Center for Bio-mediated & Bio-inspired Geotechnics

# Center for Bio-mediated and Bio-inspired Geotechnics

**Engineering Research Center**


Arizona State University in partnership with Georgia Institute of Technology, New Mexico State University, and the University of California, Davis

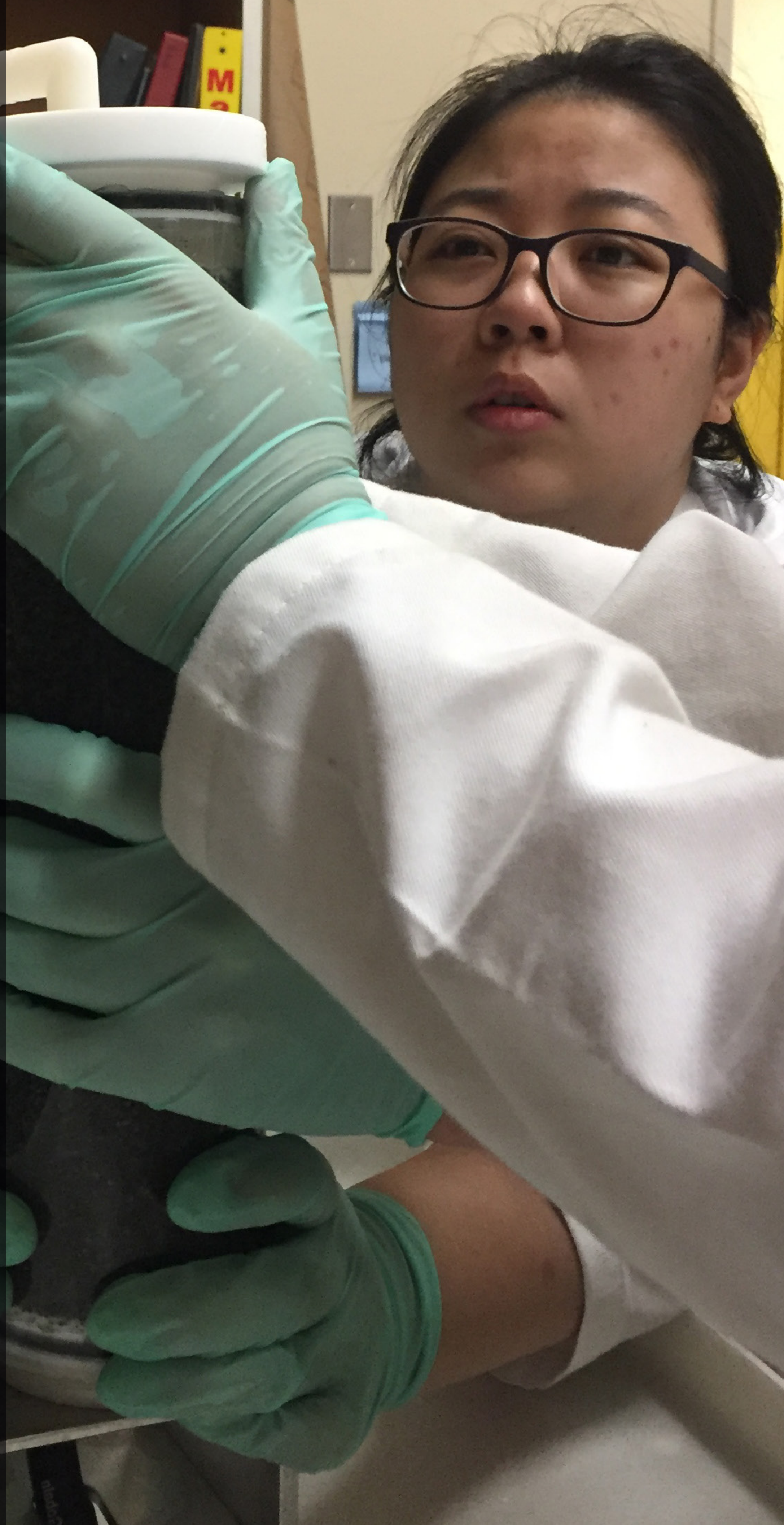
Edward Kavazanjian, Jr., Director
Claudia E. Zapata, Deputy Director


Second Annual Report
August 1, 2016 to July 31, 2017

## Volume II

Due: September 14, 2017


Cooperative Agreement
EEC-1449501

CBBG REU Ziqi Chen, an undergraduate civil engineering student at Lafayette College, is seen here working with Jordan Greer, CBBG graduate student researcher at the University of California, Davis, preparing bio-treated sand samples.

Photo courtesy of Jordan Greer/University of California, Davis

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## 1 List of CBBG Projects

| Faculty | Affiliation | Sponsor | Name of Project |
|---|---|---|---|
| **Thrust 1: Hazard Mitigation** | | | |
| **Direct support** | | | |
| **Edward Kavazanjian** | ASU | NSF | Liquefaction Mitigation via Microbial Denitrification |
| Jason DeJong | UCD | | |
| Rosa Krajmalnik-Brown | ASU | | |
| Bruce Rittmann | ASU | | |
| Leon van Paassen | ASU | | |
| Dan Wilson | UCD | | |
| **Douglas Nelson** | UCD | NSF | Microbial Ecology of Stimulated Ureolytic Biocementation |
| Jason DeJong | UCD | | |
| Mike Gomez | UW | | |
| Rebecca Parales | UCD | | |
| **Narayanan Neithalath** | ASU | NSF | Microscale Modeling of Carbonate Precipitation |
| Edward Kavazanjian | ASU | | |
| **Jason DeJong** | UCD | NSF | Stimulation of Native Bacteria for Bio-Cementation at Field-Scale Treatment Depths |
| Mike Gomez | UW | | |
| Douglas Nelson | UCD | | |
| **Timothy Ginn** | WSU | NSF | Upscaled Modeling of MICP for Field Deployment |
| Jason DeJong | UCD | | |
| Kazayuki Hayashi | Baylor | | |
| Douglas Nelson | UCD | | |
| Dan Wilson | UCD | | |
| Katerina Ziotopoulou | UCD | | |
| **Indirect Support** | | | |
| N/A | | | |

