Microbial Ecology of Stimulated Ureolytic Biocementation

Presenter: Charles Graddy, Valerie Yanez   Advisors: Douglas Nelson, Jason DeJong   Institution: University of California, Davis

Background

Study from the collaborative C2C project

- ASU, GT, UCD members in CBBG
- Queen's University Belfast Energy Efficient Materials Research Center (EEM)
- Irish Center for Research in Applied Geoscience (iCRAG)

Goal: Evaluate the limits of our stimulation techniques in a different, calcareous soil:

- Exert control on bulk rate by limiting yeast extract (YE)
- Reduce urea without sacrificing stimulation efficiency
- Impact of commercial chemical use

How do these factors affect accumulation of activity and the resultant microbial community?

Does the attached microbial community reflect what is more easily sampled in suspension?

Experiment Design

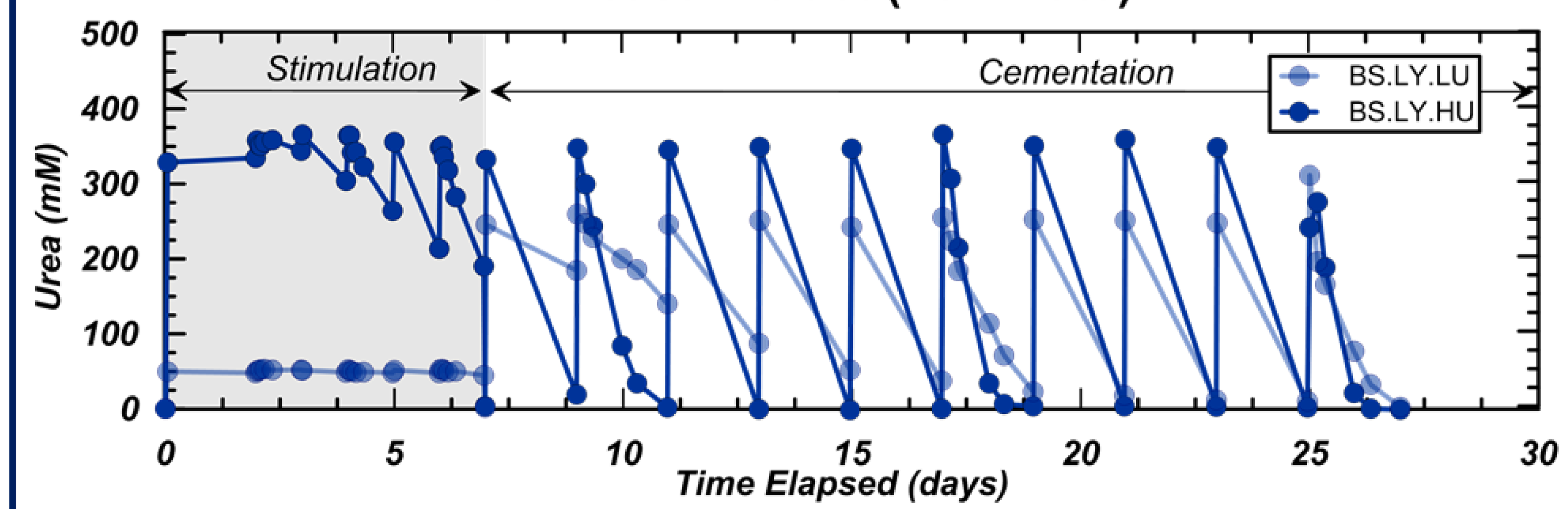
MICP treated soil columns, varying the stimulation medium organics and urea to evaluate the calcareous soil's propensity for stimulation.

Column	1	2	3	4	5	6	7
Soil	BS	BS	BS	BS	BS	**CS**	**CS**
YE(g/L)	**0.02**	**0.02**	**0.2**	**0.2**	0.2	0.2	0.2
Urea	**Low**	**High**	**Low**	**High**	Low	High	Low
Grade	Lab	Lab	Lab	Lab	**Com.**	**Com.**	Lab

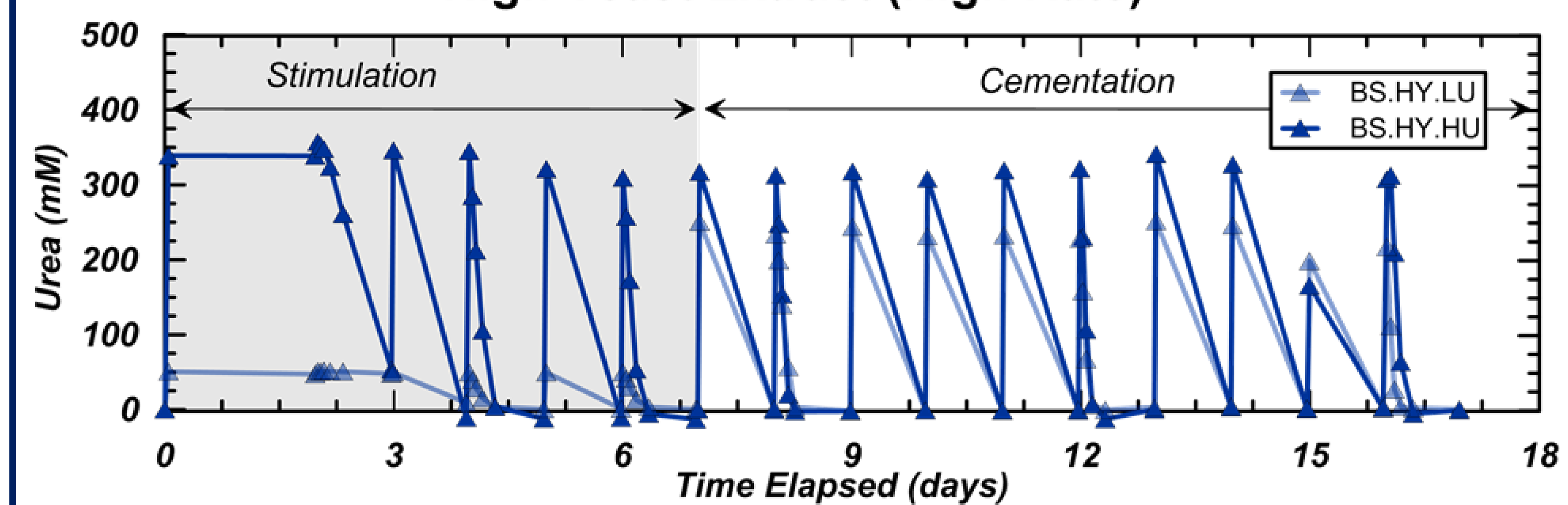
BS: Blessington Sand; CS: Concrete Sand; low YE (LY); high YE (HY); low urea (LU): 50 mM during stimulation, 250 mM during cementation; high urea (HU): 350 mM during stimulation and cementation; Lab: laboratory grade chemicals; Com.: commercial grade chemicals

Results

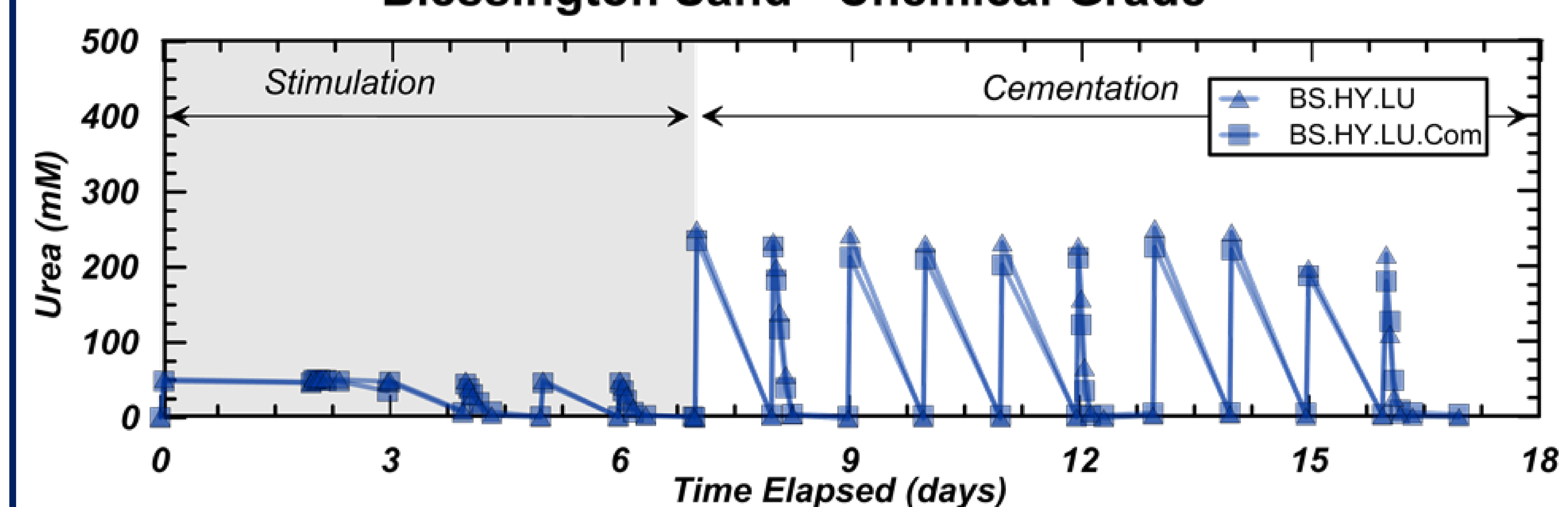
Low Yeast Extract (Low Rate)



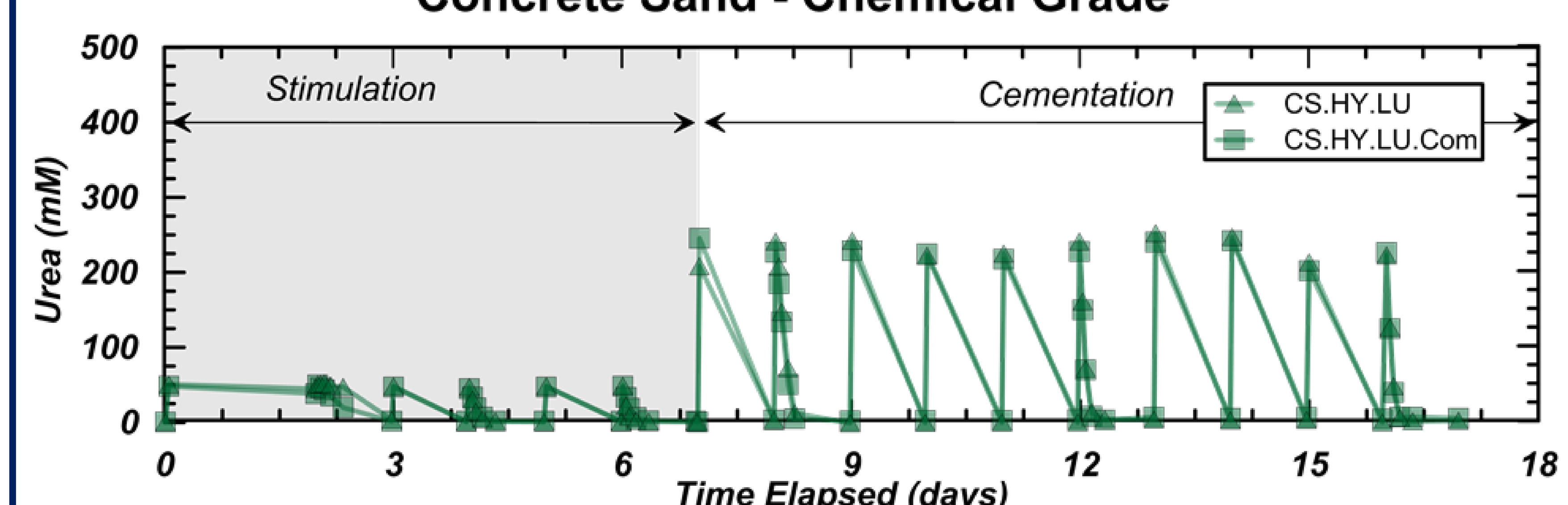
High Yeast Extract (High Rate)



