Biogeotechnical Mitigation of Earthquake-Induced Soil Liquefaction

By

Ed Kavazanjian and Leon van Paassen

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

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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)

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
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
Carbonate Precipitation Mechanisms and Polymorphs

**Mechanisms**

<table>
<thead>
<tr>
<th>Process</th>
<th>End Products</th>
<th>Undesirable Side-Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ureolysis (Microbial and Free Enzyme)</td>
<td>NH(_3) (ammonia)</td>
<td>Toxic gas</td>
</tr>
<tr>
<td></td>
<td>NH(_4^+) (ammonium)</td>
<td>Toxic salts, acidification</td>
</tr>
<tr>
<td>Sulfate Reduction</td>
<td>H(_2)S (hydrogen sulfide)</td>
<td>Toxic gas</td>
</tr>
<tr>
<td>Fermentation of Fatty Acids</td>
<td>CH(_4) (methane)</td>
<td>Explosive gas</td>
</tr>
<tr>
<td>Denitrification</td>
<td>N(_2) (nitrogen)</td>
<td>None</td>
</tr>
</tbody>
</table>

Note: microbial methods may be via augmentation or stimulation

**Polymorphs**

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

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 CaCO₃ 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)
Liquefaction Mitigation via MICP

Centrifuge Testing at UC Davis on lightly-cemented ($\approx 1.2\% \text{ CaCO}_3$) 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
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

$D_r = 45\%$

Correlate $V_p$ with $S_r$

O’Donnell et al. (2016A, 2016B)
Stage 2: Carbonate Precipitation

CyDSS and TX Testing (Sr = 100%)

Increase in stiffness, dilatancy, strength of treated columns (even after failure)
MIDP: Key Findings

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 a two-stage process
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
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)
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)
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

ureum + calcium chloride → CaCO₃ + ammonium chloride

Denitrification

calcium-fatty acid + calcium nitrate → bacteria + CaCO₃ + N₂(g)
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
- Reaction rate > Flow rate

Inward flow
- 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

3% CaCO$_3$  1.5% CaCO$_3$  0.75% CaCO$_3$
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!
Trench excavation and sampling

Test pit with treatment, after 3 hrs: Stable!

Test pit no treatment, after 3 hrs: Collapsed!
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
Biogenic gas formation to mitigate liquefaction?

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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