation

- Earthquake-Induced Liquefaction

Environmental Protection

- Surface and Ground Water Remediation

Infrastructure Construction

- Fugitive Dust Control
- Foundations and Ground Anchors

Subsurface Exploration

- More Efficient and Self-Boring Probes

Example: Calcium Carbonate ($CaCO_3$) Precipitation

One of the most common minerals in nature

Most studied process in biogeotechnical engineering

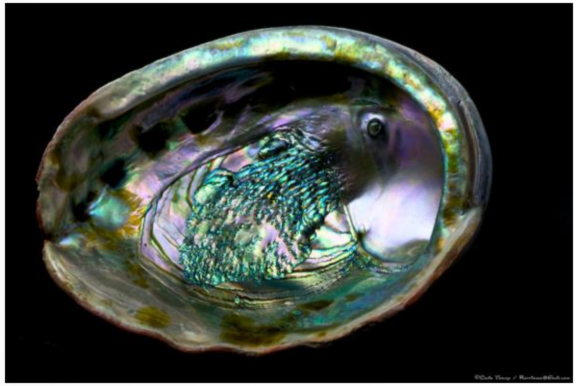
- Increases strength, stiffness, dilatancy

Many $CaCO_3$ precipitation mechanisms

- Some anthropogenic
- Some generate biogas (→ desaturation)

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

Carbonate Precipitation on an Engineering Time Scale
(often non-desired)



www.mendonomasightings.com/

Mollusk shells

Mineral scale on pipes

Fouling of well screens

Clogging of water treatment plant filters

Clogging of drainage systems in dams, landfills, and tailings piles

Carbonate Precipitation on a Geologic Time Scale

Cemented sand

Carbonate sediments

Gypsum nodules

Stalactites, stalagmites

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

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The Biogeotechnical Challenge

Accelerate beneficial processes to occur in a time frame of interest

and/or

Induce adverse processes in a context where the effect is beneficial

JennBredemeier.deviantart.com

Carbonate Precipitation Mechanisms and Polymorphs

Mechanisms

Process	End Products	Undesirable Side-Effect
Ureolysis (Microbial and Free Enzyme)	NH_3 (ammonia) NH_4^+ (ammonium)	Toxic gas Toxic salts, acidification
Sulfate Reduction	H_2S (hydrogen sulfide)	Toxic gas
Fermentation of Fatty Acids	CH_4 (methane)	Explosive gas
Denitrification	N_2 (nitrogen)	None

Note: microbial methods may be via augmentation or stimulation

Polymorphs

- Calcite (preferred)
- Vaterite and Aragonite
- Amorphous (least stable)

Potential Applications

Justanothercinemanic.tumbl.com

Liquefaction mitigation

Bearing capacity

Tunneling and excavations

Slope stabilization

Fugitive dust / erosion control

“Bio-bricks”

Mitigation of Liquefaction

Densification: Vibration, cavity expansion

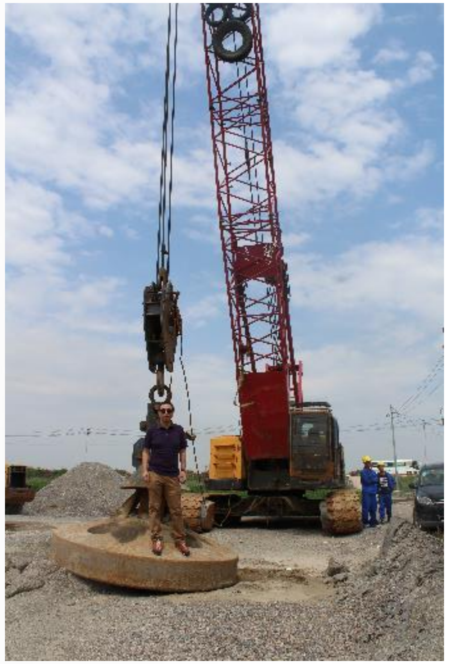
- Disruptive to existing facilities

Reinforcement: Soil mixing, stone columns

- Not beneath existing facilities, disruptive

Grouting: Penetration, compaction grouting

- Limited applicability, expensive



➡ **No cost effective mitigation for existing facilities**

Biogeotechnical Liquefaction Mitigation

Three different biogeotechnologies

- Microbially Induced Carbonate Precipitation (MICP) via ureolysis
- Enzyme Induced Carbonate Precipitation (EICP) via ureolysis
- Microbially Induced Carbonate Desaturation and Precipitation (MIDP) via denitrification

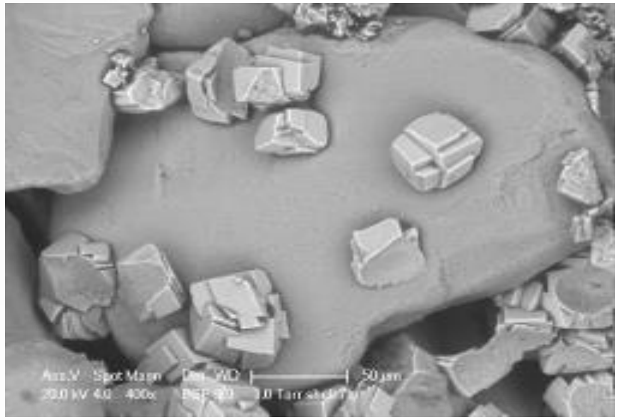
Photos courtesy of www.geerassociation.org

Hydrolysis of Urea (Ureolysis)

Most studied $CaCO_3$ precipitation mechanism
- Western Australia, Delft, Cambridge, UC Davis
- Precipitation increases peak strength, dilatancy

Advantage
- Rapid improvement

Limitations
- May be limited to fine sand or coarser soil
- Ammonium chloride by-product



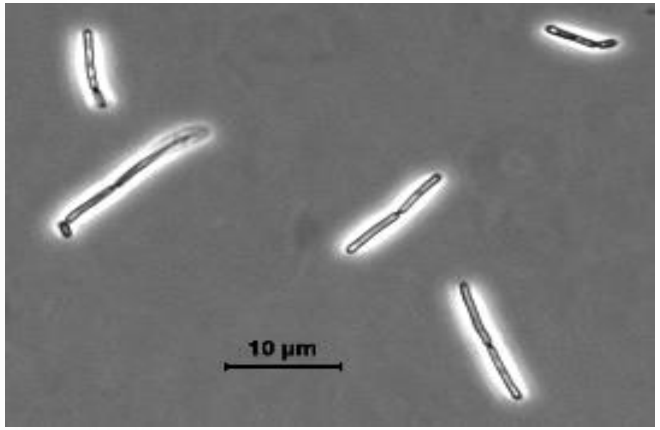
MICP and EICP

MICP via ureolysis (Bio-mediated)

- Microbes produce urease enzyme

EICP via ureolysis (Bio-inspired)

- Urease derived from agricultural sources (Jack Bean)