Blessington Sand - Chemical Grade



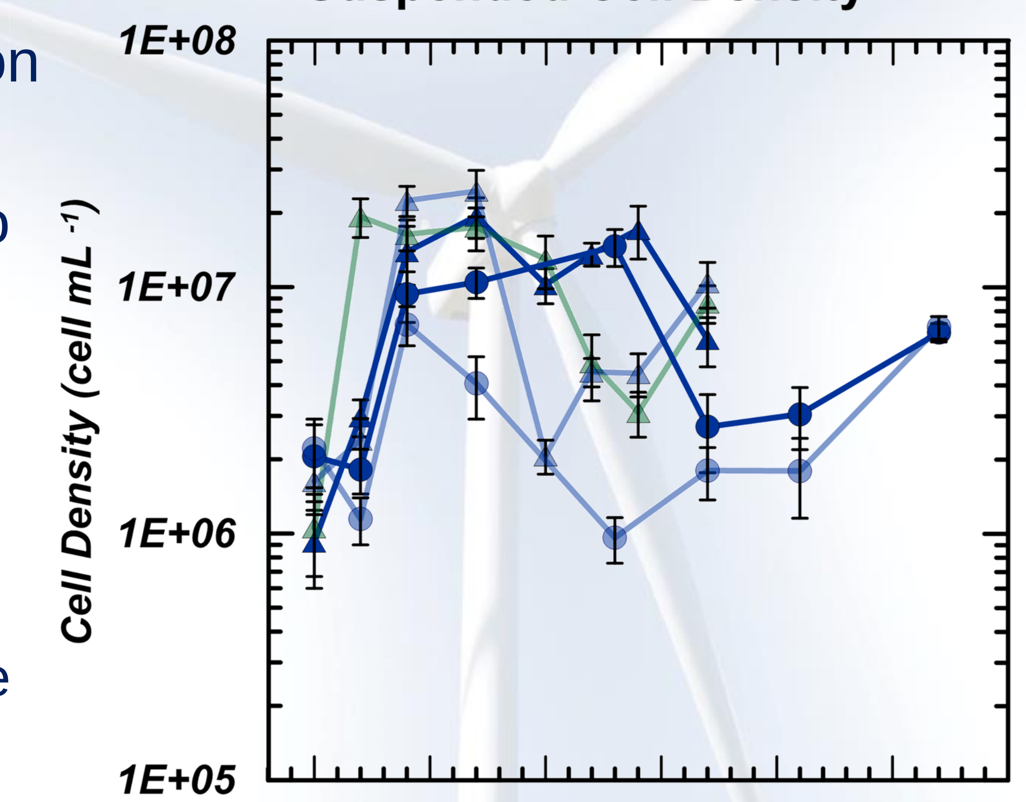
Concrete Sand - Chemical Grade



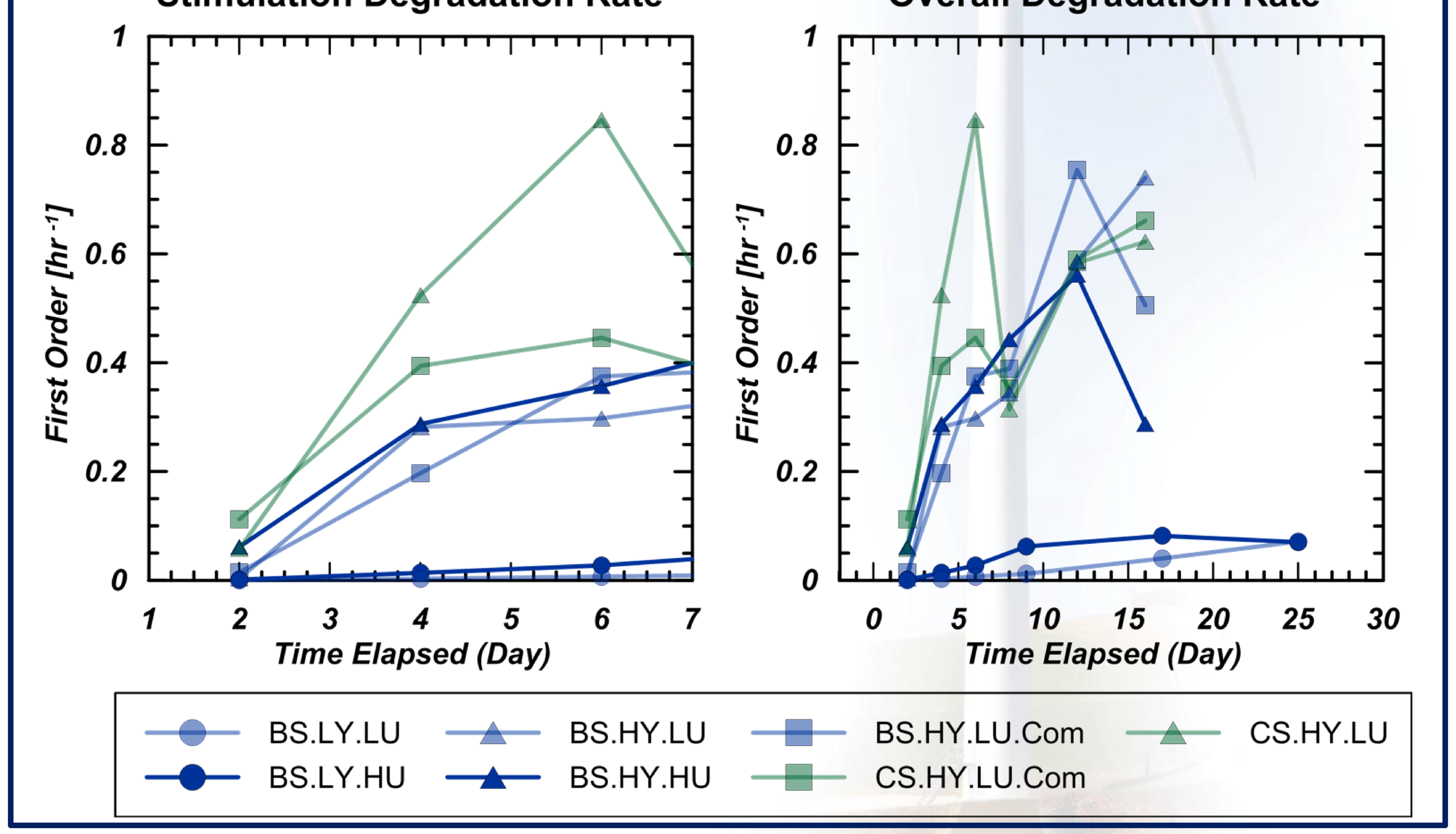
Results and Conclusions

- Commercial grade chemicals used have negligible impact on bulk ureolytic activity
- YE concentration was able to control degradation rate
- Urea can be reduced and stimulation proceeds, **to a point**
  - Able to find the lower limit of efficacy; lower than in concrete sand

Suspended Cell Density



Stimulation Degradation Rate / Overall Degradation Rate



Ongoing Work

Molecular characterization of samples to characterize microbial community changes associated with:

- Urea reduction and the presumed loosening of stimulation stringency
- Reduced organics to control rate
- The unsuccessfully stimulated column and its eventual succession

Analysis of attached vs suspended microbial communities and biomass

Ira A. Fulton Schools of Engineering, Arizona State University · UC DAVIS University of California · Georgia Institute of Technology · NM State University · NSF · Center for Bio-mediated & Bio-inspired Geotechnics CBBG

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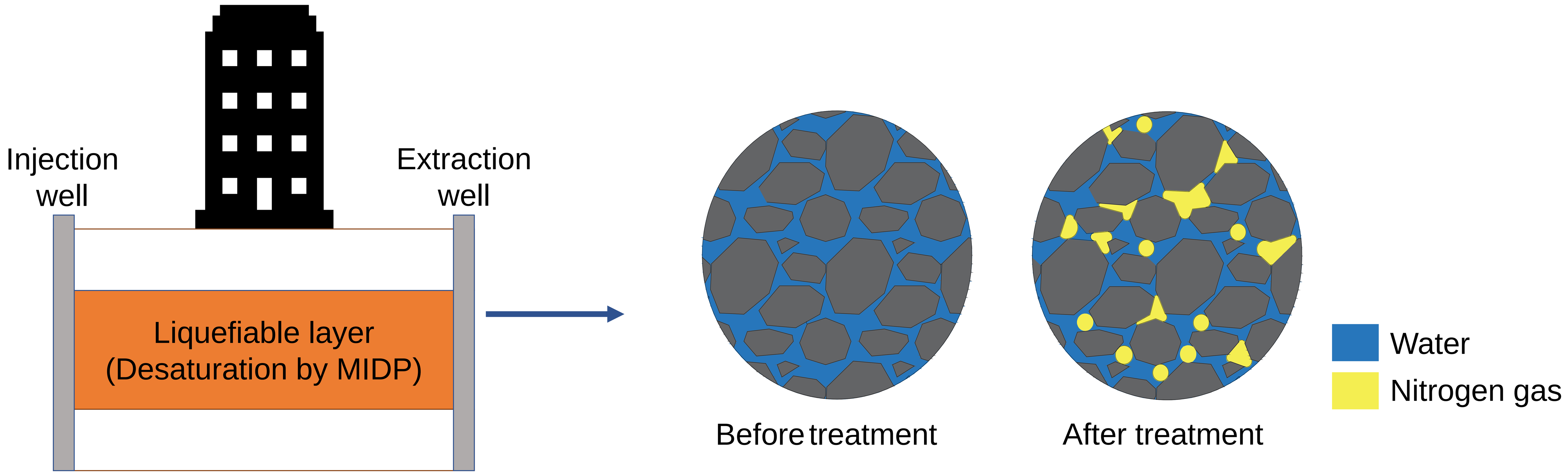
Liquefaction Mitigation via Microbial Denitrification

Presenter: Patrick Kwon, Deepesh Karmacharya Advisor: Leon van Paassen Institution: ASU

Background

Previous research has demonstrated that a small reduction in the degree of saturation can effectively mitigate liquefaction. Stimulating denitrifying micro-organisms in the subsurface results in the formation of nitrogen gas. Nitrogen gas has low solubility, is non toxic, and not a greenhouse gas. Entrapped gas in the pores as a result of Microbial Induced Desaturation (MID) increases the compressibility of the pore fluid and reduces generated excess pore pressure during cyclic loading.