| Faculty | Affiliation | Sponsor | Name of Project |
|---|---|---|---|
| **Thrust 2: Environmental Protection and Restoration** | | | |
| **Direct Support** | | | |
| **Zohrab Samani** | NMSU | NSF | Activated Landfill for Rapid Organic Degradation |
| Paola Bandini | NMSU | | |
| **Cesar Torres** | ASU | NSF | Electro-kinetic Transport for Mineral Precipitation and Soil Remediation |
| Rosa Krajmalnik-Brown | ASU | | |
| **Hinsby Cadillo-Quiroz** | ASU | NSF | Enhancing Methane Production from Landfills |
| Edward Kavazanjian | ASU | | |
| Rosa Krajmalnik-Brown | ASU | | |
| Leon van Paassen | ASU | | |
| **Sheng Dai** | GT | NSF | Microbial Effects on Mechanical and Geochemical Properties of Porous Media |
| Joel Kostka | GT | | |
| Rosa Krajmalnik-Brown | ASU | | |
| **Sheng Dai** | GT | NSF | Microbial Manipulation of Flows in Subsurface Geomaterials |
| **Anca Delgado** | ASU | NSF | Microbial Metabolic Chain Elongation |
| **Rosa Krajmalnik-Brown** | ASU | NSF | Microbial Metabolic Exploration from Extreme Environments for Bioremediation and Energy Recovery |
| Everett Shock | ASU | | |
| Cesar Torres | ASU | | |
| **Zohrab Samani** | NMSU | NSF | Rehabilitation and Restoration of Degraded Soils Using Liquid Organic Fertilizer |
| Paola Bandini | NMSU | | |
| **Charalambos Papelis** | NMSU | NSF | Microbially Enhanced Iron-Modified Zeolite Permeable Reactive Barrier |
| Paola Bandini | NMSU | | |
| **Indirect Support** | | | |
| **Rosa Krajmalnik-Brown** | ASU | Industry | Groundwater Detoxification through Combined Remediation and Zero-Valent Iron Reduction |

| Faculty | Affiliation | Sponsor | Name of Project |
|---|---|---|---|
| **Thrust 3: Infrastructure Construction** | | | |
| **Direct Support** | | | |
| **Rebecca Parales** | UCD | NSF | Biofilm Enabled Permeability Reduction in Sands |
| Douglas Nelson | UCD | | |
| Ruixing Wang | UCD | | |
| **Paola Bandini** | NMSU | NSF | Bio-inspiration for Resilient Earthen Construction |
| Brad Weldon | NMSU | | |
| **Paola Bandini** | NMSU | NSF | Bio-inspired Unsaturated Soil Improvement and Reinforcement: Mechanisms and Strategies |
| Craig Newston | NMSU | | |
| **Chloe Arson** | GT | NSF | Bio-inspired Design of Interwoven Flow Networks under Topological Constraints for Optimizing Subsurface Utility Systems |
| David Hu | GT | | |
| **Edward Kavazanjian** | ASU | NSF | Engineering Applications of Enzyme-Induced Carbonate Precipitation |
| Nasser Hamdan | ASU | | |
| Narayanan Neithalath | ASU | | |
| Leon van Paassen | ASU | | |
| **Jason DeJong** | UCD | NSF | Tree Root Inspired Foundations |
| Alejandro Martinez | UCD | | |
| Daniel Wilson | UCD | | |
| **David Frost** | GT | NSF | Root-system Evaluation for Multi-function Foundation Bio-inspiration |
| Jason DeJong | UCD | | |
| Daniel Wilson | UCD | | |
| Jeanette Yen | GT | | |
| **Indirect Support** | | | |
| N/A | | | |

| Faculty | Affiliation | Sponsor | Name of Project |
|---|---|---|---|
| **Thrust 4: Cross-Cutting Research** | | | |
| **Direct Support** | | | |
| **David Frost** | GT | NSF | Geotechnics of Bio-locomotion and Self-Excavating Systems |
| Douglas Cortes | NMSU | | |
| Jason DeJong | UCD | | |
| Daniel Goldman | GT | | |
| **Ximin He** | ASU | NSF | Hydrogel-Enhanced EICP for Soil Stabilization |
| Nasser Hamdan | ASU | | |
| Edward Kavazanjian | ASU | | |
| **Sheng Dai** | GT | NSF | Laboratory for Bio-mimetic and Bio-inspired Studies |
| **Alissa Kendall** | UCD | NSF | Life Cycle Sustainability Assessment Framework for Geotechnical Engineering |
| Jason DeJong | UCD | | |
| **Douglas Cortes** | NMSU | NSF | GUSANO Utilitarian Subterranean Annelid-Inspired Geo-probe |
| **Indirect Support** | | | |
| N/A | | | |

| Faculty | Affiliation | Sponsor | Name of Project |
|---|---|---|---|
| **Other CBBG Projects** | | | |
| **Direct Support** | | | |
| **Delia Saenz** | ASU | NSF | Diversity and Integration |
| Martha Mitchell | NMSU | | |
| **Wilhelmina Savenye** | ASU | NSF | Education and Outreach – University Education |
| Claudia Zapata | ASU | | |
| Colleen Bronner | UCD | | |
| Susan Brown | NMSU | | |
| Wendy Newstetter | GT | | |
| Jeannette Yen | GT | | |
| **Wilhelmina Savenye** | ASU | NSF | Education and Outreach – Pre-College Education |
| Claudia Zapata | ASU | | |
| Leon van Paassen | ASU | | |
| Susan Brown | NMSU | | |
| Colleen Bronner | UCD | | |
| David Frost | GT | | |
| **Colleen Bronner** | UCD | NSF | Outreach Strategies for Engagement of Women in Civil Engineering |
| **Paola Bandini** | NMSU | NSF | Tribal Initiative |
| Martha Mitchell | NMSU | | |