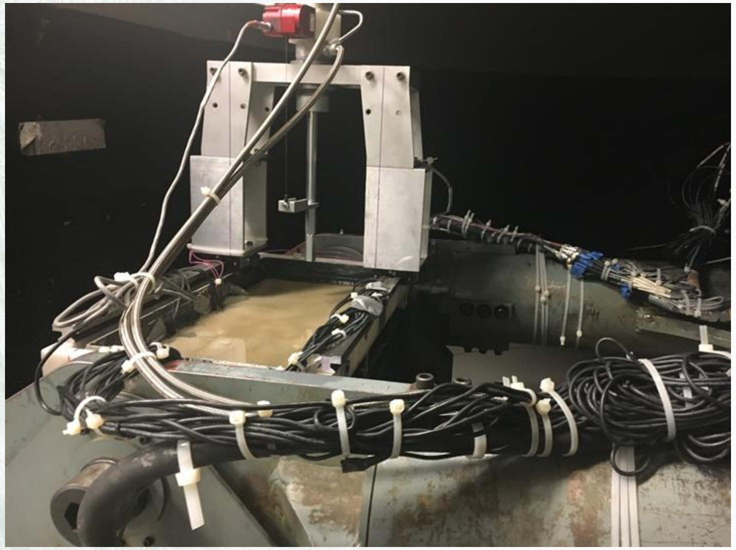
Sporosarcina pasteurii

Jack Bean

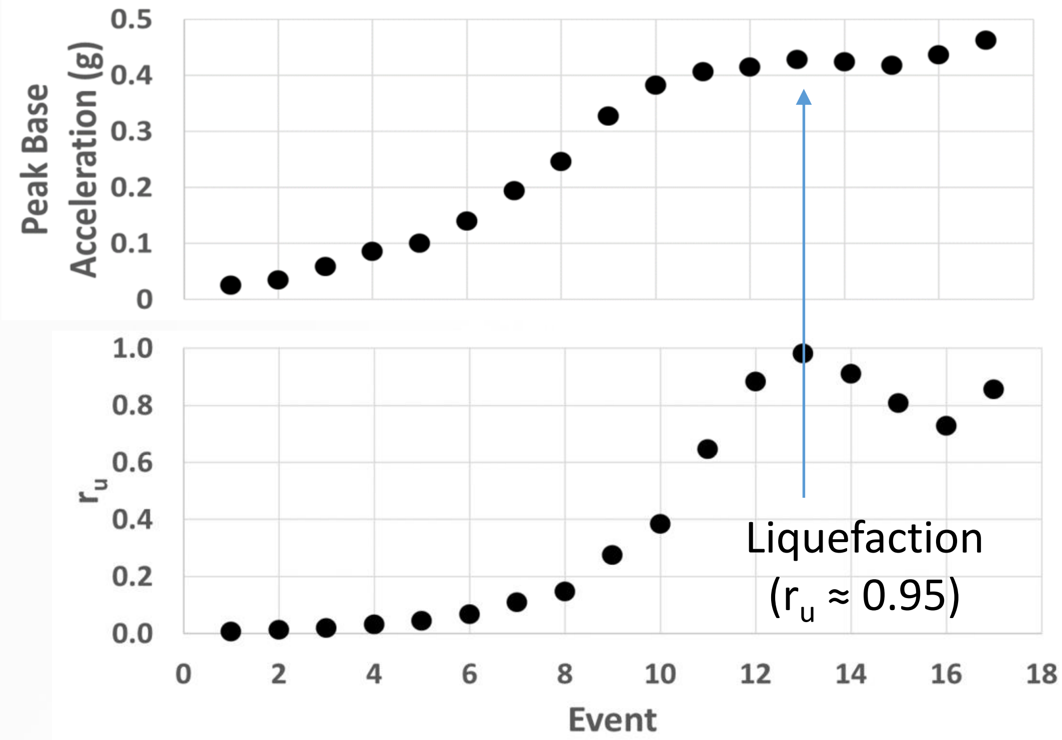
Liquefaction Mitigation via MICP

Centrifuge Testing at UC Davis on lightly-cemented (**≈ 1.2% $CaCO_3$**) Ottawa F-65 sand (D_R = 40%)

Eighteen (18) “Events” of 15 cycles of uniform loading



Centrifuge model and CPT rack .



EICP Columns

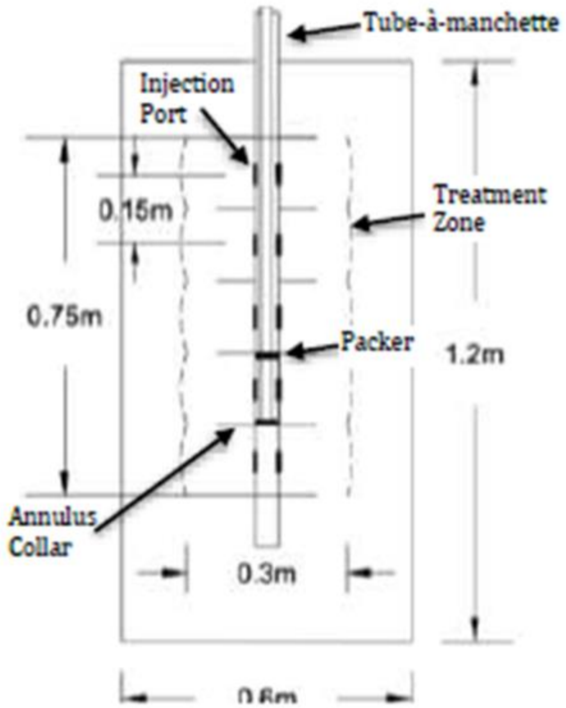
Installed using *tube-a-manchette*

After 3 injections:

- UCS > 500 kPa
- $CaCO_3$ content < 3%

Field scale tests in progress

Costs currently ≈ \$60/m^3



Box Schematic

Exposed EICP Bio-cemented Soil Column

MIDP via Denitrification

Relies on dissimilatory reduction of nitrate (denitrification)

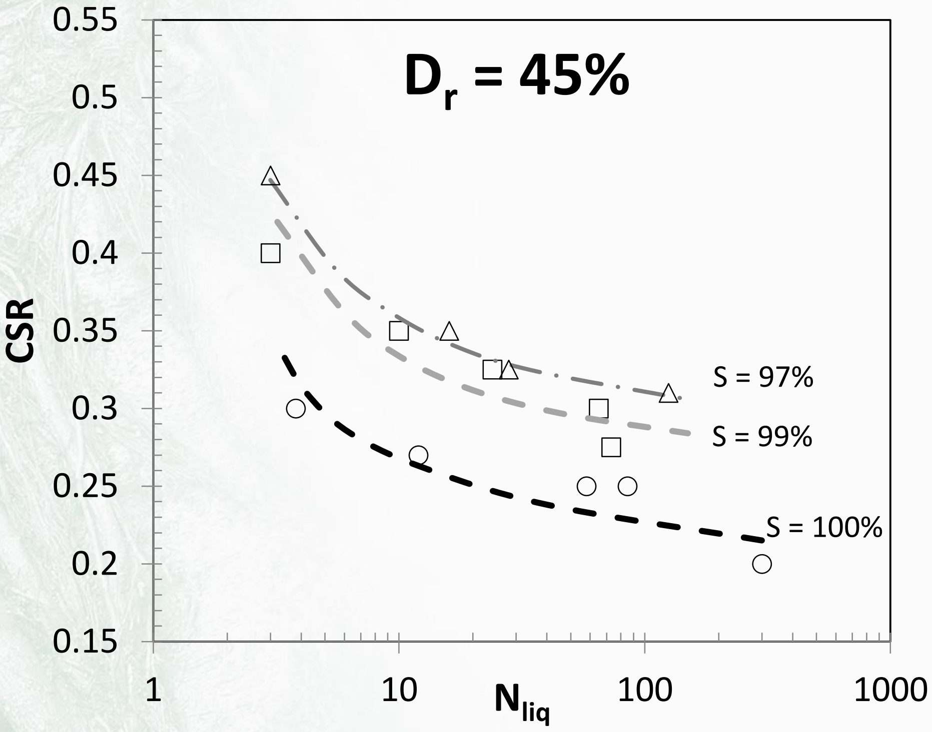
- Need nutrients, calcium source
- Uses (ubiquitous) indigenous microbes

Two Stage Process

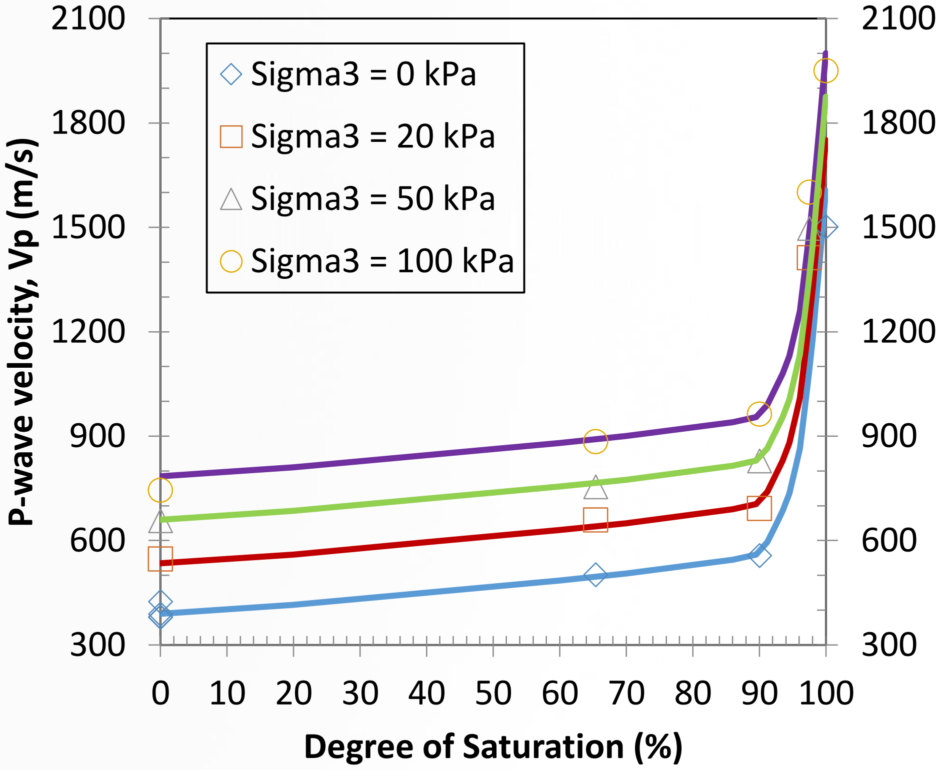
- Stage 1: Microbial desaturation
- Stage 2: Carbonate precipitation