Research objective

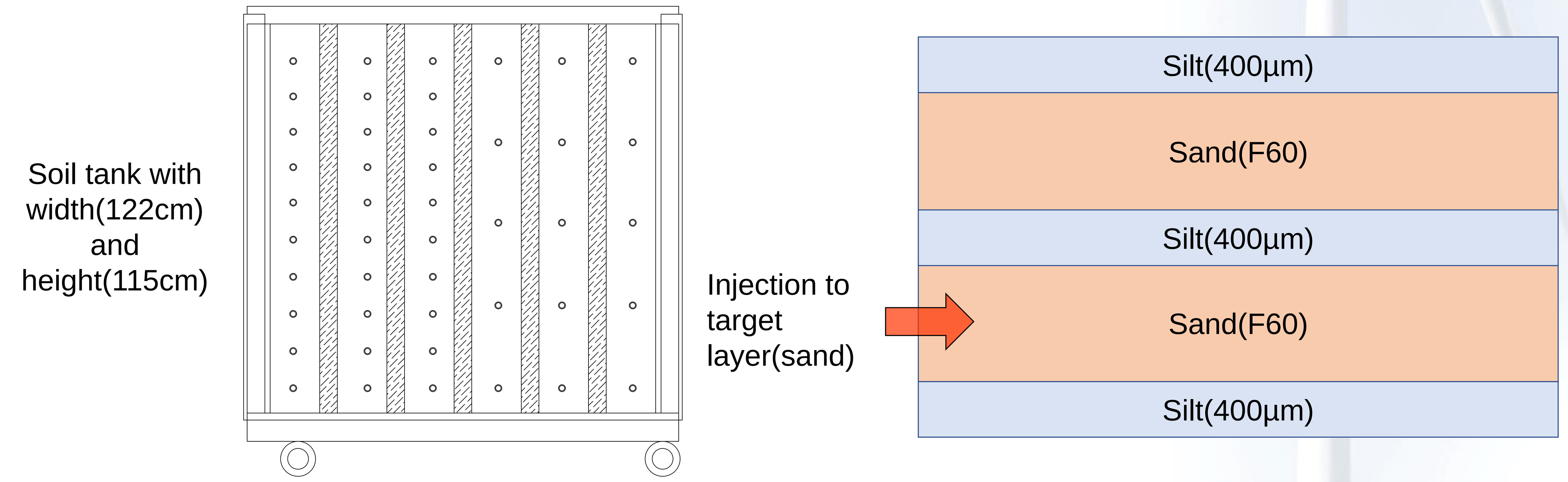
Determine the formation and distribution of biogenic gas by MID and its effect on degree of saturation in stratified soils containing silts and sands.

Methodology

Layered soil tank with silt (d50 = 40μm) and fine sand (Ottawa F60)

a) Inject substrate to target sand layer only to desaturate liquefiable layer.

b) Monitor electrical conductivity, moisture content, pore pressure.

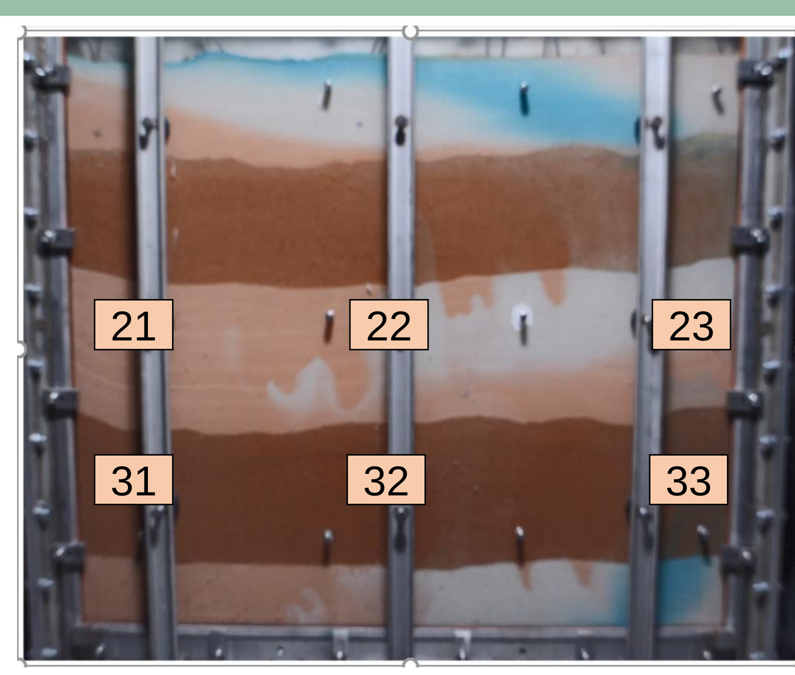


Previous research

Demonstrated benefits of MID(P)

- The substrate can be injected more uniformly and further from an injection well compared with direct air injection (He et al., 2014)
- Using calcium salts as substrates results in calcium carbonate precipitation, which enhances gas persistence and provides more durable mitigation of liquefaction with after multiple treatment cycles.

Large scale tank tests have demonstrated how the distribution and persistence of substrates and products is affected by grain size and soils stratification



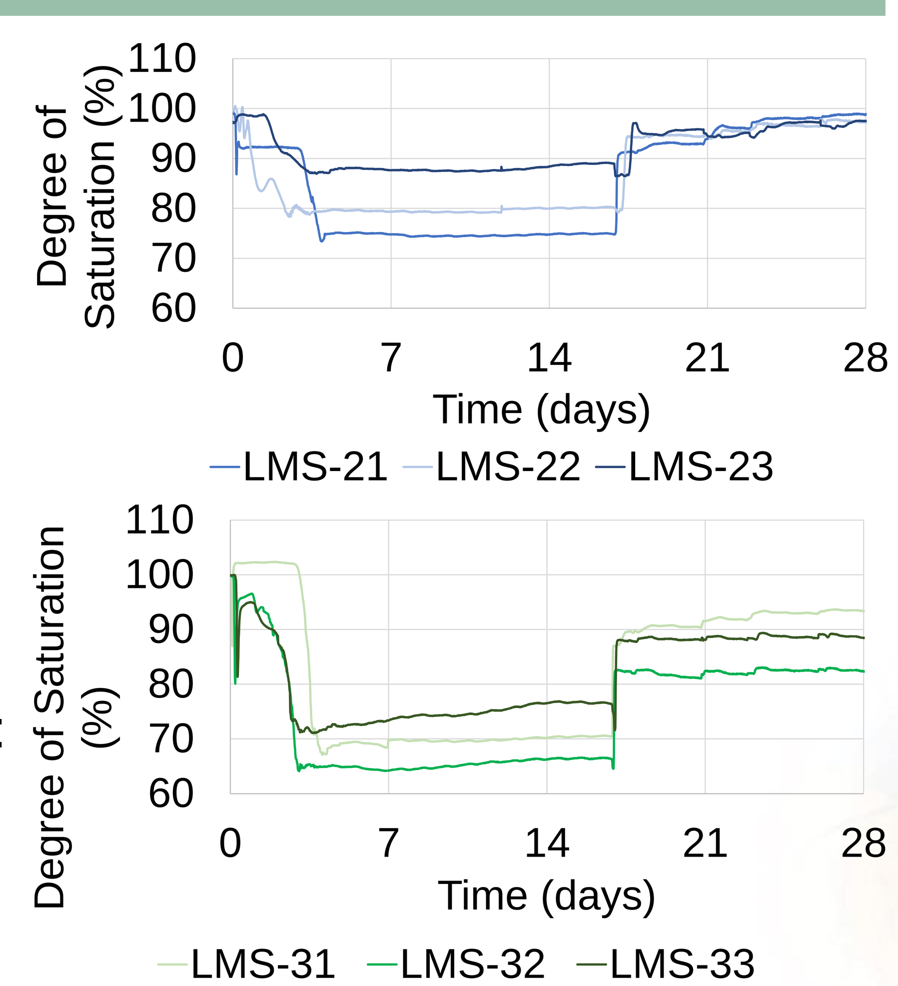
Large scale tank test with layered sands:

- Ottawa 20-30 (d_{50}: 0.54 mm) and
- Ottawa F60 (d_{50}: 0.23 mm)

Treatment solution contained

- 25 mmol/L calcium nitrate
- 25 mmol/L calcium acetate
- Nutrient and trace element solution.

Varying hydraulic conductivity and fluid density affects the substrate distribution



Degree of saturation in the middle fine sand layer, 21, 22 and 23 (top) and lower coarse sand layer, 31, 32, 33 (bottom), measured using TDR (TEROS12) sensors

Future study

- Develop model to predict the formation, migration and stagnant distribution of gas in the pores
- Validate the model based on large scale tank test
- Use the model for:
  - Data interpretation from Portland field trial
  - Design new field trials (e.g. Amsterdam, Richmond, Utah, California)
- Determine the affect of heterogeneity in the gas distribution on the mechanical response
  1. Liquefaction resistance in layered air distribution
  2. Buoyant force effect on layered soil

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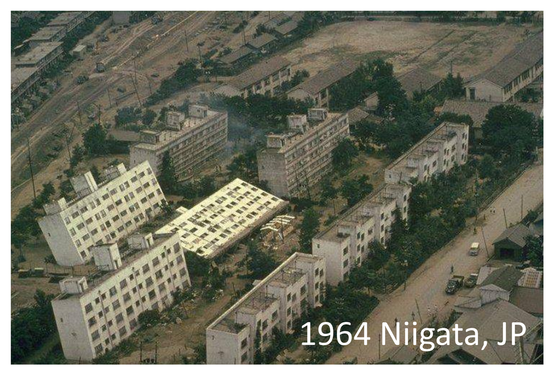
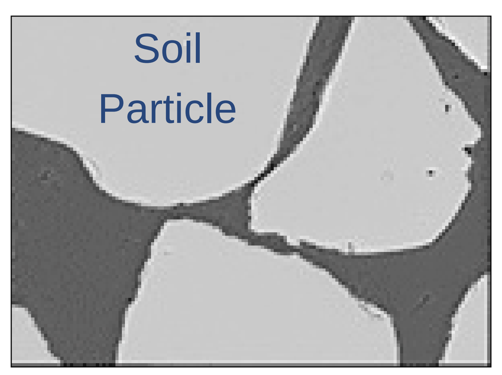
MICP Physical Modeling to Assess Liquefaction Mitigation

Presenter: Alex San Pablo Advisors: Jason DeJong Institution: UC Davis

Background

- Microbially Induced Calcite Precipitation (MICP) is a ground improvement technique that uses ureolytic bacteria to induce calcite precipitation on soil particles.
- MICP can be used to mitigate the effects of liquefaction by:
  - Cementing at particle contacts
  - Increasing density and particle angularity





Experimental Design

Objectives:

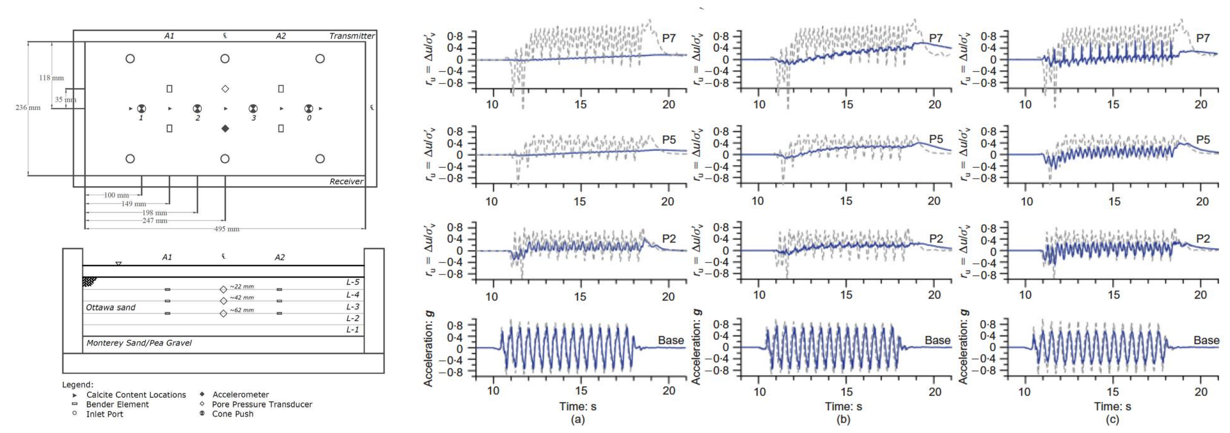
- Evaluate resistance of MICP treated zones to liquefaction triggering
- Track cementation degradation using Vs and CPT
- Investigate reconsolidation settlement post-triggering

Key Parameters:

- Initial relative density (40% and 65%)
- Cementation level (ΔVs = 100, 300, 500 m/s)
- Cementation level finite treatment zone (Depth = 100%, 70%, 40%)
- Foundation type and contact stress