## 2 Project Summaries

### 2.1 Thrust 1: Hazard Mitigation

#### 2.1.1 Thrust 1: Liquefaction Mitigation via Microbial Denitrification

**ERC Team Members**

*CBBG Faculty*
Edward Kavazanjian (SSEBE ASU)
Bruce Rittmann, (SSEBE ASU)
Leon van Paassen, (SSEBE ASU)

*Other Research Staff*
Hamed Khodadadi Tirkolaei, ASU

*Graduate Students*
Caitlyn Hall, (SSEBE ASU)
Elizabeth Stallings (SSEBE ASU)

*Undergraduate Students*
Juan Paez (SSEBE ASU)
Sarah Montgomery (SSEBE ASU)
Angela Egan (SSEBE ASU)

**Project Goals**

The goal of this project is to develop a cost-effective and non-disruptive means of mitigating the potential for earthquake-induced soil liquefaction under and around existing facilities using microbially induced desaturation and precipitation (MIDP).

**The project's role in support of the strategic plan**

Mitigation of earthquake-induced soil liquefaction is the initial focus of the geologic hazard thrust. A cost-effective means of mitigating earthquake-induced soil liquefaction would be a major step toward enhancing the resiliency of trillions of dollars of civil infrastructure at risk from earthquake-induced liquefaction worldwide. Because of the prevalence of essential infrastructure facilities built on liquefiable ground without consideration of the losses associated with this phenomenon, a cost-effective non-disruptive mitigation technique would have considerable commercial value. This project is one of three biogeotechnologies (MICP, EICP, and MIDP) pursued by the CBBG that has the potential to satisfy the need for mitigation of earthquake-induced liquefaction. All three of these technologies have the potential to satisfy this need, and each may be the preferred solution in a given situation,

**Fundamental Research, Education, or Technology Advancement Barriers**

Fundamental research questions that must be answered to develop MIDP as a liquefaction mitigation technique include: 1) in what range of soil types can this technology be effective; 2) what is the effect of the steady state pore pressure and soil grain size on the desaturation component of MICP; 3) what level of treatment is necessary to achieve a desired level of improvement in the liquefaction resistance of the soil; 4) what are the quantities of substrate and nutrients needed to achieve the desired level of treatment; 5) how long will it take to achieve the desired level of treatment; and 6) what is the permanence of the improvement in liquefaction resistance that can be achieved using this technology.

The primary technology advancement barrier that must be overcome to apply this technique in the field is the question of how to deploy the necessary substrate and nutrients so that it is well distributed throughout the treatment zone. An associated issue is the cost of achieving a specified level of treatment, which should be compared to the risk associated with earthquake-induced liquefaction at the site.

**Any research aspect that involves foreign collaborations, especially indicating the length of time US faculty or students spent abroad conducting their work, and vice versa, and the value added of that work to the student's/faculty' work.**

CBBG is collaborating with the Technical University at Delft (TU Delft) on development of the biogeochemical model that will be used to predict quantities of substrate and nutrients needed to achieve the desired level of treatment and to estimate how long will it take to achieve the desired level of treatment. CBBG student Cailyn Hall, currently working on the second-generation biogeochemical model, spent 6 weeks at TU Delft in the summer of 2017 working with researchers there on enhancing the model. The computational tool made available by TU Delft researchers has significantly improved the efficiency and effectiveness of the model.

**Achievements in previous years**

In the first year of the project, CBBG researchers demonstrated in bench scale testing that denitrification (dissimilatory reduction of nitrogen) could effectively increase the resistance to earthquake-induced liquefaction of a uniform medium to fine sand in two different ways: 1) by desaturation the soil through production of biogas and 2) by precipitating calcium carbonate (calcite). These two processes operate on different time scales and are anticipated to have different degrees of longevity. Desaturation happens quickly in laboratory columns (on the order of several days) but is not expected to persist for very long time periods and carbonate precipitation, Significant calcite precipitation takes on the order of months in the laboratory but the precipitated calcite is expected to persist for tens to hundreds of years under typical conditions in situ. Therefore, we refer to this technique as Microbial Induced Desaturation and Precipitation (MIDP) and characterize it as a two-stage process for mitigation of earthquake-induced liquefaction.

Achievements during the first year of CBBG operation on this project included relating the increase in liquefaction resistance to the levels of desaturation and carbonate precipitation. Figure 1A shows the degree of saturation of a specimen of Ottawa 20-30 sand in a semi-stagnant column as a function of time. This figure shows that in a matter of days following the introduction of nutrients to stimulate the denitrifying microorganisms the degree of saturation dropped to below 94%. . Figure 1B shows the relationship between degree of saturation and liquefaction resistance. Together, these figures show that substantial increase (on the order of 40 percent) in the liquefaction resistance of a soil can be achieved in a matter of days in a laboratory column test.