Stage 1: Desaturation: Abiotic Testing (Ottawa 20-30 Sand)

Cyclic DSS testing



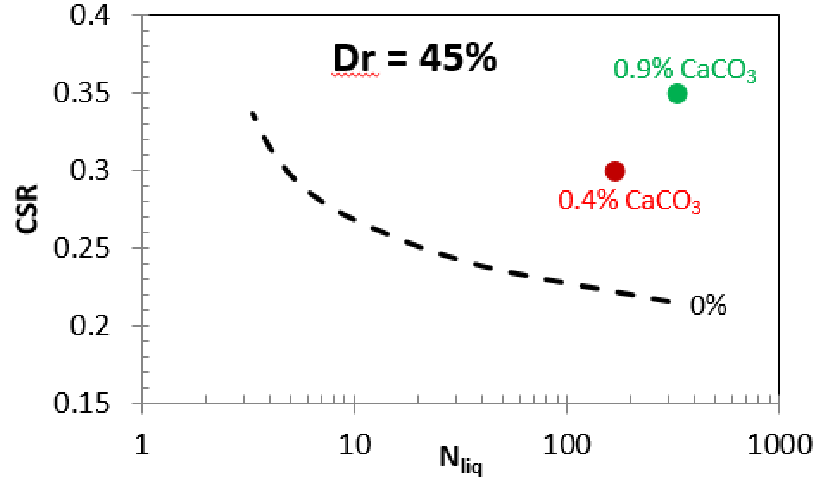
Correlate V_p with S_r



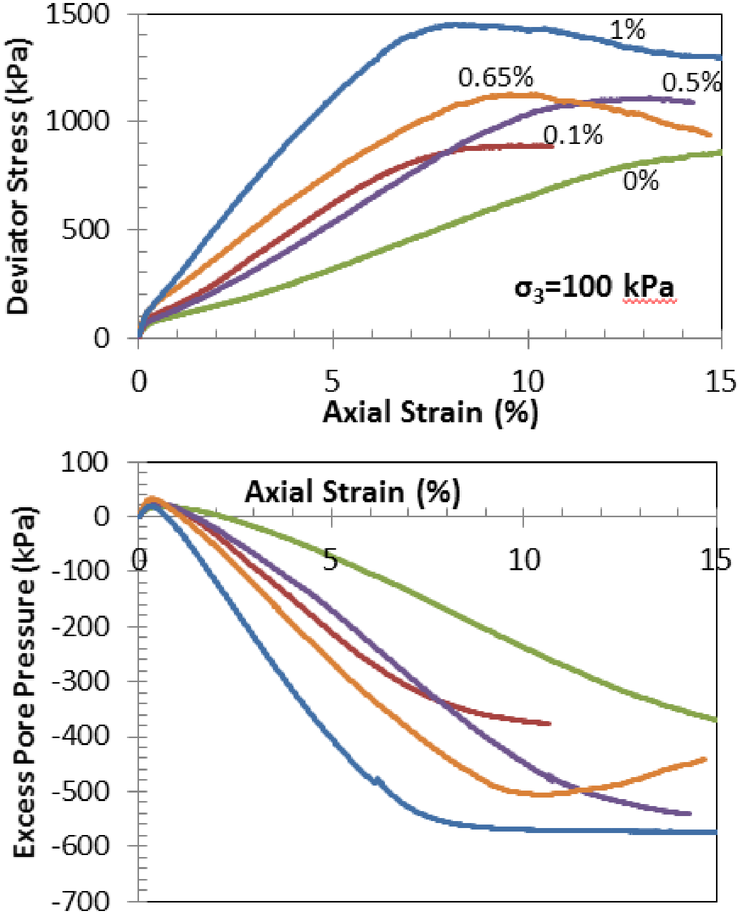
O'Donnell et al. (2016A, 2016B)

Stage 2: Carbonate Precipitation

CyDSS and TX Testing (Sr = 100%)



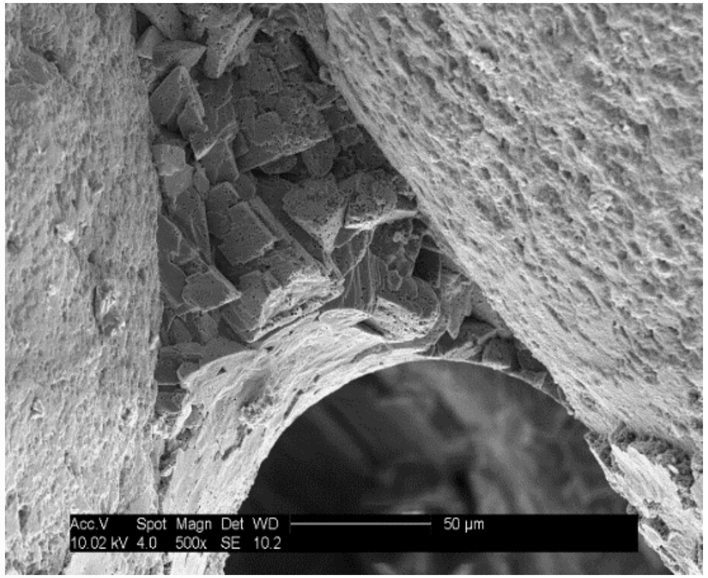
O’Donnell et al. (2016B)



Yang et al. (2016)

Increase in stiffness, dilatancy, strength of treated columns (even after failure)

MIDP: Key Findings



O'Donnell (2015)

Abiotic Experiments:

- Small amount of desaturation leads to significant increase in liquefaction resistance

Biotic Experiments:

- Small amount of calcite precipitation leads to significant increases in dilatancy, stiffness, strength, cyclic resistance

Conclusion: Denitrification shows promise for mitigation of liquefaction potential as <u>a two-stage process</u>

Issues to Consider (all Biogeotechnologies)

- Cost
- QA/QC
- Durability
- Environmental impacts
- Unanticipated side effects

- **Implementation at field scale**

How to realize a field demonstration?

1. Find a project site / owner / contractor
2. Define the treatment recipe
3. Inject substrates in the ground
4. Monitor biochemical conversion.
5. Remove the remaining by-products (if necessary).

Project site: Toronto, Ontario Summer 2018

- Redevelopment project.
- Hydrocarbon contaminated soils
- Running' sands
- Bioengineered banks
- Enable stable excavation of a steep underwater slope (1:2)

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Field trial in Toronto, Ontario summer 2018

Port Lands Area – Soil & Groundwater Remediation and Treatment Technologies – Part B: Field-Scale Pilot Testing:

Ethical Solutions - surfactant enhanced injection combined with chemical oxidation technology *($278,100)*

Geosyntec Consultants – demonstration of self-sustaining smouldering remediation in both in-situ and ex-situ environments technology *($869,110)*

Groundwater Technology BV* - in-situ biological cementation using urea-based solution to enhance geotechnical stability of soils technology *($313,022)

WATERFRONToronto

Arizona State University

TU Delft

Groundwater Technology

ACCUWORX INC.™ Taking On The Toughest Jobs™

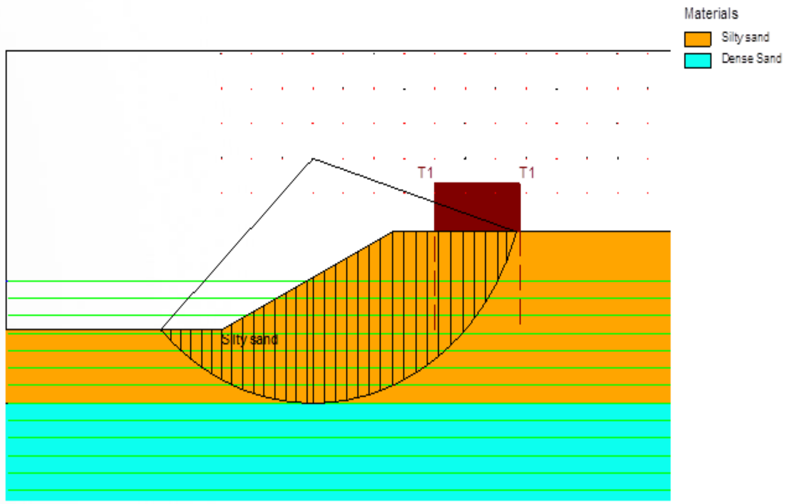
Deltares Enabling Delta Life

Define the recipe: set the target

Slope stability assessment:

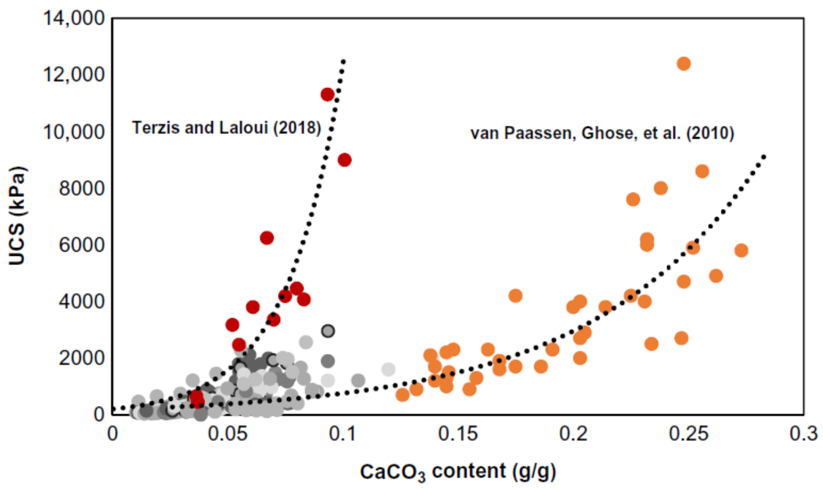
Factor of Safety 1

- Drained: Mohr-Coulomb model: cohesion = 5 kPa, Phi = 20 degrees
- Undrained: cohesion >16 kPa required



Cementation:

- 1 to 3 % of $CaCO_3$ by dry weight



Define the recipe: select the process

Urea hydrolysis

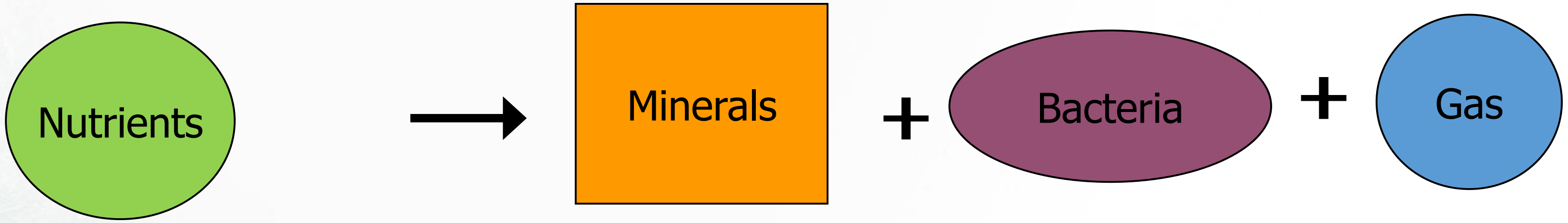
Urease enzymes

ureum + calcium chloride → $CaCO_3$ + ammonium chloride

Denitrification

Denitrifying bacteria

calcium-fatty acid + calcium nitrate → bacteria + $CaCO_3$ + N_2(g)



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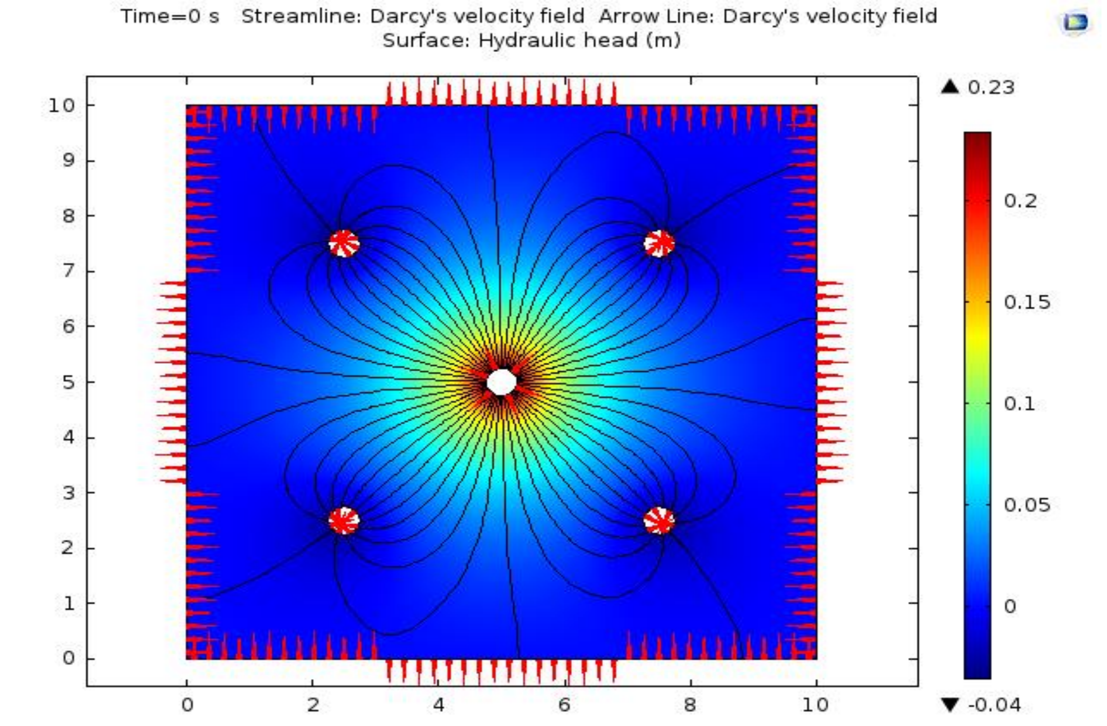
Inject the substrates

- What is the well configuration?
- What is the well distance?
- What flow rate?
- What concentration?



4 injection wells + 1 extraction well

Closed water balance

Simulation Results

Find the right balance between:

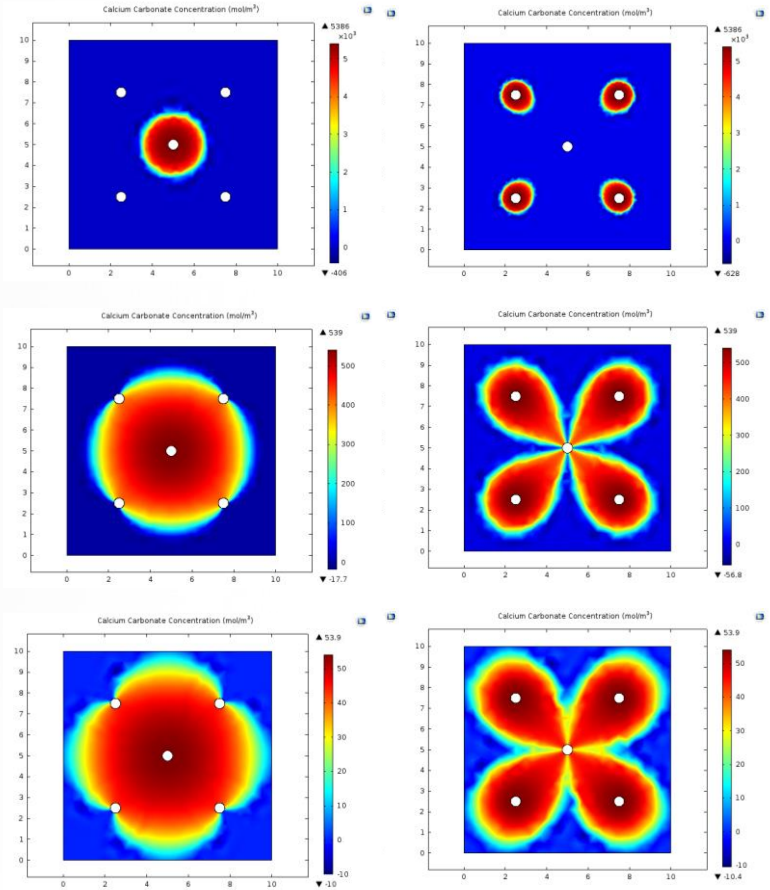
- concentrations,
- reaction rate (reaction time)
- flow rate (hydraulic residence time)