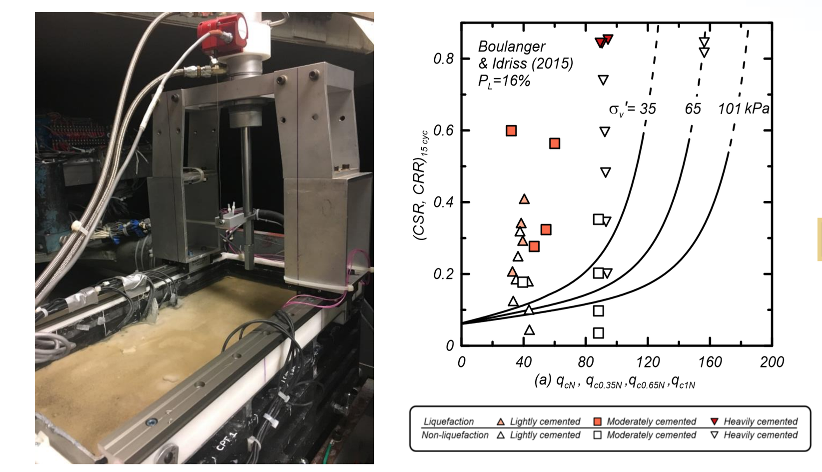
Previous Centrifuge Tests

Montoya et al. (2013)



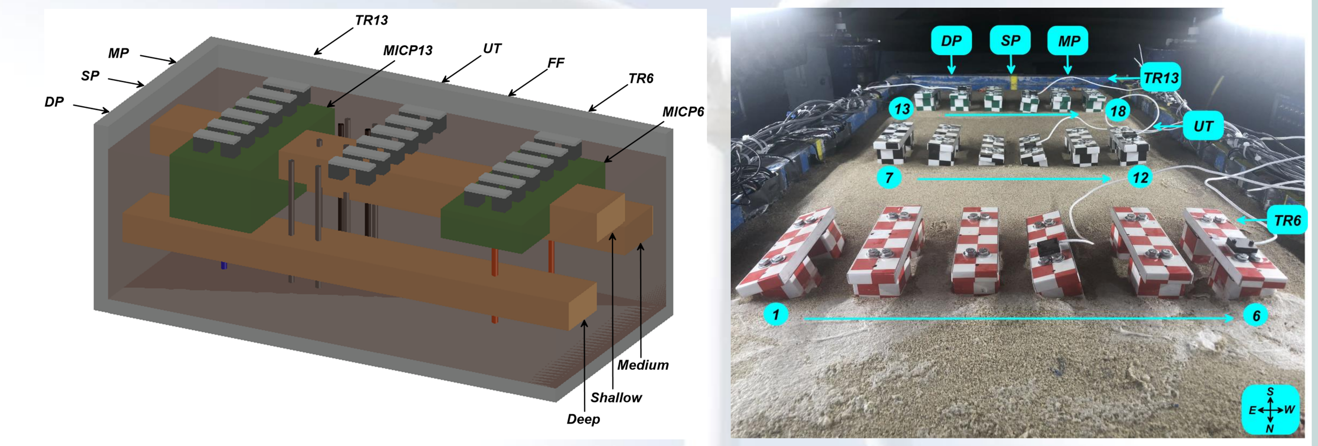
- Investigated cementation integrity, response of MICP to dynamic loading, and foundation settlement.
- Tracked cementation degradation through Vs measurements.

Darby et al. (2019)

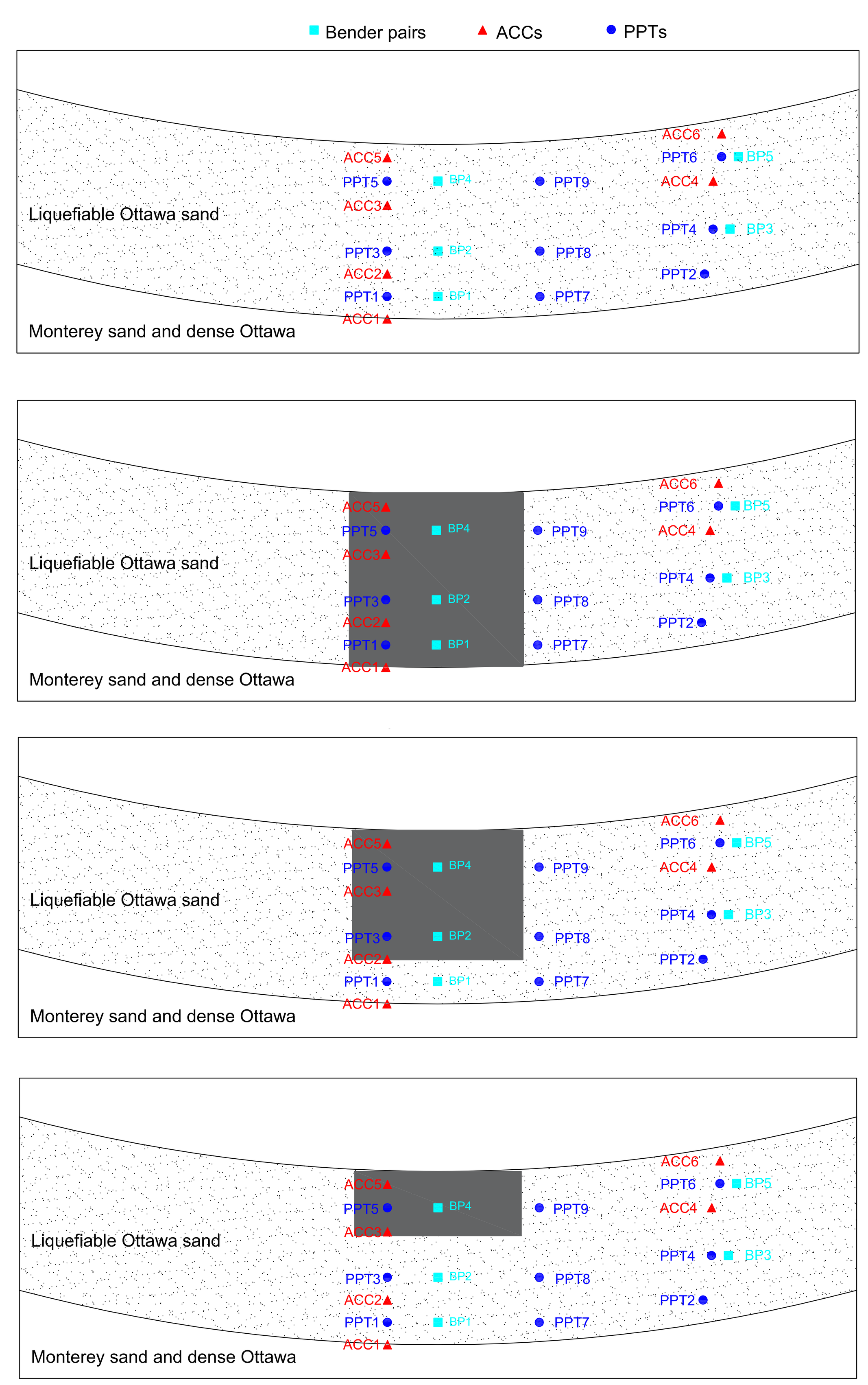


- Added CPT instrumentation to assess performance of MICP through shaking events.
- Developed liquefaction triggering curves for MICP soils.

Zamani et al. (2020)



- Studied effect on the dynamic response of MICP treated soils surrounded by untreated soil (dense and loose).
- Quantified total and differential settlements of foundations.