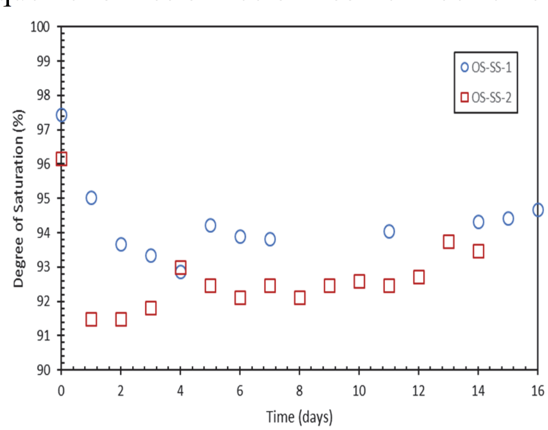


Figure 1A. Degree of Saturation vs. Time

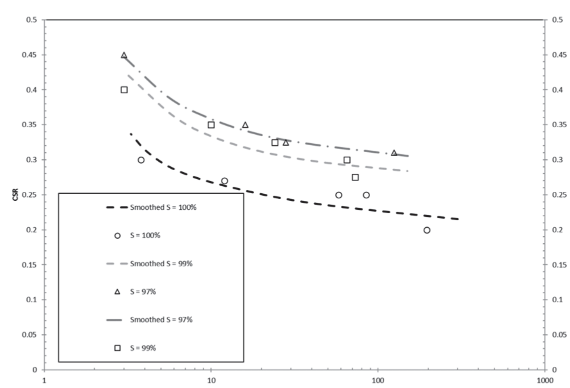


Figure 1B. Degree of Saturation vs. Cyclic Shear Resistance

Another accomplishment in Year 1 of this project was development of a first generation stoichiometric model to relate input values for nitrate, calcium chloride, and acetate (the electron donor) to gas and calcite production. Figure 2A shows the comparison between the calcium concentration in the pore fluid and time predicted by the model and measured in the semi-stagnant columns (the difference is the amount of calcium precipitated in the form of carbonate) while Figure 2B compares measured and predicted gas generation.

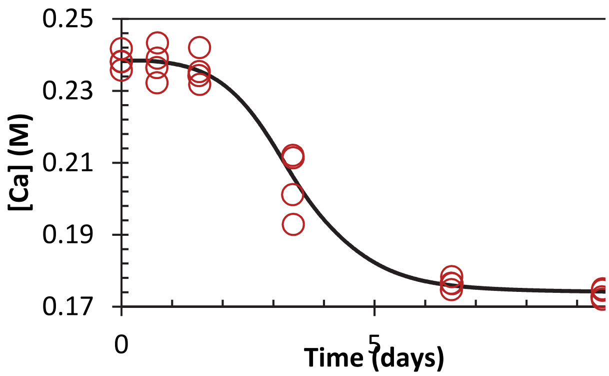


Figure 2A. Calcium concentration versus time

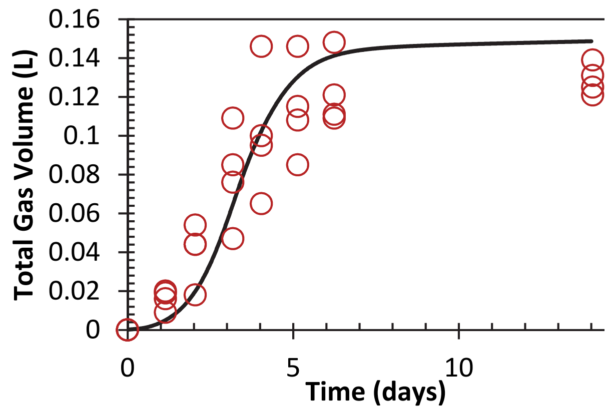


Figure 2B. Gas generation versus time

**Achievements during the past year**

Research completed in Year 2 demonstrated that stimulation of indigenous denitrifying microbes is at least as effective, and perhaps more effective, than introducing exogenous microbes for denitrification. Year 2 research also demonstrated that denitrification happened faster and more efficiently in columns with continuous flow of the denitrifying media than in semi-stagnant columns. Work on the stoichiometric biogeochemical model relating input nutrient and mineral constituents to the resulting biogas generation and carbonate precipitation rates continued in Year 2 with development of a second-generation model that considers the effects of inhibiting factors, such as nitrous acid accumulation and low pH, and microbial kinetics on biomass growth and CaCO3 precipitation. Results from the second-generation model, illustrated in Figure 3, showed better agreement with respect to accumulation of intermediate products of the reaction while maintaining good agreement with gas generation and carbonate precipitation.

In Year 2, work was also initiated on the third-generation of the biogeochemical model, on benchtop tank testing of gas generation, and on centrifuge testing at the UC Davis testbed. The third generation model is being developed in collaboration with the Technical University at Delft (TU Delft), taking advantage of their "tool box" for biogeotechnical modeling. The benchtop and centrifuge testbed tests are investigating the desaturation stage (i.e., the first stage) of the MIDP (denitrification) mitigation process using bio-augmentation to accelerate gas generation for physical modeling purposes. The benchtop testing is focusing on gas migration within soil and is being conducted in a Plexiglas tank to include visual monitoring of bubble formation. The centrifuge tests are focusing on the effect of steady state pore pressure (i.e., depth below the water table) and grain size (i.e., pore size) on gas bubble generation and migration.