Outward flow   Inward flow

Reaction rate > Flow rate

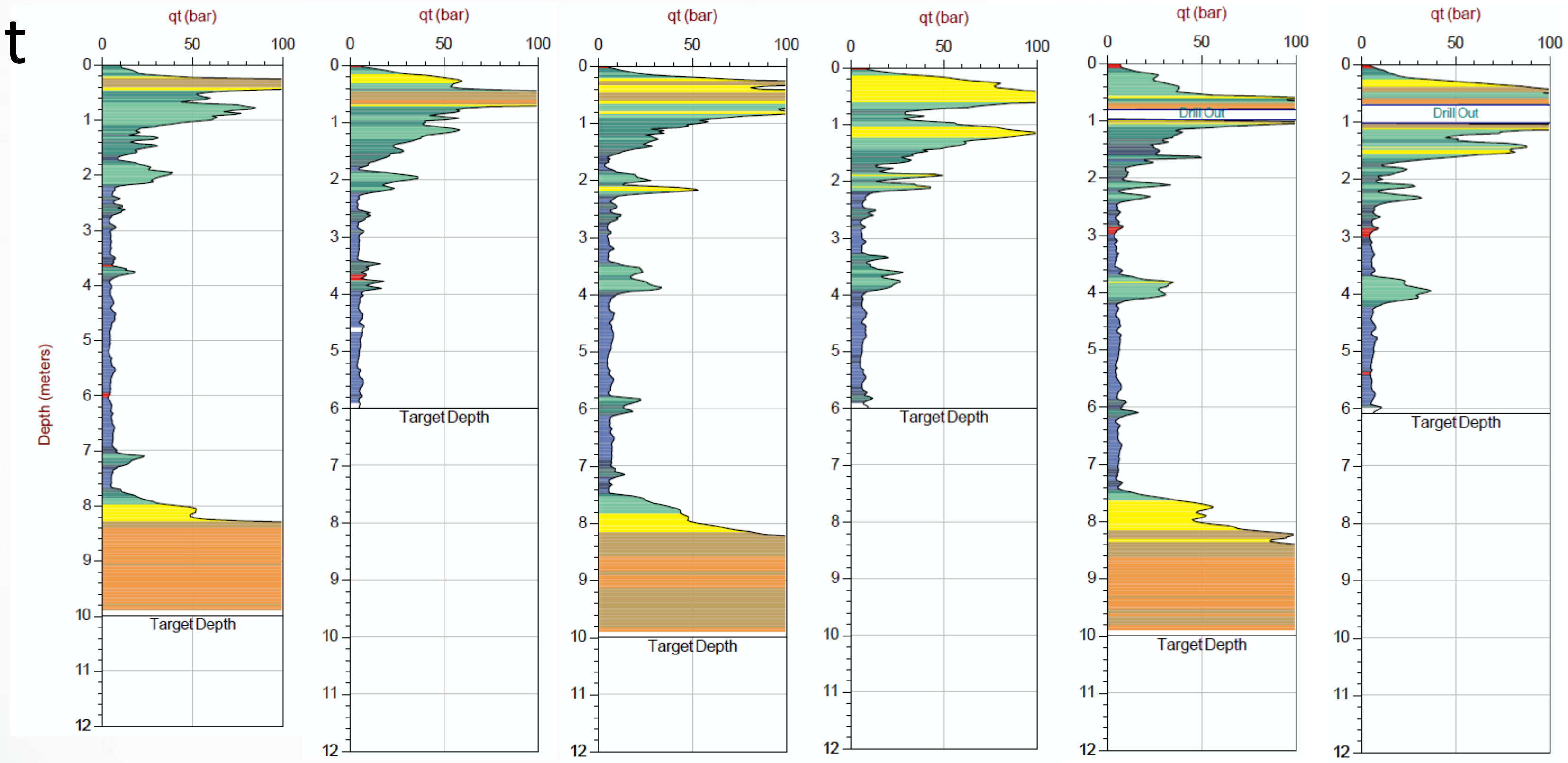
Reaction rate = Flow rate

Reaction rate < Flow rate



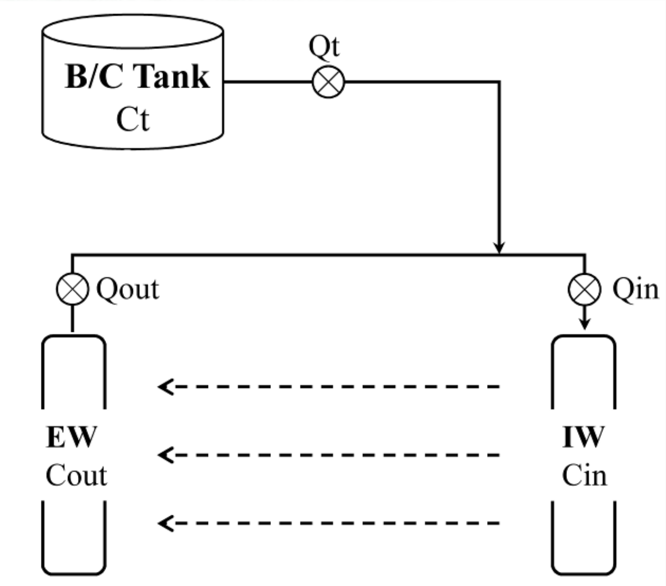
Site characterization : Cone penetration test results

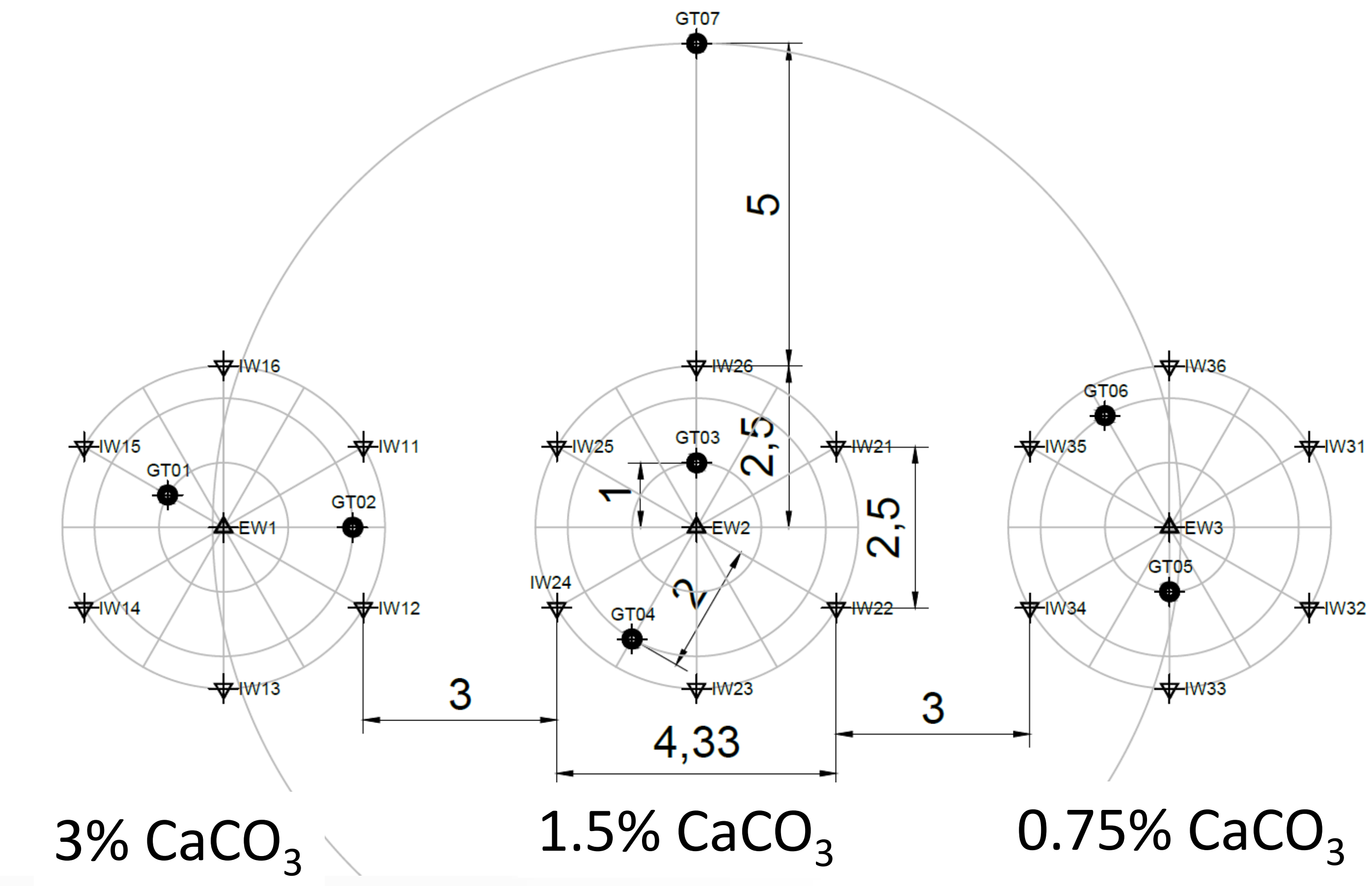
- Mostly clay and silt
- Problem??