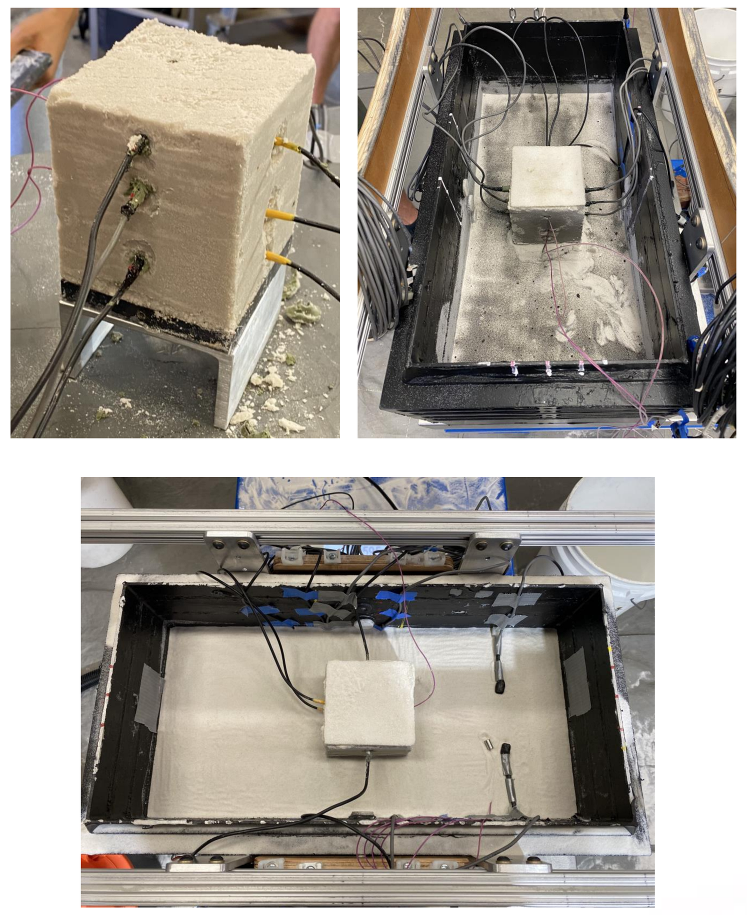
No cementation

100% depth

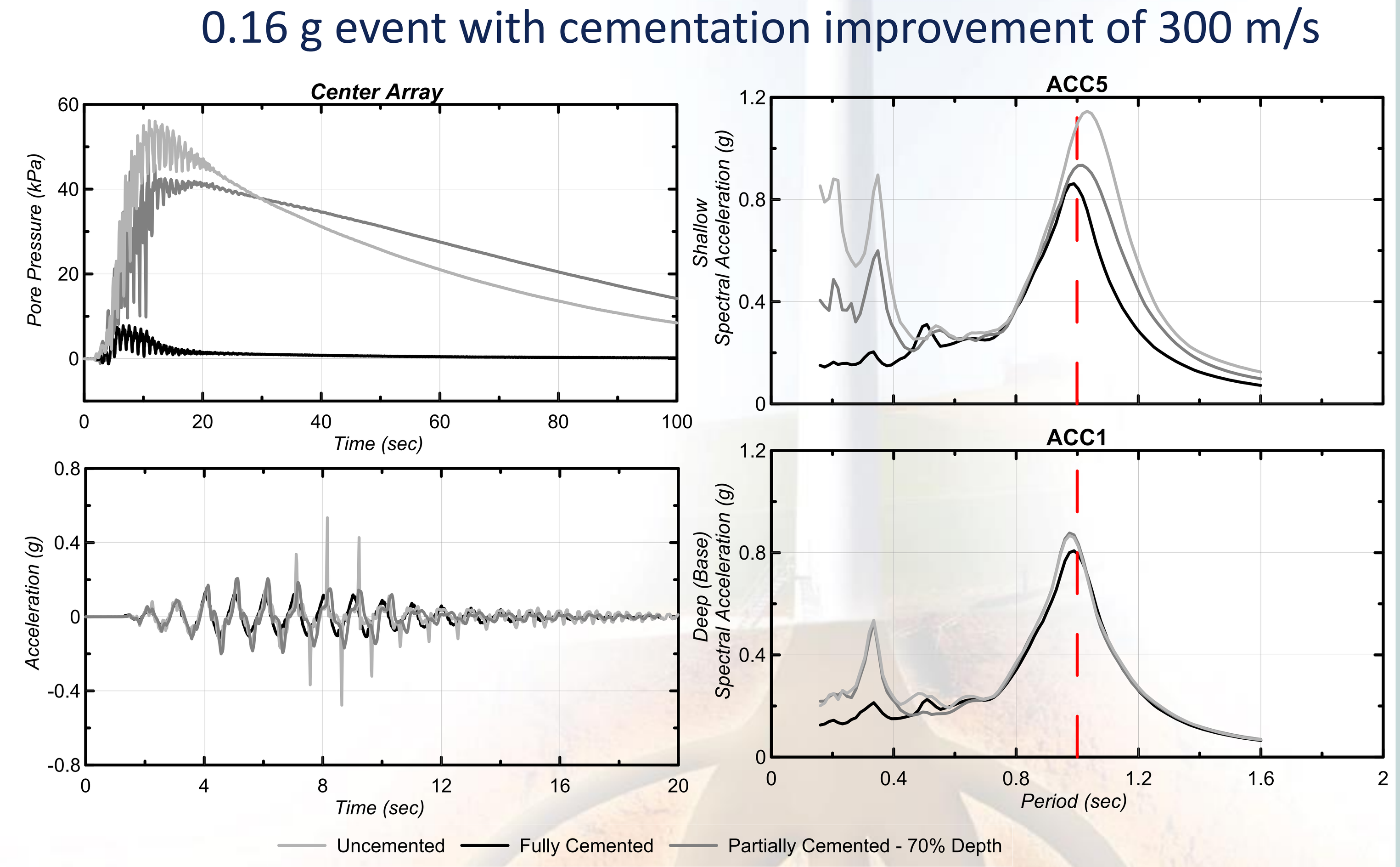
70% depth

40% depth

Results



0.16 g event with cementation improvement of 300 m/s



Top left: 100% depth block cemented to dVs = 300 m/s.
Top right: Placement of MICP treated block on dense sand.
Bottom: MICP block surrounded by loose pluviated soil and various sensors.

- Higher excess pore pressure generation in the finite MICP zone as compared to a fully cemented model due to cementation degradation, however still lower than the uncemented model.
- Slower pore pressure dissipation in the finite MICP zone is due to upward flow from liquefied soil below the treated zone.
- Response spectra data shows degradation for the uncemented model as the period shifts to the right near the surface.

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PR37 : Up-scaling of Stimulated Ureolytic MICP for Field-scale Deployment

Presenter: Minyong Lee Advisors: Michael Gomez, Jason DeJong, Doug Nelson Institution: UW & UCD

Project Overview

The goal of this project is to develop field-ready treatment techniques that can reliably enrich native ureolytic microorganisms to successfully complete bio-cementation while improving soil engineering performance and minimizing environmental impacts.

3-Plane Diagram: Enabling Technology

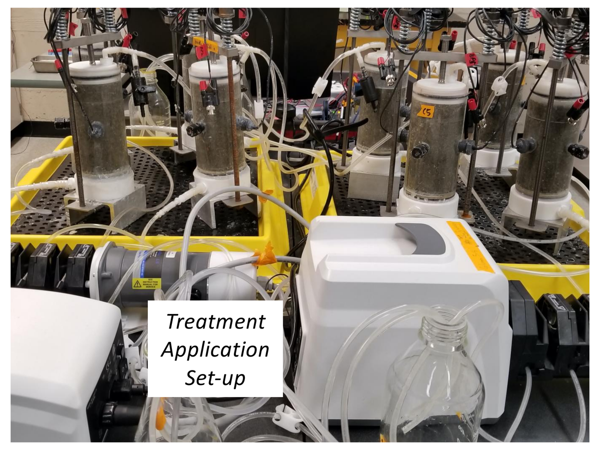
Year 6 Accomplishments

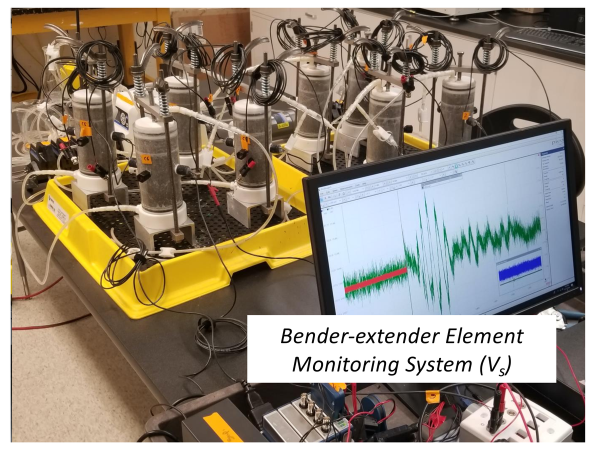
(i) Verification of MICP treatment success in carbonate and marine sands
(ii) Investigation of the effect of rinse injection chemistry and sequencing on post-treatment NH_4^+ removal
(iii) Examination of the liquefaction behavior of bio-cemented sands as a function of cementation level
(iv) Demonstration of MICP success and NH_4^+ by-product removal using field trial site soils to support permitting efforts with regulatory agencies

Motivation for NH_4^+ Removal Experiments

- During the MICP process, NH_4^+ by-products are generated at concentrations twice that of supplied urea
- If left untreated, generated NH_4^+ by-products can have serious human health and environmental implications
- In order to up-scale MICP technology towards commercial use and minimize environmental impacts, concerns regarding produced NH_4^+ must be addressed
- Project work aims to minimize impacts associated with NH_4^+ removal while meeting site regulatory requirements

Experimental Approach





Set-Up: 16 soil column experiments to evaluate effect of various post-treatment NH_4^+ rinsing strategies including effect of rinse solution chemistry and injection sequencing

MICP Treatments: (i) daily stimulation injections for 6 days, (ii) daily cementation injections for 10 days (250 mM urea & $CaCl_2$)

Rinsing: (i) NH_4^+ rinse solutions containing either 50 mM, 200 mM, or 500 mM NaCl (Na), $CaCl_2$ (Ca), KCl (K), or DI water (DI) [all pH adjusted to 9.0], (ii) rinse injections applied in either one 12 PV injection (C = continuous) or twelve 1 PV daily injections (S = staged)

Other Variations: (i) pre-treatment with 500 mM KCl before stimulation (C-K-200-P), (ii) MICP treatment solutions with 200 mM KCl added (C-K-200-T), (iii) MICP with lower reagent concentrations (C-Ca-200-L), (iv) No rinsing

Monitoring: (i) Vs before/after treatments, (ii) aqueous samples during MICP and rinsing, (iii) soil samples for $CaCO_3$ and sorbed NH_4^+ measurements

Plan for Year 7

- Examine effect of rinse solution KCl concentrations on NH_4^+ removal
- Further explore the effect of KCl additions during stimulation and cementation on ureolytic activity and enrichment
- Examine the effect of hybrid rinse injections (single injections followed by daily staged injections) and explore other management techniques

Results: Sorbed and Aqueous NH_4^+ after Rinsing

- Staged daily injections improved NH_4^+ removal when compared to continuous injections
- KCl-based rinse solutions achieved highest NH_4^+ removal
- Correlation between salt concentration and NH_4^+ removal is cation dependent
- DI water injections achieved similar aqueous removal but much less removal of sorbed NH_4^+
- Reduced reagent concentrations did not improve removal
- KCl additions during bio-cementation treatments resulted in lowest sorbed NH_4^+ of all continuous columns

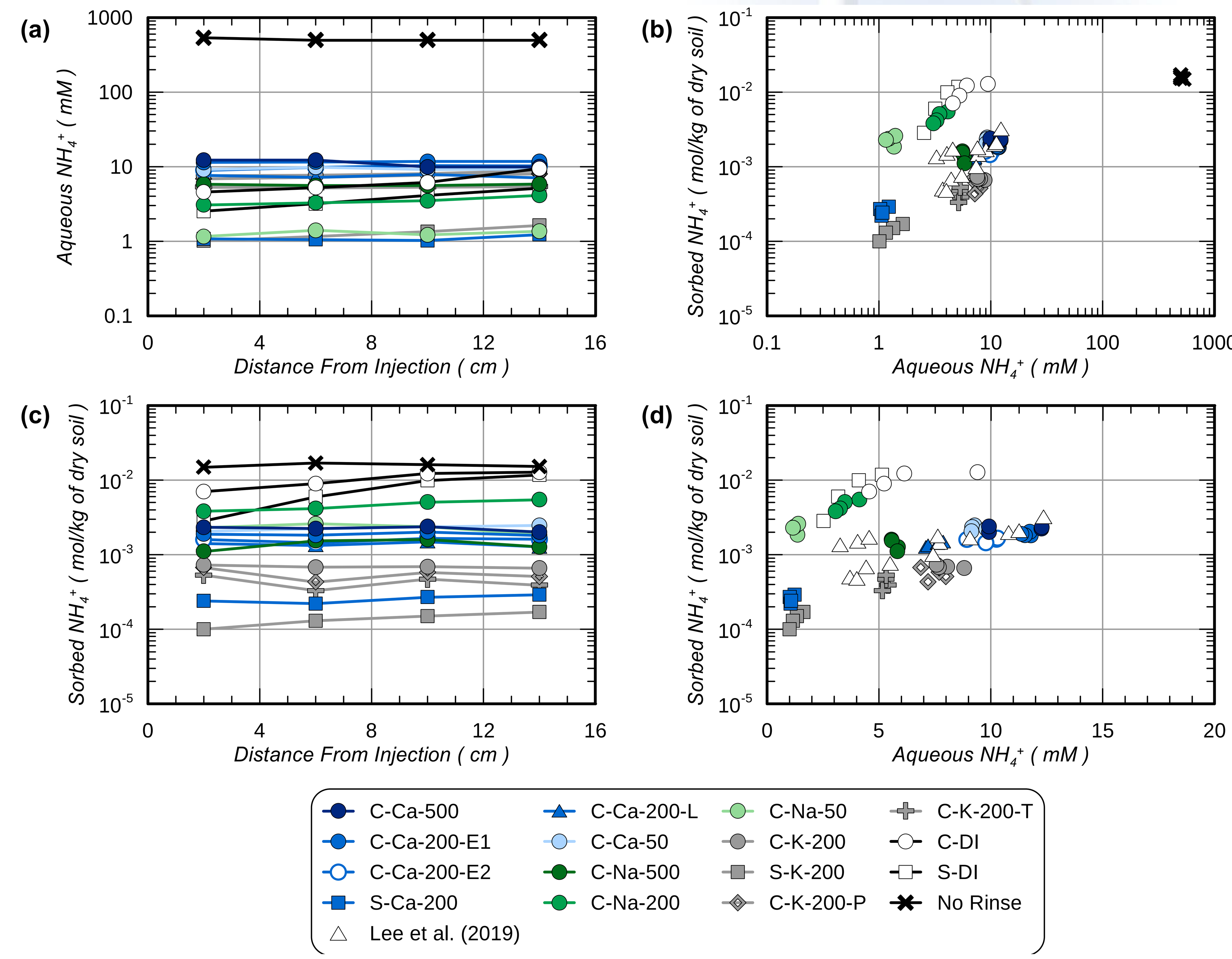


Figure 1. Measurements of **(a)** soil solution NH_4^+ concentrations versus column lengths, **(b)** normalized sorbed NH_4^+ masses versus soil solution NH_4^+ concentrations (log-scale), **(c)** normalized sorbed NH_4^+ masses versus column lengths, and **(d)** normalized sorbed NH_4^+ masses versus soil solution NH_4^+ concentrations (linear-scale)

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Constitutive Modeling of Bio-Cemented Soils

Presenter: Maya El Kortbawi **Advisors: Katerina Ziotopoulou & Ross Boulanger** **Institution: UC Davis**