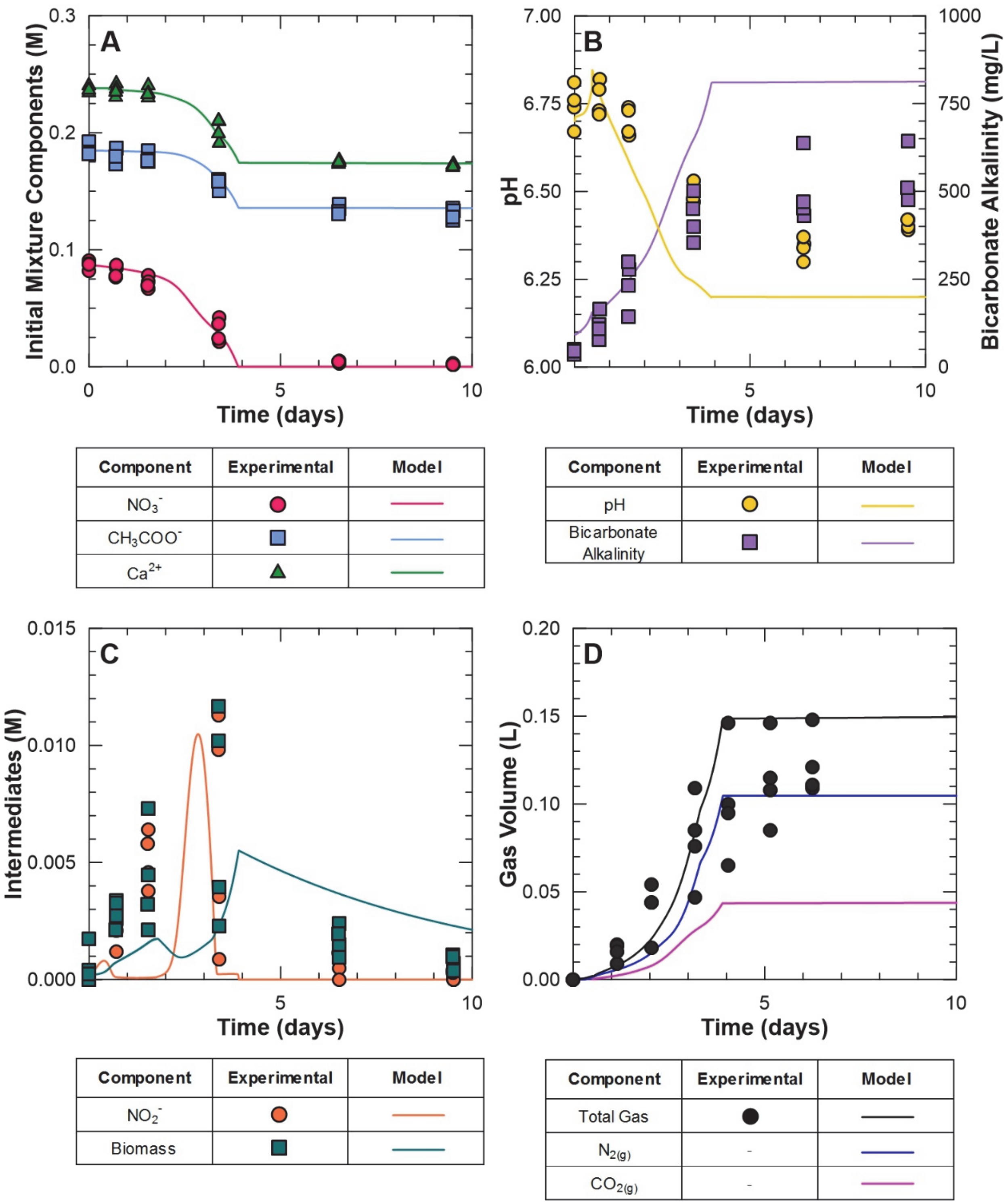


Figure 3. Results from the third generation biogeochemical model

**Summary of other relevant work being conducted within and outside of the ERC and how this project is different**

Related work being conducted within the ERC includes research on ground improvement via microbially induced carbonate precipitation (MICP) and research on ground improvement via enzyme induced carbonate precipitation (EICP). Potential applications of both of these alternative techniques include mitigation of earthquake-induced liquefaction. Some of the MICP testing is being conducted on the UC Davis centrifuge in parallel with the MIDP centrifuge test to facilitate comparison of the effectiveness of these techniques. Related work outside of the CBBG is being conducted in ASU laboratories on gas bubble generation and migration using micro-fluidic chips. Also, as part of CBBG infrastructure development, a large test pit has been constructed on the ASU Polytechnic campus that will serve as a test bed for field scale development of all three carbonate precipitation technologies (MIDP, MICP, and EICP).

**Plans for the next year**

Plans on this project for next year include continue development and validation of the third stoichiometric model for MIDP, bench scale testing in triaxial test cells on the effect of steady state pore pressure on gas bubble formation and migration, completion of the centrifuge model tests, and initiation of field scale experimentation of the MIDP technology in the large test pit recently completed on the ASU Polytechnic campus.

**Expected milestones and deliverables for the project**

It is anticipated that demonstration of the effectiveness of this technology at a field site will take place by the end of year 4 and by the end of year 5 the technology will be available for deployment for liquefaction mitigation on actual infrastructure projects.

**Member company benefits**

A practical technique for liquefaction mitigation beneath and around existing infrastructure facilities is of significant interest and great benefit to member companies engaged in ground improvement specialty contracting, including Hayward Baker, Nicholson Construction, Schnabel Construction and GeoPier, who could market the technology nationally and internationally. It is also of interest to the facility owners who are members of the Industrial Partner Program, including Republic Industries and Freeport McMoRan, and the public agencies who are Associate members, as they all have facilities at risk from this phenomenon

**If relevant, commercialization impacts or course implementation information**

Information on this technique and its potential benefits has been incorporated in graduate classes on Ground Improvement and on Geotechnical Earthquake Engineering at Arizona State University. It will also be incorporated in a new graduate course on Biogeotechnical Engineering, to be offered for the first time in the Fall 2017 semester. The graduate student working on this project will enroll in the NSF I-Corp program during the 2017-2018 academic year and develop a marketing plan for this technology.

### 2.1.2 Thrust 1: Microbial Ecology of Stimulated Ureolytic Bio-cementation

**ERC Team Members**

*CBBG Faculty*
Douglas Nelson, UC Davis
Rebecca Parales, UC Davis
Jason DeJong, UC Davis

*Graduate Student*
Charles Graddy

*Undergraduate Students*
Sydney Morrill
Lindsay Kline
Alana Erickson
Rebecca Kandel

**Project Goals**

The goal of this project is to develop and refine, from a microbiological perspective, the use of microbially induced calcite precipitation (MICP) to the point that it can be a cost-competitive means of mitigating the potential for earthquake-induced soil liquefaction under and around existing facilities.