Field implementation

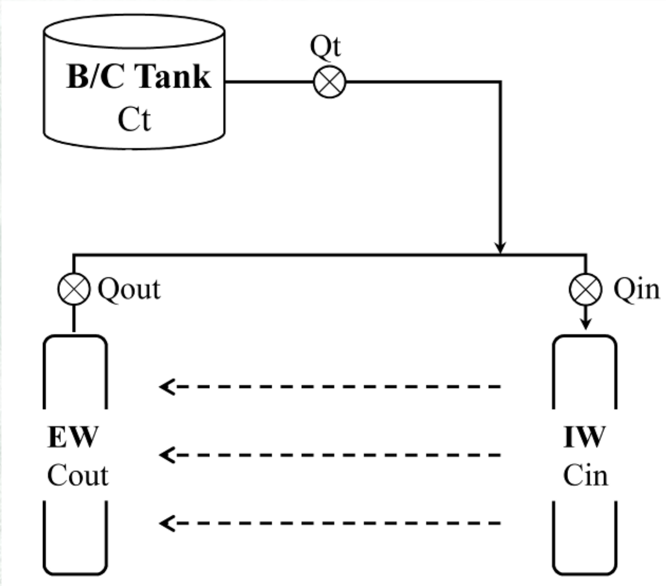
- Final well plan: 3 plots





Field implementation

- Final well plan



Monitoring

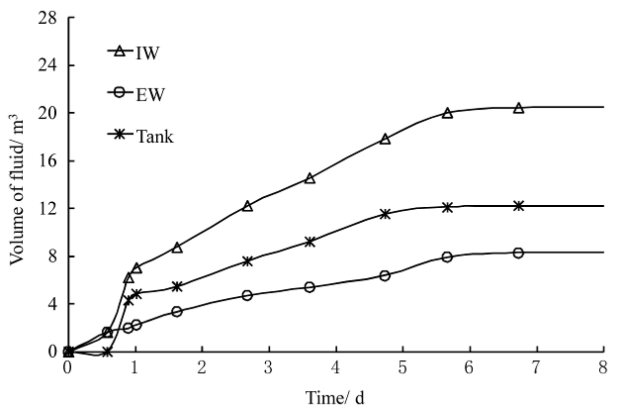
- Flow rates
- Groundwater monitoring and sampling
- SCPTU
- Seismic analysis
- Trenching
- Sampling

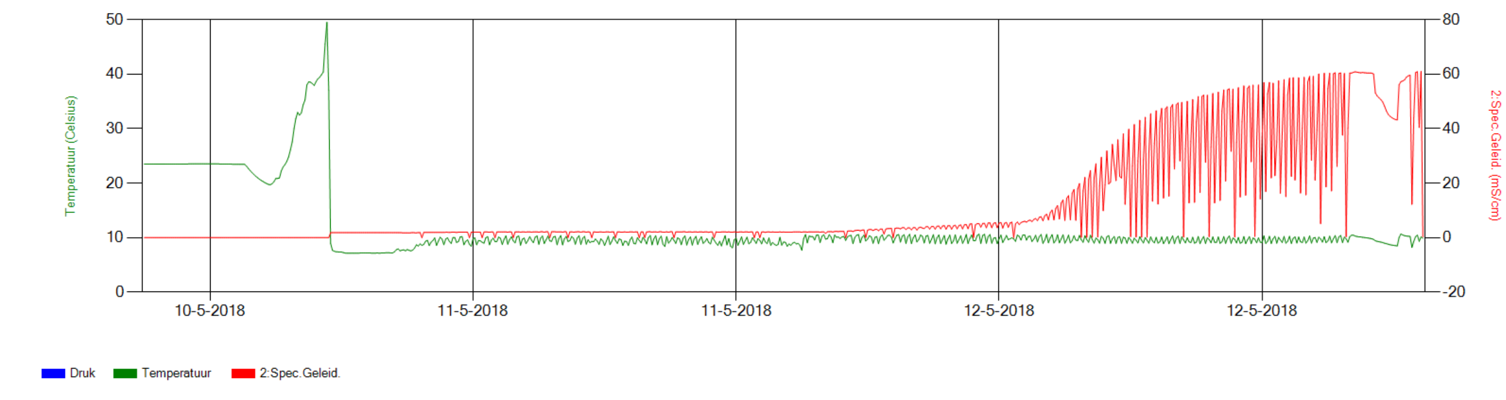
Monitoring

Flow rate

CTD Divers in extraction and monitoring wells:

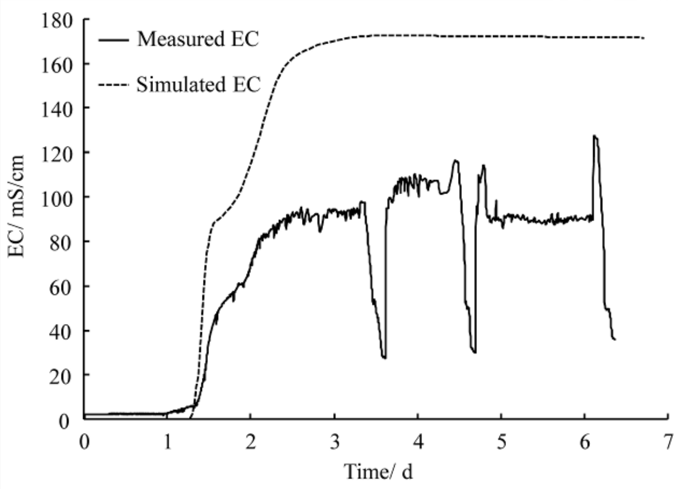
- Precipitation on the diver!
- Electrical conductivity indicated conversion!

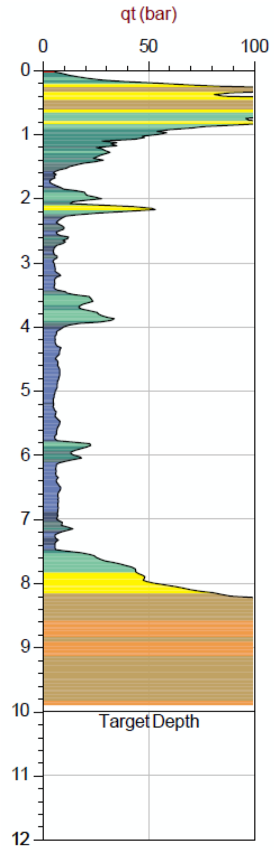




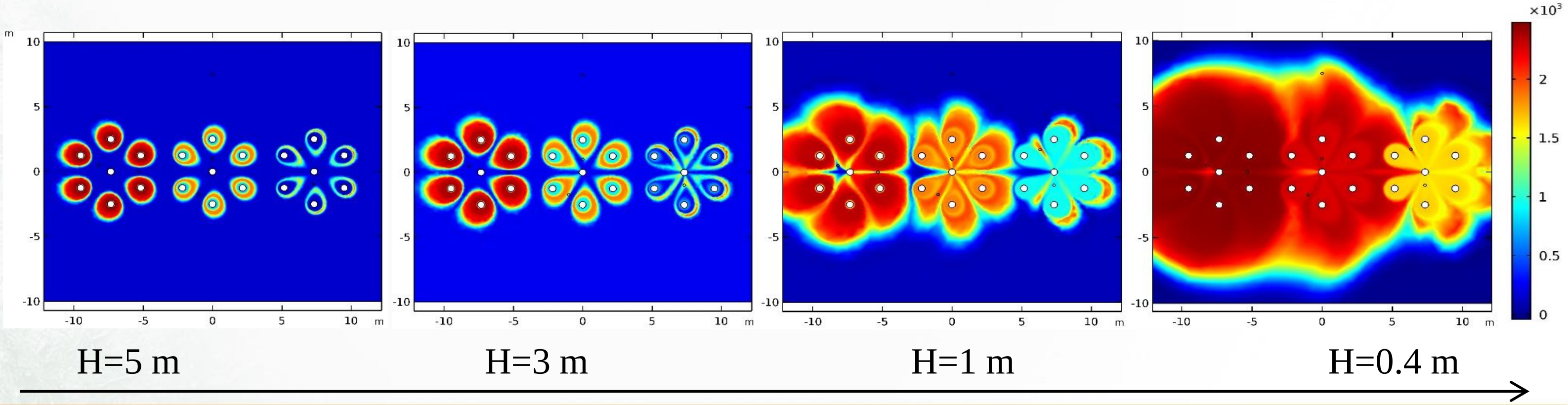
Simulation of the monitoring results

- Lower flow rate than anticipated
- Fast 'breakthrough'