1. MOTIVATION

- Despite significant advances in the development of MICP for field-scale applications, currently no quantitative frameworks exist to accurately predict the behavior of bio-cemented soils in the field.
- Natural cementation typically exists in aged soils, but it is not incorporated in design because:
    1. It is difficult to characterize, and thus
    2. It is not well understood

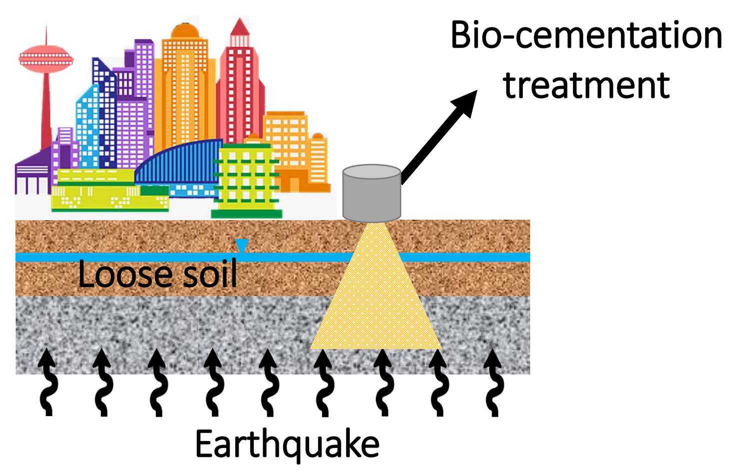

Figure 1: Bio-cementation towards mitigating effects on liquefaction on infrastructure

2. RESEARCH OBJECTIVES

To formulate, implement, validate and calibrate a constitutive modeling framework describing the monotonic and cyclic response of bio-cemented soils in order to support the field deployment and design of in-situ mineral precipitation technologies as soil improvement methods.

A. **Formulation** (framework and equations)
B. **Implementation** (in a programing language)
C. **Validation** (proof of performance, capture the physics that we are aware of and can rationally hypothesize)
D. **Calibration** (fine tuning)

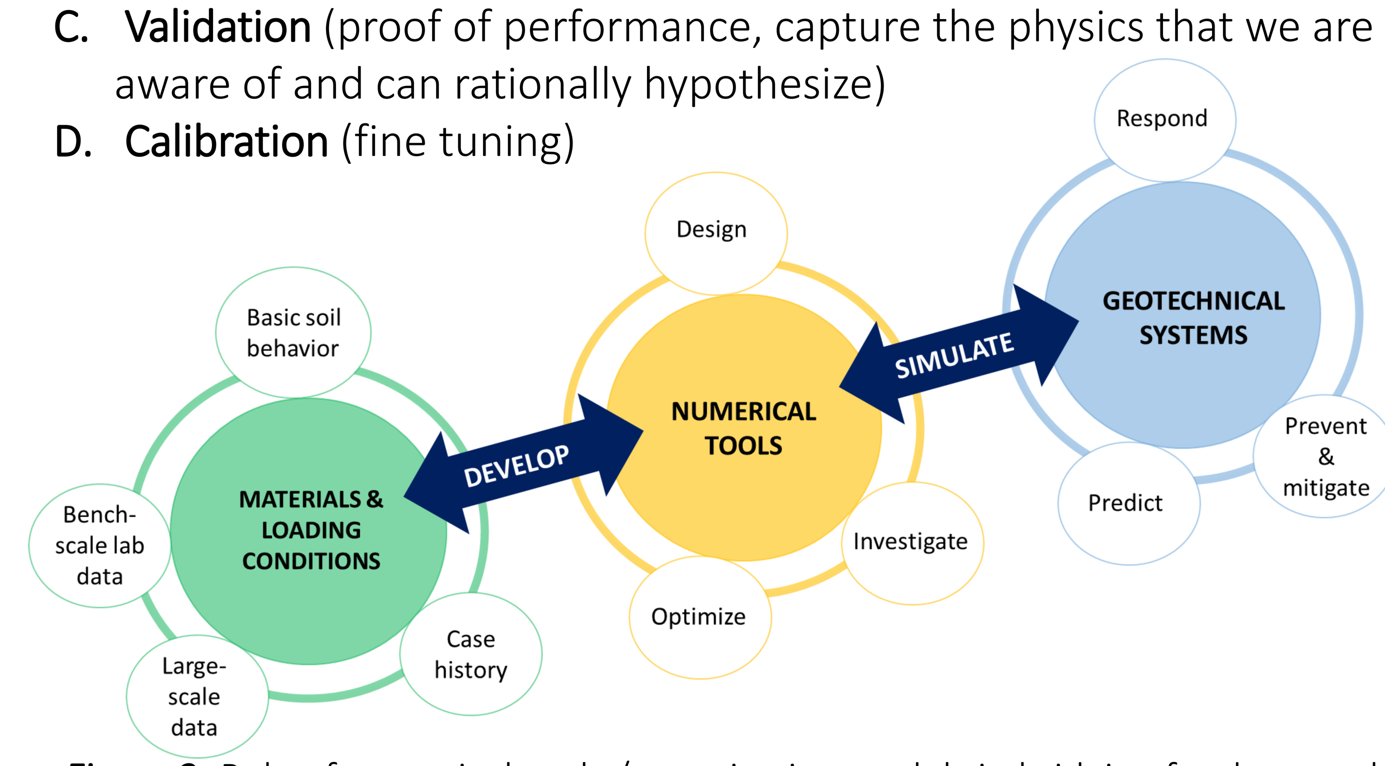

Figure 2: Role of numerical tools / constitutive models in bridging fundamental knowledge at the element level to system level knowledge of geosystems

3. MODEL DEVELOPMENT: PM4SandC

Behaviors*

Increased initial stiffness	**Shift** in the critical state line
Increased "apparent" cohesion	**Dilative** volumetric behavior
Brittle post-triggering behavior	**Increased** cyclic resistance

Input parameters

VsR : cementation ratio or level of improvement $^{V_{s,cem}}/_{V_{s,uncem}}$
c' and ϕ'_{peak}: cemented strength parameters (from empirical correlations)
e_{deg} and e_{res}: degradation parameters at onset and end of degradation, respectively
$Rate_{deg}$: degradation rate

Constitutive space

a- shape of loops is made stiffer than clean sands using stiffer shear and plastic moduli
b- constitutive space is shifted and dilatancy and bounding surfaces are enlarged
c- degradation of all cemented parameters upon accumulation of plastic shear strains to their uncemented states

*The magnitude of these effects varies according to the level of cementation. They may be more significant in the pre-triggering phase but less significant in the post-triggering phase

4. PM4SANDC SPACE AND CALIBRATION RESULTS

Constitutive space

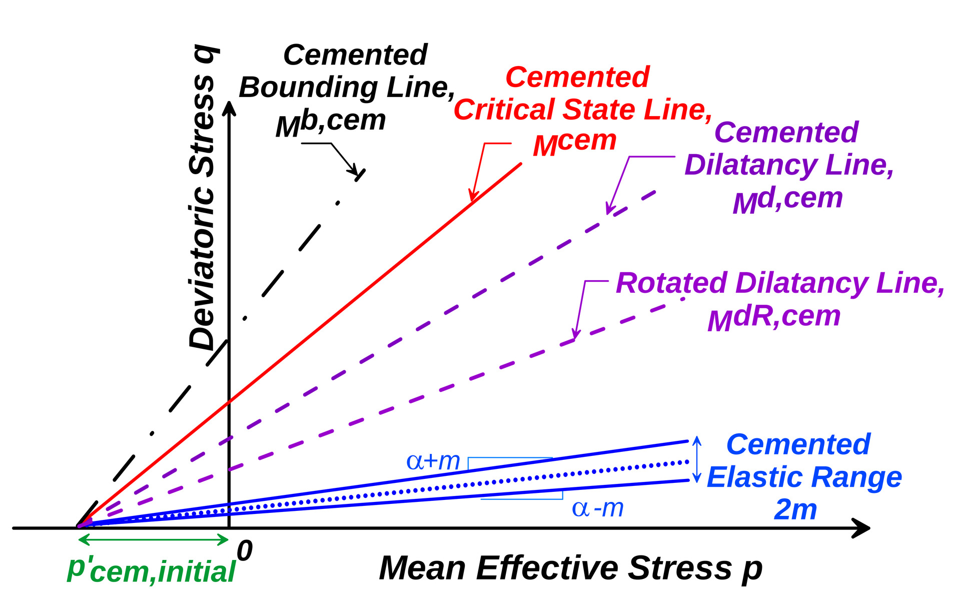

Figure 3: Constitutive model PM4Sand framework in the q-p' space

Generalized calibrations for VsR = 1 (uncemented clean sands), VsR = 2 (lightly cemented sands), VsR = 4 (moderately cemented)

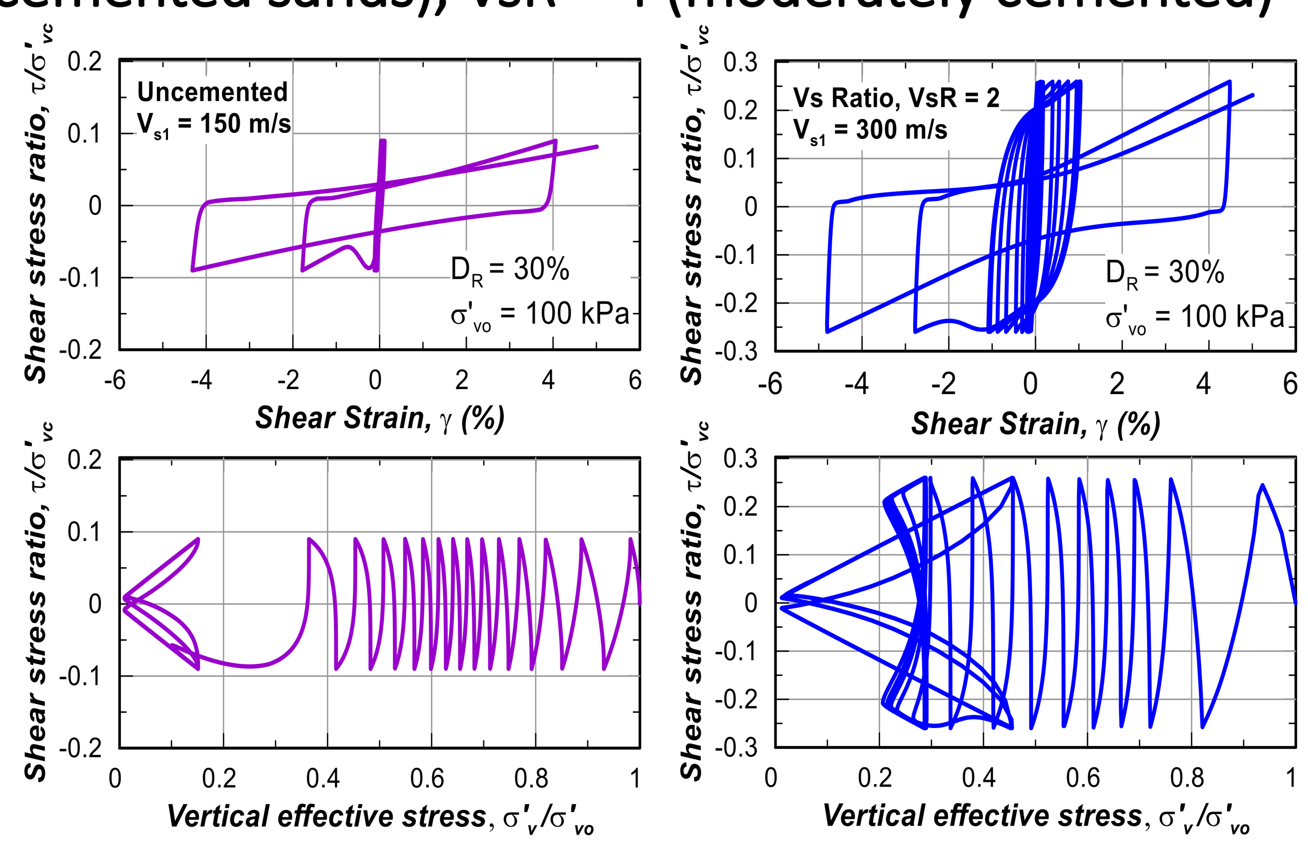

Figure 4: Simulation results for undrained cyclic DSS test on D_r=30% specimen under various CSRs corresponding to their cementation level and under confining pressure of 100 kPa