**The project's role in support of the strategic plan**

Mitigation of earthquake-induced soil liquefaction is a focus of the hazard mitigation thrust. A cost-effective means of mitigating earthquake-induced soil liquefaction would be a major step toward enhancing the resiliency of at-risk civil infrastructure. MICP, through bio-stimulation of *in situ* microbes -- as compared with the more widespread bio-augmentation approach -- offers possible advantages, which include removing high costs associated with producing and transporting large volumes of cultured bacteria prior to injection and avoiding societal objections to injection into native soils of large volumes of non-native bacteria. This project is one of several biogeochemical approaches being pursued by CBBG. Given the magnitude of investment in civil infrastructure and potential for enormous earthquake damage, pursuit of these diverse technologies seems justified at this time.

**Fundamental Research, Education, or Technology Advancement Barriers**

Fundamental research and technology advancement barriers that must be dealt with to develop and commercialize this technique include: 1) what range of soil types is amenable to this treatment; 2) what level and duration of treatment are necessary to achieve a liquefaction resistance of a soil above threshold criteria; 3) what is the permanence of the improvement in liquefaction resistance that can be achieve using this approach; 4) how can this method of treatment be applied in the field; 5) how, based on an understanding of the changing community structure of the native bacteria enriched throughout this process -- including the physiological properties of individual ureolytic isolates, can costs be minimized, while also achieving permanence of calcite deposition across the widest possible range of soil types in field settings?

**Any research aspect that involves foreign collaborations, especially indicating the length of time US faculty or students spent abroad conducting their work, and vice versa, and the value added of that work to the student's/faculty' work.**

N.A.

**Achievements in previous years**

UC Davis research on this problem demonstrated in a Large Tank Experiment that, in two side-by-side 1.7-meter diameter cylinders of quarried sand, bio-stimulation of *in situ* ureolytic bacteria could achieve soil improvement equivalent to bio-augmentation with the bacterium, *Sporosarcina pasteurii* (ATCC 11859; NCIMB 8841) – as evaluated by shear-wave velocity and cone penetration test measurements. Additional research on tests of sands from 12 different quarries and of native sand/gravel collected aseptically from 1, 5 and 12 m showed (collectively called RAPID experiment) that the capacity for MICP via bio-stimulation of native ureolytic bacteria is broadly distributed in natural soils, and perhaps universal. A collection of 314 cultures of bacteria from the Large Tank and RAPID experiments and an experiment that was a “Patch On” to the Large Tank experiment was achieved. These were passaged repeatedly on selective and non-selective media to test for contaminants and, when judged axenic, were supplemented with a sterile cryo-protectant and stored in an ultra cold freezer (-80°C; liquid $N_2$ backup) to facilitate future physiological and genetic studies as desired.

16S rRNA sequencing showed that a wide variety of other ureolytic strains closely related to, but not identical to, *S. pasteurii* ATCC 11859 were enriched by Day 12 in the bio-stimulation tank (Figure 4). Colonies were selected based on appearing most similar to the urease positive strain of *Sporosarcina pasteurii* (ATCC 11859; NCIMB 8841), which was added at a total of $10^{13}$ cells to the nearby bio-augmentation tank. On Day 5 shortly after the bio-augmentation tank had been inoculated, only strain 11859 was cultured from it; however, by the time cultures were isolated on Day 12 and Day 13, the abundance of introduced strain 11859 had declined and only represented 6% of the isolates, i.e. 1 of 17 (Figure 4). All but 2 of the 37 isolates from the bio-stimulation tank were urease-positive.