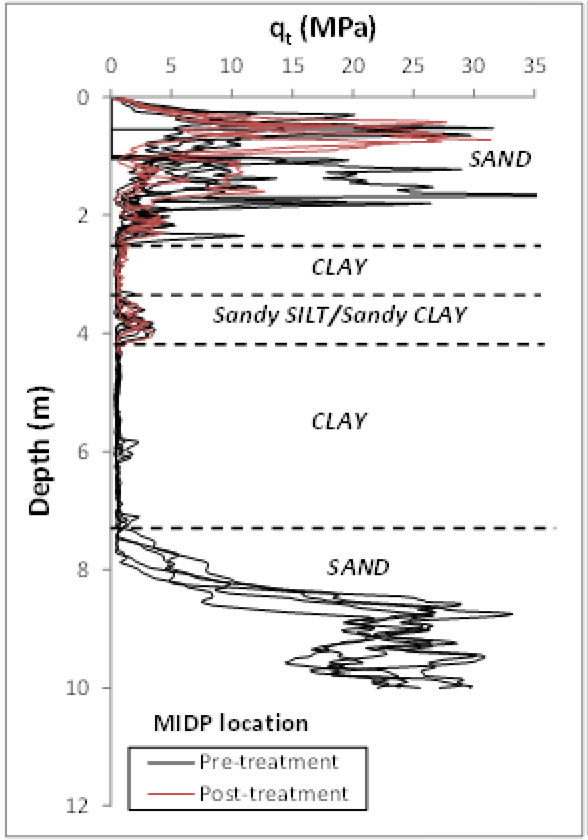


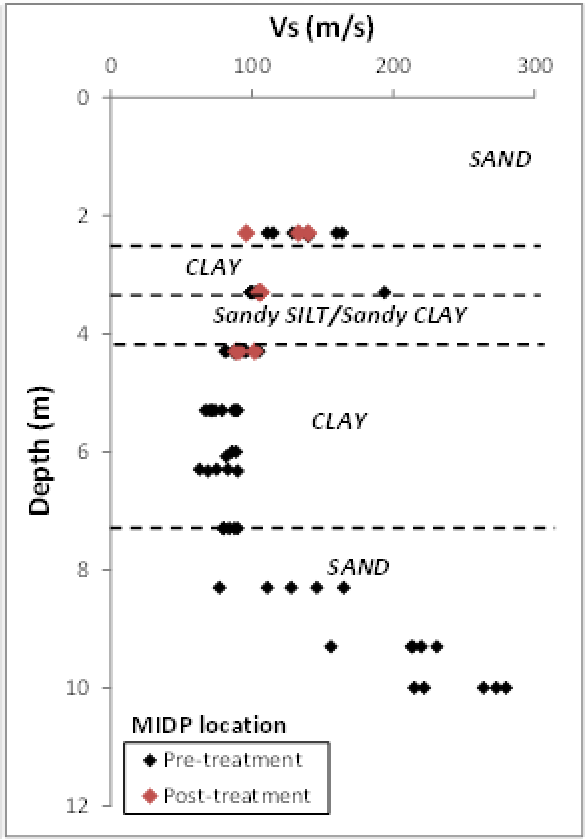
- Preferential flow



Seismic cone penetration tests

- Cone resistance
- S-wave velocity
- No measurable strength increase!



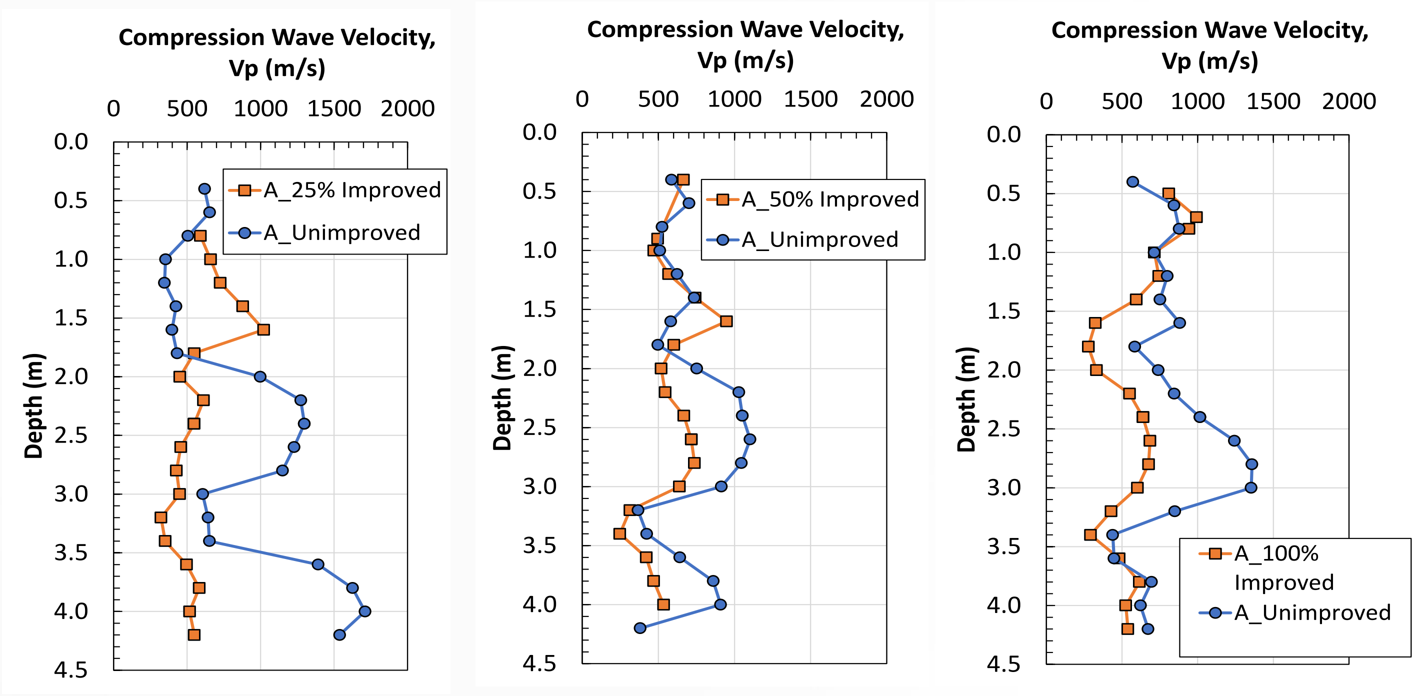


Seismic post analysis

- RAPID grant
- NHERI@UTexas: the large “T-Rex” hydraulic shaker and the mobile instrumentation laboratory
  - Liquefaction resistance
  - Crosshole shear wave velocity measurements

Seismic analysis – P-wave velocities

Reduced P-wave velocity MIDP location!



Ira A. Fulton Schools of Engineering Arizona State University

UC DAVIS UNIVERSITY OF CALIFORNIA

Georgia Institute of Technology

NM STATE UNIVERSITY

NSF

Trench excavation and sampling

Preliminary Conclusions – Lessons learned in Toronto

- Demonstrated evidence: MICP and MIDP can be implemented at field scale.
- Evaluated injection, mixing, monitoring and sampling methods are available.
- Limited evidence on the obtained strength
- Reactive Transport models are available and useful (although limited predictability)

A happy client!

Preliminary Conclusions – Lessons learned in Toronto

But what about

- Costs?
- QA/QC?
- Environmental impact?