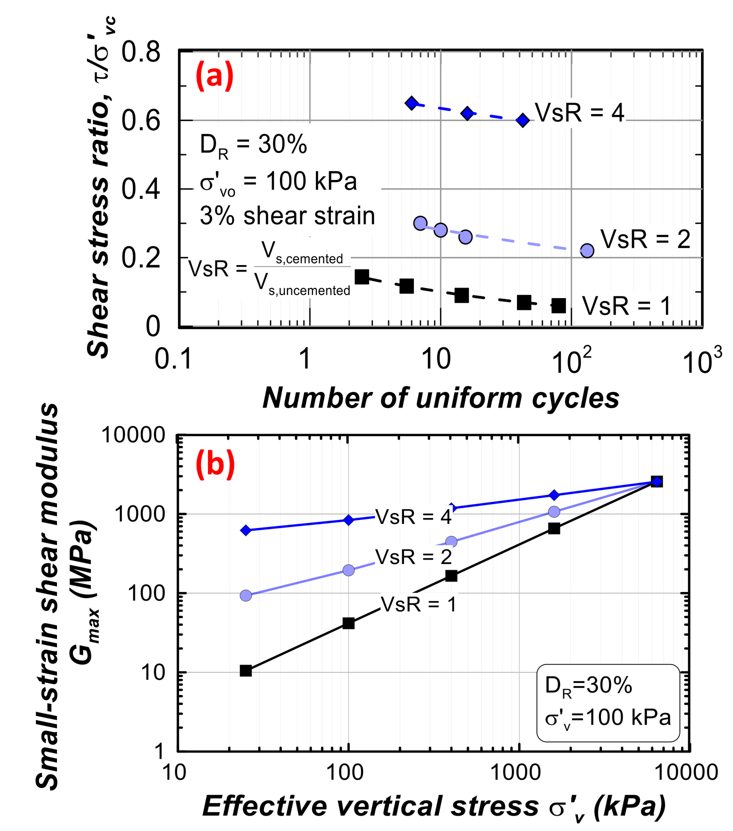

Figure 5: Simulation results for (a) CSR versus N curves from undrained cyclic DSS tests, (b) drained strain-controlled cyclic DSS tests on D_R=30% specimen under confining pressure of 100 kPa

5. YEAR 7 PLANS

- Release a beta-version dll with a draft of the manual to investigate whether a practicing engineer can use it in her analyses: (a) with reasonable engineering effort (important for usability and adoption) and (b) with the model yielding acceptable results.
- Depending on extra data, incorporate and validate data from UW DSS tests and UCD centrifuge tests.
- Finalize generalized calibration of PM4SandC such that it behaves reasonably across all loading paths and for all ranges of conditions (treatment levels and overburdens) as well as provides a good match with any available experimental data. Expand implementation to 3D conditions.
- Perform 1D site response analysis validation for the centrifuge model tests from A. San Pablo undergoing at UCD. Parametric investigation and exploration on the effect of spatial variability of treatments on the system level response.
- Release final version and disseminate to Prof. Pedro Arduino (UW) and Dr. Long Chen (currently with Haley & Aldrich) to perform an implementation of the model in OpenSees. Disseminate to PLAXIS (Bentley Systems) and invite them to implement PM4SandC in their platform as well. Potential for future merging to PM4Sand3D.
- Submit and publish 3 journal papers: Application of Axisymmetric Cone Penetration Model to Bio-Cemented Sands; Formulation, Calibration, and Validation of PM4SandC; System level analyses of bio-cemented systems (analyses against centrifuge model tests).

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PR54: Industry MICP Field Trials

Researchers: Jason DeJong, Mike Gomez (Doug Nelson, Alex San Pablo, Minyong Lee, & Charles Graddy)

Institutions: UCD, UW

Overview

The goal of this project is to effectively upscale MICP ”know how” to industry partners through a collaborative field trial project. The project will:

1. Improve our understanding of MICP performance at the field-scale
2. Develop capabilities in practice to employ CBBG technologies
3. Establish approaches and methods needed to design, interpret, and verify MICP success.

Industry Interactions

- Biweekly meetings with Golder Associates for Delta, B.C. field trial. Outreach to Port of Vancouver, B.C. and Tsawwassen Springs (First Nations).
- Collaboration with Geosyntec for field trial with OCSD. Outreach to CA DWR and USACE.
- Discussions with industry groups including Haley & Aldrich, GeoLogic, TetraTech, and Landau Associates.
- Collaboration with ConeTec to develop in situ monitoring probes for MICP treatment and to support work for Delta, B.C. site.

Year 6 Accomplishments

- MICP field trial plan including materials, well layout, and treatment targets and program largely complete. Monitoring and sampling program at 60% design.
- Delta, B.C. project specific column testing used to assess the use of industry grade chemicals, verify biostimulation feasibility, and demonstrate cementation effectiveness and NH_4^+ by-product removal feasibility to support the permitting process.
- New in situ push-in probes that can monitor treatment delivery and shear wave velocity increases during treatments were developed in collaboration with ConeTec.

3-Plane Diagram: Systems Integration

Support of Field Trial Program

- Target cementation level based on lab DSS & centrifuge results.
- Treatment plan uses industry grade products & ‘optimized’ formula.
- Well spacing & pumping system design based on test well pump tests & large-scale tank and trough results.
- QA/QC for bio-chemo-geo processes to occur through in situ monitoring and sampling wells for ex site testing in near-real time.

Project Output Integration with Other Projects

- PR1 – Frequent sampling to verify biostimulation & map population evolution.
- PR37 – Spatial mapping of improvement in time, post-sampling to quantify improvement, post-CPTs for QA/QC, & post-testing to develop CSR-N curves.
- PR36 – Possible centrifuge testing to model improved site conditions.
- PR38 – PM4C calibration to field data & FLAC modeling of site conditions.

Year 7 Plans

- **COVID RESTRICTIONS END and FIELD TRIAL COMPLETED!**
- Support of pre-treatment activities with CBBG team on site for treatment program (stimulation, cementation, flushing, QA/QC).
- Perform post-trial laboratory work and data processing.
- Advance OCSD field trial effort towards full design.
- Incorporate lessons learned into guidance and connect work with centrifuge and numerical modeling efforts.

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Multi-scale Investigation of Bio-Based Mineral Precipitation in Carbonate Bearing Granular Soils and Construction Related Waste

Presenter: Shaivan Shivaprakash   Advisors: Susan Burns, Jason DeJong, Leon van Paassen   Institutions: GT/UCD/ASU

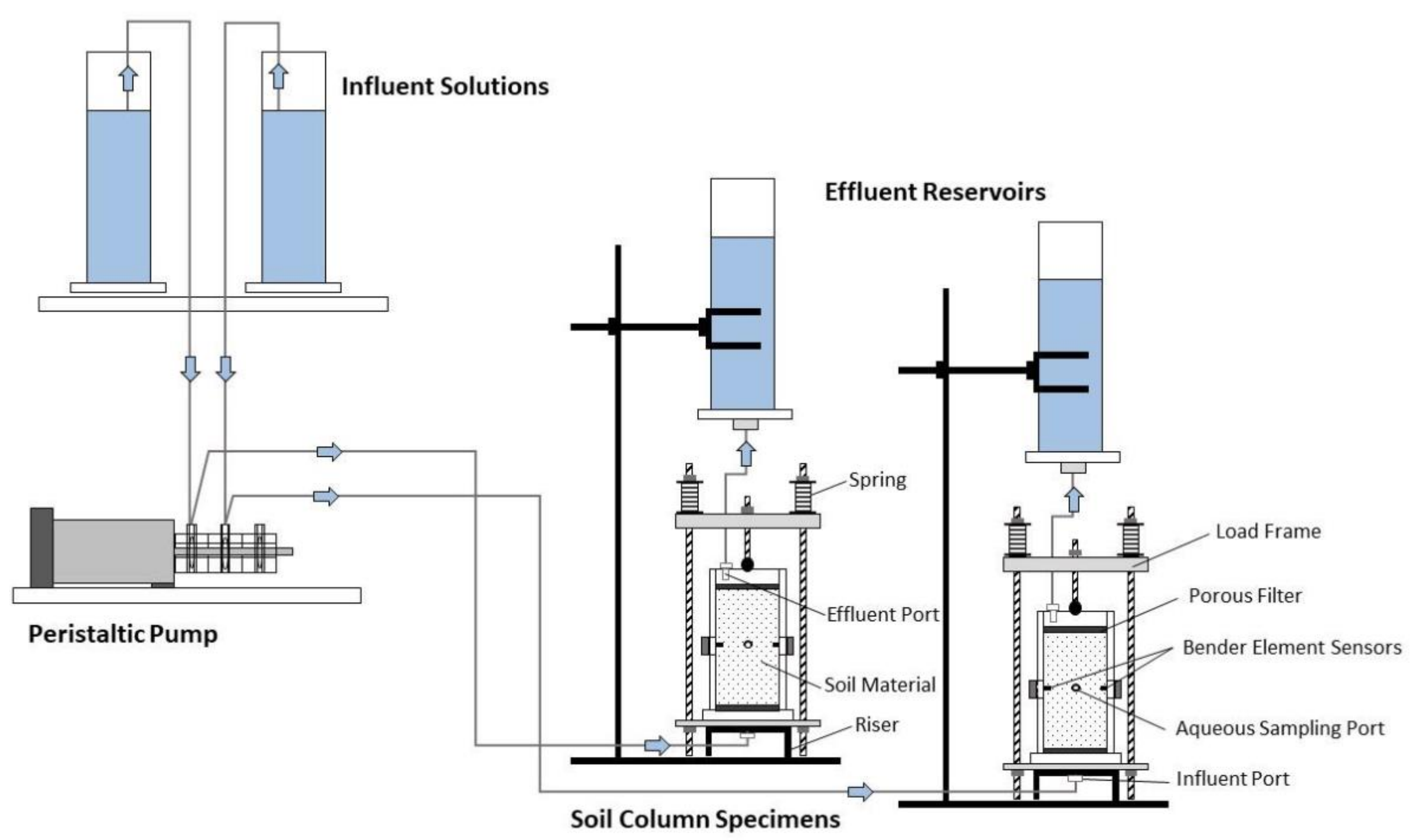
Background

- Goal: Extend MICP technique to carbonate rich limestone deposits and construction and demolition waste
- Team: Collaborative effort between ASU, GT, UCD and Irish partners Queen's University Belfast Energy Efficient Materials Research Center (EEM) and University College Dublin / SFI-funded Irish Center for Research in Applied Geoscience (iCRAG)