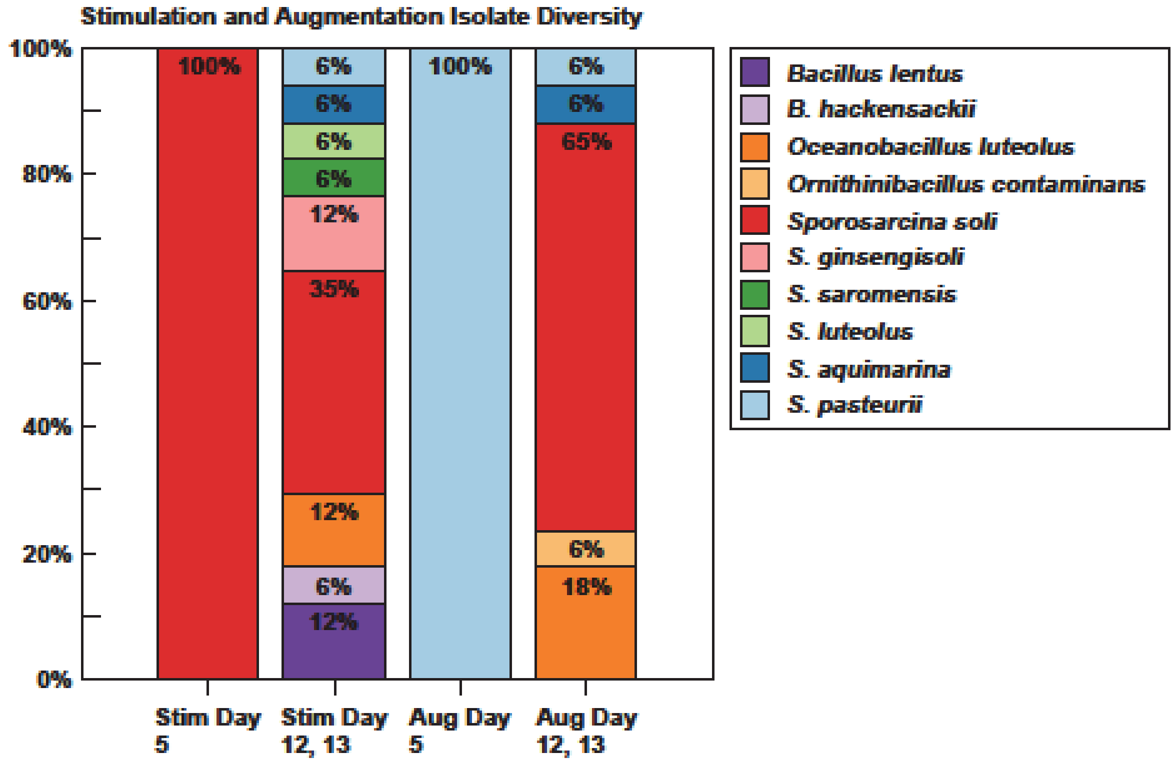


Figure 4. Species diversity of cultures isolated from bio-stimulation and bio-augmentation Large Tanks on Day 5 and Day 12 & 13. See Figure 7 for further details on stimulation tank diversity.

A study of the physiology of 8 randomly selected ureolytic bacteria from the Large Tank Experiment has been completed. Findings also include:

- Whole cell rates of ureolysis follow Michaelis-Menten kinetics, with half-maximum values achieved at urea concentrations ranging from 38 to 520 mM. For reference, urea concentrations used in successful bio-stimulation of quarried sands and native soils range from 0 – 350 mM.
- Maximum rates of urea hydrolysis vary from strain to strain by 100-fold, ranging from about 0.6 - 60 µmol $min^{-1}$ $mg^{-1}$ protein.

**Achievements in past year**

<u>Compared Ureolysis With Alternative MICP Processes</u>

Urea hydrolysis by *Sporosarcina pasteurii* has been the biological process and organism most fully explored to drive MICP. Nonetheless, other biological processes, namely sulfate reduction, iron reduction, and denitrification have also been proposed (Castanier et al., 1999, DeJong et al., 2010). The range of whole cell urease kinetic properties determined for the 4 strains isolated from the bio-stimulation tank represent the first opportunity to compare their ability to produce carbonate species (in $CO_2$ equivalents) and alkalinity (essential for driving the inorganic carbon equilibrium toward carbonate to promote precipitation) with available literature rates for denitrifying, iron-reducing and sulfate-reducing pure cultures. Presented here (Figure 5) are the range of production rates for heterotrophic bacteria respiring anaerobically with these other electron acceptors in literature studies that were not specifically focused on MICP and rates calculated for 5 strains of this study at 350 mM urea, the initial concentration of urea used in this experiment. The type strain of *S. pasteurii*, used in the bio-augmentation tank, produces alkalinity and carbonate species at rates that are, roughly, two orders of magnitude greater than the most active of the other proposed biological processes. Rates for the isolated ureolytic strains ranged from 40% of the corresponding rates for the *S. pasteurii* type strain to two orders of magnitude lower. Even the lowest measured rates for the indigenous ureolytic isolates were on the same order as the highest known rates for the other metabolic processes (Figure 5).

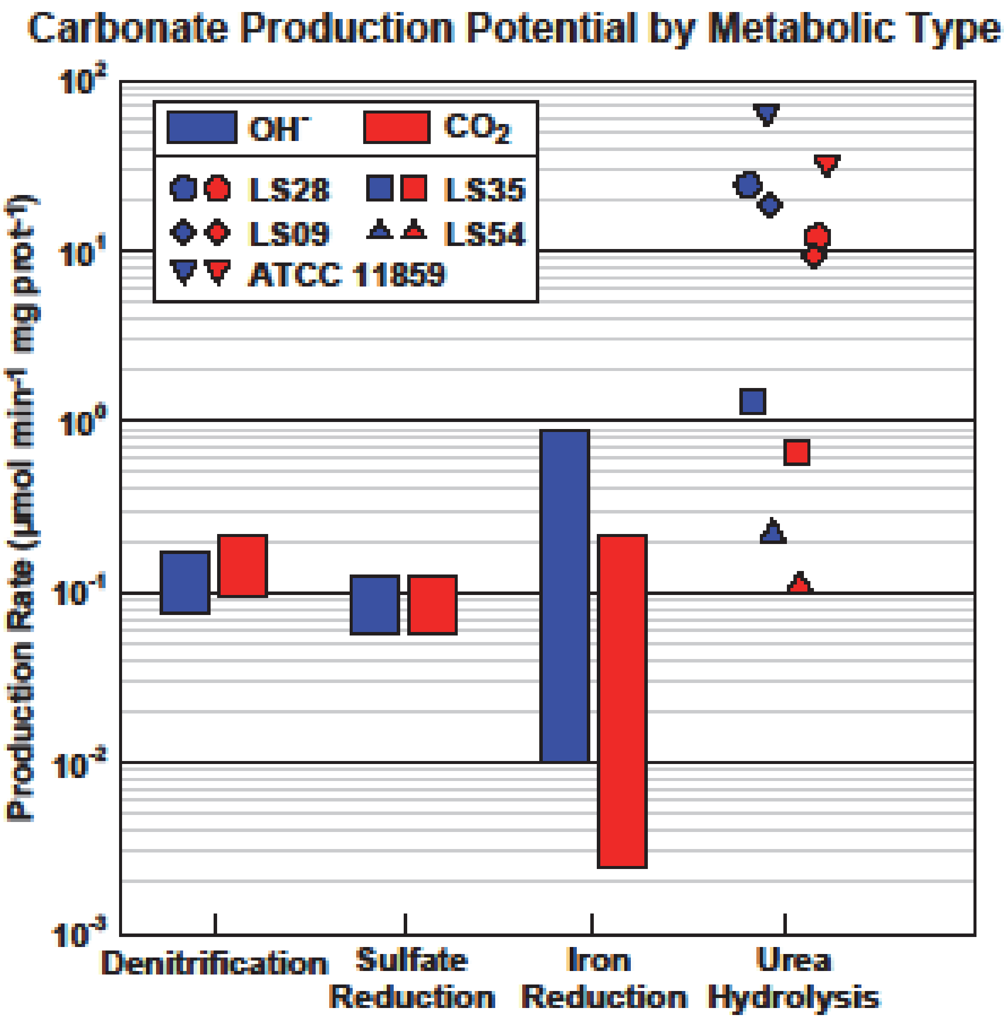


Figure 5. Ranges of whole cell production rates of carbonate (in equivalent CO2) and alkalinity for three alternative MICP pathways. Urea hydrolysis rates represent bacteria at pH 8.5 and 350 mM urea.