- Search for applications, projects, potential clients, contractors and stakeholders

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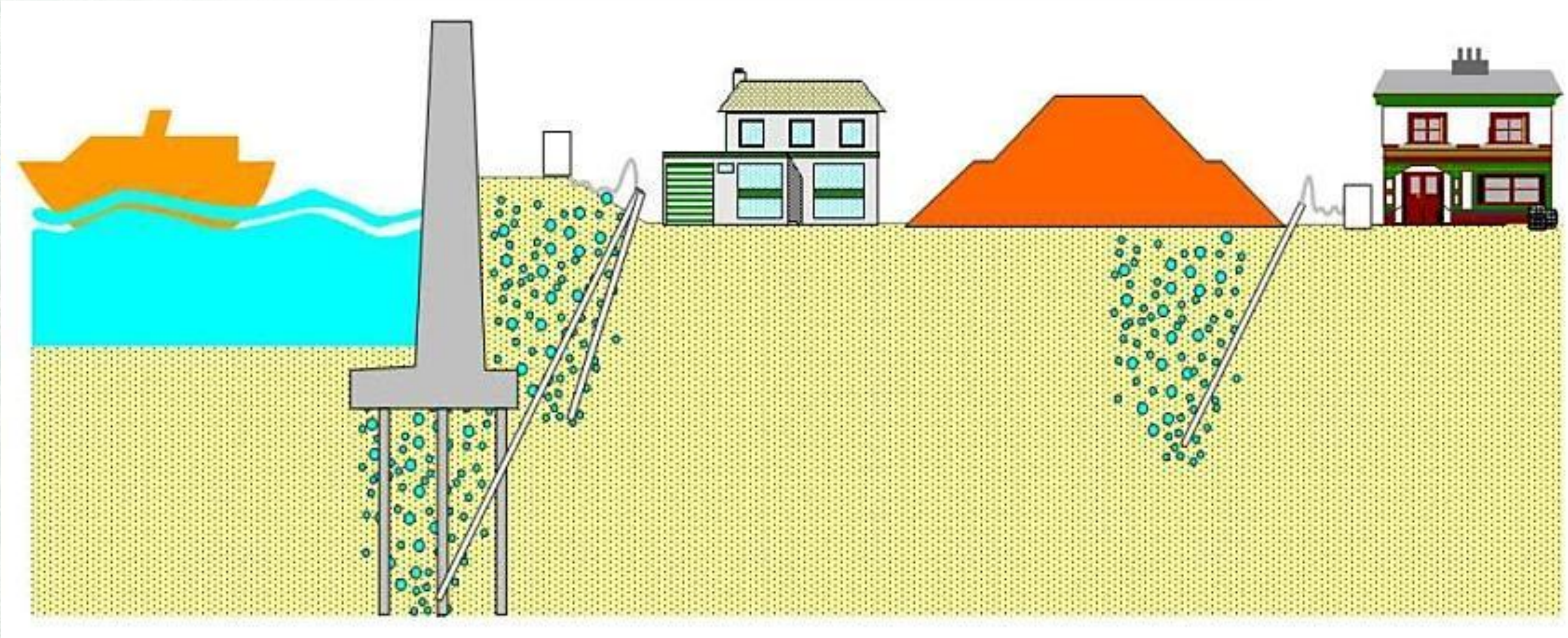
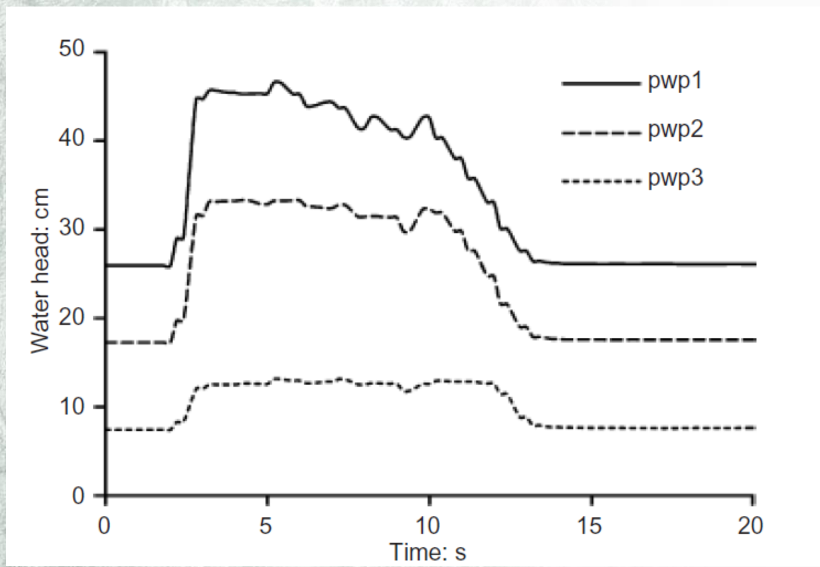
Biogenic gas formation to mitigate liquefaction?

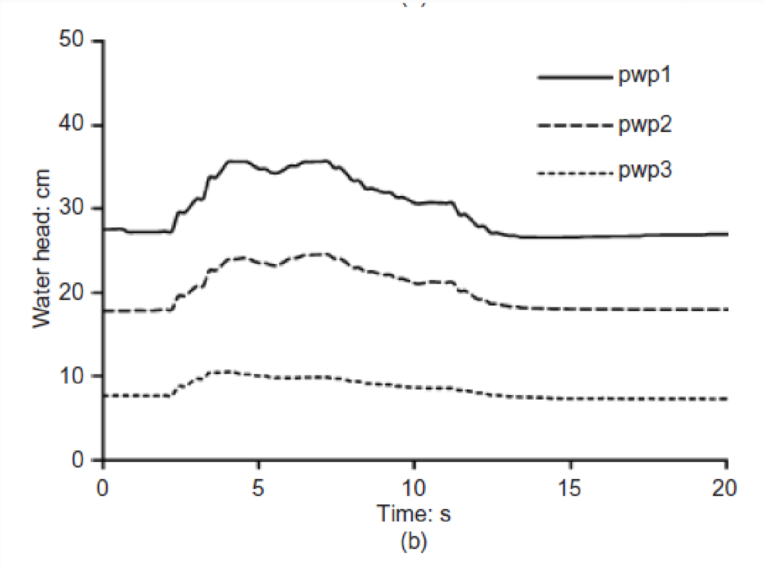


O'Donnell et al 2016, Pham et al 2016

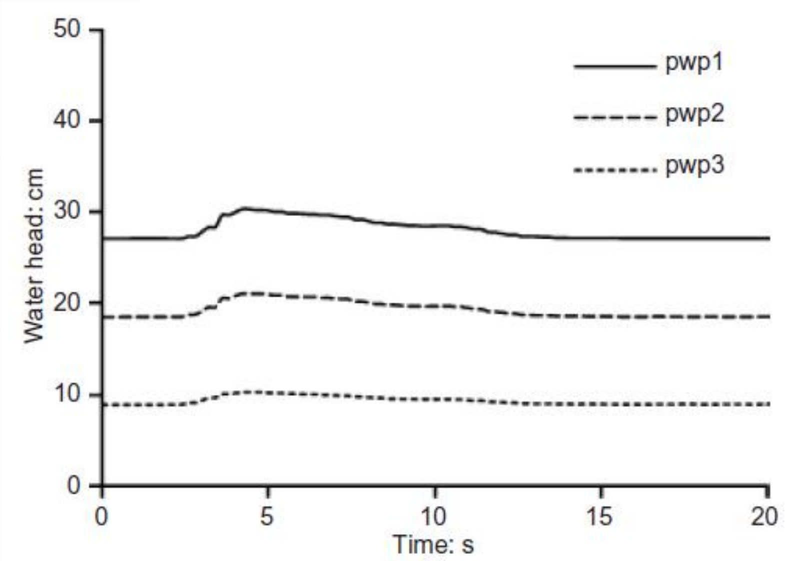
A small amount of gas can mitigate liquefaction



D_r = 52%, S_r = 100%



D_r = 51%, S_r = 95%



D_r = 43%, S_r = 80%

He et al, 2013

Benefits of Microbially Induced Desaturation (MID)

- Significantly cheaper than other biogeo options
  - 30 x less substrate than MICP
- Faster than MIDP (only 1 flush)
- Relatively benign side effects

But

- Unsaturated permeability may be an issue
- Heave, gas venting may be issues
- Applicable for fine grained soils?
- Does desaturation persist?

Portland

First full scale trial on Microbial Induced Desaturation (MID) for liquefaction mitigation in the world!!

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