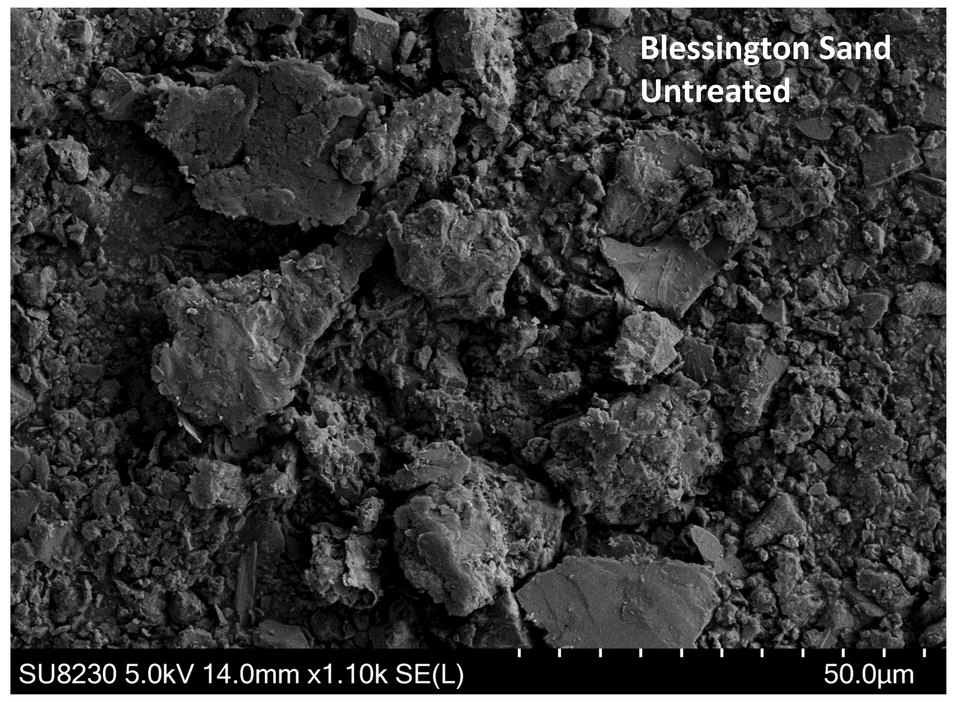
Research Objectives

- Elucidate the effects of mineralogy, surface chemistry, and texture on mineral precipitation
- Extend MICP treatment schemes from silica rich sands to carbonate bearing materials
- Facilitate biogeochemical modeling and elucidate the relationships between the precipitation kinetics, mass and morphology of precipitated carbonate, and meso-scale mechanical and hydraulic properties
- Perform field scale tank tests to investigate the influence of field conditions on mineral precipitation, assess heterogeneities of bulk engineering properties, and characterize by-products

Treatment Scheme: BioStimulation Blessington Sand



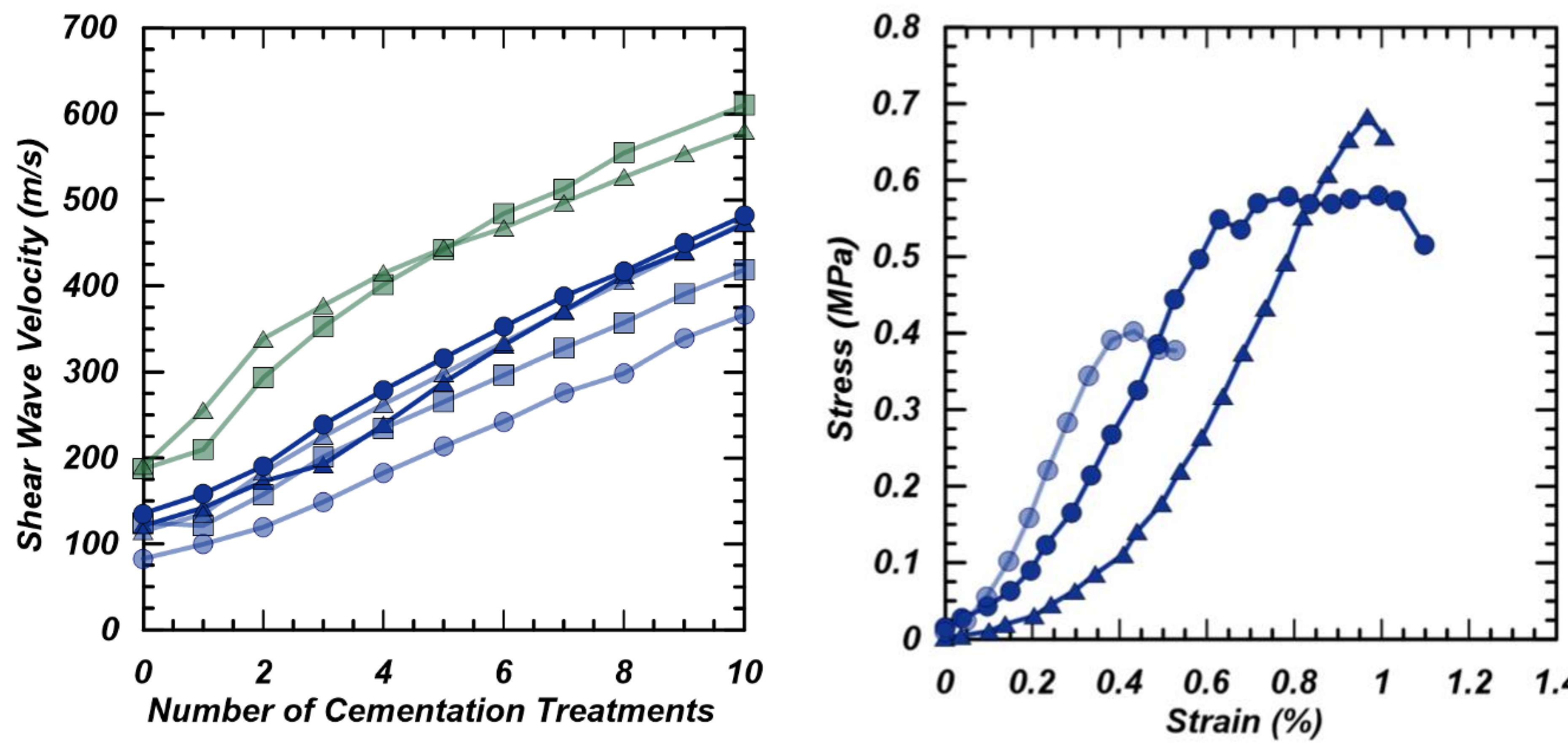
Calcite Morphology for Untreated Blessington Sand and C&D Waste



Summary

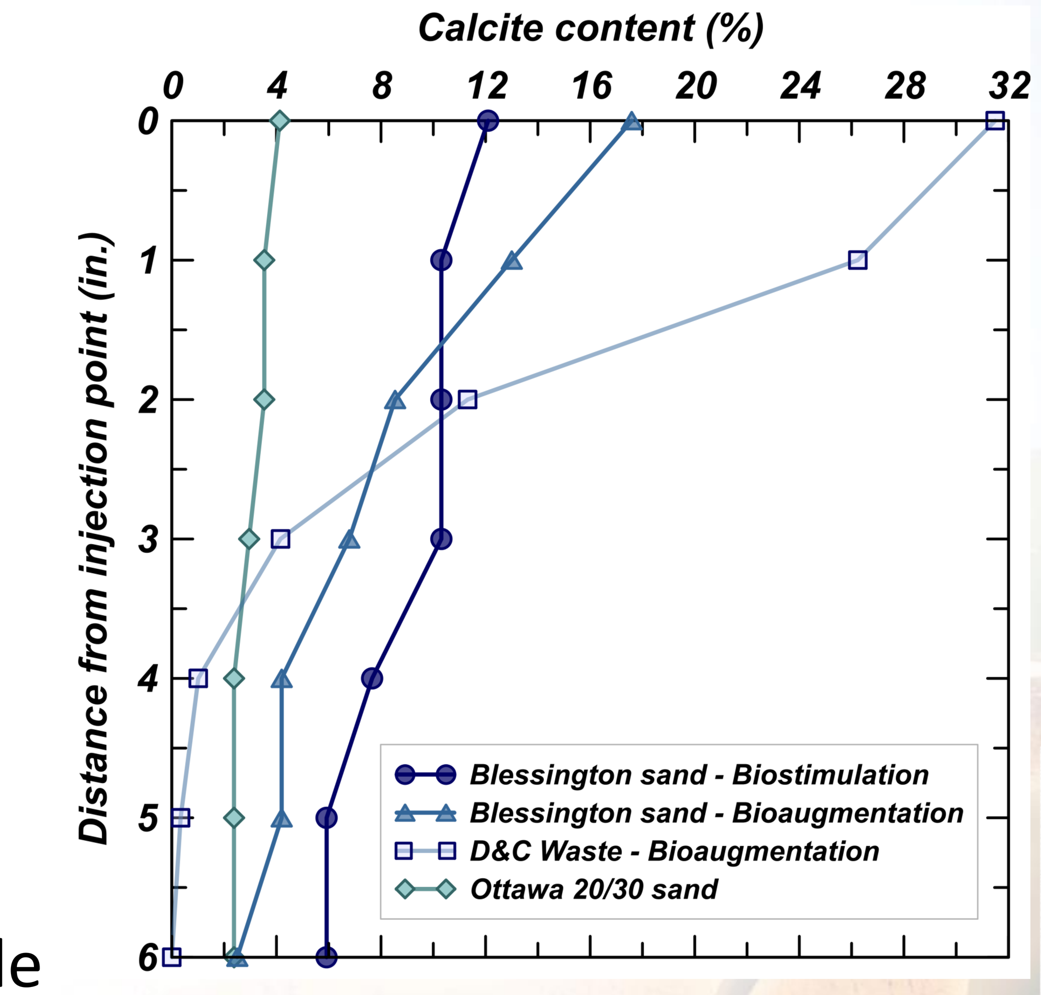
- Both BioStimulation and BioAugmentation successful in lab scale treatment for high carbonate sand and C&D waste
- Calcite morphology and deposition = f(treatment and carbonate form)
- Mineralogy is consistent with naturally occurring carbonate phases and minerals found in cementitious phases
- Uniformity of calcite deposition in the treated columns is a continued focus of study

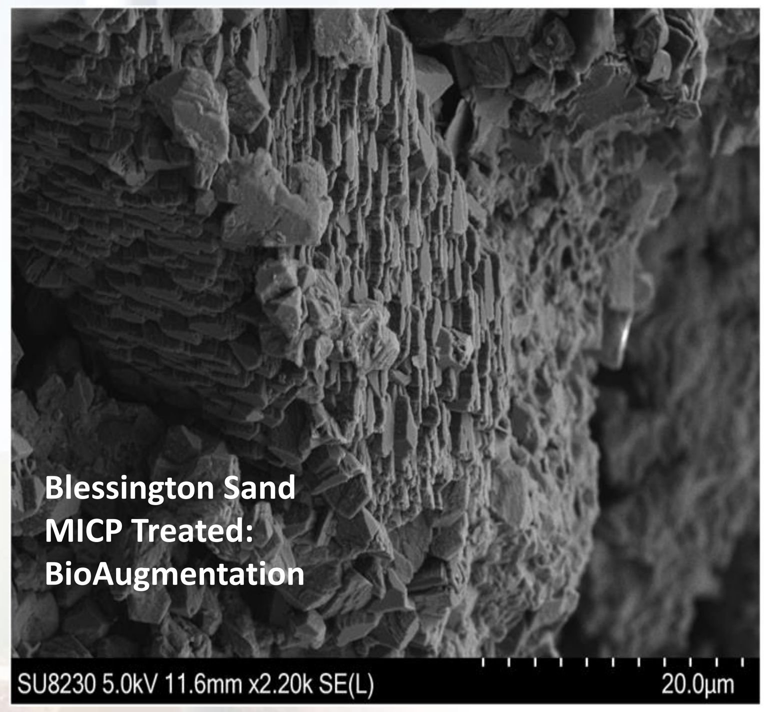
Results: BioStimulation Blessington Sand



Vs and Unconfined Compressive Strength as f(treatment conditions)

Calcite Content for BioStimulation/Augmentation Blessington Sand and C&D Waste





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