<u>Extended 16S rRNA Characterization to Strains from RAPID and "Patch On" Experiments.</u>

Of the 314 pure cultures isolated from the Large Tank, Patch On, and RAPID experiments 54% have now had their 16S rRNA encoding DNA sequenced to a high level of refinement (Figure 6). For the most complete data set (Large Tank) we have gained additional insights into ureolytic diversity in the bio-stimulation tank beyond that depicted in Figure 4. For example, over the course of 13 days, 7 distinct strains of *Sporosarcina soli* were isolated (Figure 7) along with 2 distinct strains each of *Bacillus lentus*, *Oceanobacillus luteolus*, and *Sporosarcina pasteurii* (neither being

ATCC 11859). In all a total of 19 distinct strains were isolated from 0.1 mL samples of dilutions of tank effluent ranging from $10^{-1}$ to $10^{-5}$, painting a surprisingly diverse picture of bacteria present in this extremely ureolytic enrichment at abundances of a minimum of $10^2$ to $10^6$ cells per ml (Figure 7), with 81% of the colonies isolated belonging to the genus *Sporosarcina* (Figure 7) and 94% (35/37) of the isolated being urease positive. Because we designed colony selection in the Large Tank experiment to focus on morphology similar to the ATCC strain of *S. pasteurii* (to test for cross contamination from the augmented tank), Figure 7 and Figure 4 undoubtedly under-represent actual diversity present in those tanks. By contrast, diversity in the RAPID experiment, pooled over 1, 5 and 12 m depths (Figure 8) and in the "Patch On" experiment, is biased in the opposite direction. There we focused on sampling as many colony types as possible. In spite of this bias that favored rare types, 73% and 51% of the isolates obtained on two different culture media belonged to the genus Sporosarcina. Diverse colony selection reflected an attempt to obtain the broadest possible physiological diversity of pure cultures so that, when DNA extraction from column fluids was perfected and provided a measure of relative abundances unbiased by culture medium selection, the chance of having representative pure cultures would be maximized.

Figure 6. Progress (8/15/17) sequencing 16S rRNA from bacterial cultures and fluid DNA clones derived from three distinct sand/soil column experiments.

| Experiment | Cultures/Fluid DNA Clones | Total | Identified | % |
|---|---|---|---|---|
| Large Tank – Bio-stimulation | Cultures | 37 | 37 | 100% |
| Large Tank – Bio-augmentation | Cultures | 26 | 25 | 96% |
| RAPID – Bio-stimulation: 1 meter soil depth | Cultures | 77 | 27 | 35% |
| RAPID – Bio-stimulation: 5 meter soil depth | Cultures | 98 | 39 | 40% |
| RAPID – Bio-stimulation: 12 meter soil depth | Cultures | 57 | 26 | 46% |
| **Totals** | **Cultures** | **314** | **169** | **54%** |

<u>Achieved Success Troubleshooting Methods for DNA Extraction and Cloning from Aqueous Samples.</u> We have very recently achieved a milestone, i.e. the necessary breakthroughs to enable linking pure culture physiology with relative abundance of these same strains in bio-stimulation treatments. After substantial effort expended optimizing ligation and transformation reactions, extracted and amplified DNA from dilute aqueous bacterial suspension is now readily supplying the desired E. coli clones. 400 DNA clones from the "Patch On" experiment are in hand: 100 each from the bio-stimulation column on days 0, 5 and 13 as well as 100 from Day 13 bio-augmentation column. Importantly, the 4 "test clones" sequenced to date gave excellent data, and we expect rapid progress on the remaining 396 to provide a broad picture of diversity vs. time for the bio-stimulation column and an endpoint picture for the bio-augmentation column.

Figure 7. Bacterial species and strain diversity and abundance for colonies cultured from bio-stimulation large tank.

| Species | Strain | Number of colonies tested Day 1 | Day 3 | Day 5 | Day 12 | Isolates | From 10-fold dilution |
|---|---|---|---|---|---|---|---|
| *Sporosarcina soli* | LS25/LS26 | | | 2 | | 2 | 3 |
| | Cluster A | | | 7 | 2 | 9 | 1 to 4 |
| | Cluster B | | 3 | | 4 | 7 | 1 to 5 |
| | LS02/LS03 | 2 | | | | 2 | 2 |
| | LS17 | | 1 | | | 1 | 5 |
| | LS21 | | | 1 | | 1 | 3 |
| | LS01 | 1 | | | | 1 | 2 |
| *S. pasteurii* | LS48* | | | | 1 | 1 | 2 |
| | LS09* | 1 | | | | 1 | 2 |
| *S. luteola* | LS46 | | | | 1 | 1 | 3 |
| *S. ginsengisoli* | LS33/LS34 | | | | 2 | 2 | 3 |
| S. aquamarina | LS47 | | | | 1** | 1 | 3 |
| S. saromensis | LS45 | | | | 1 | 1 | 1 |
| *Oceanobacillus luteolus* | LS49 | | | | 1*** | 1 | 3 |
| | LS38 | | | | 1** | 1 | 2 |
| *O. polygoni* | LS07 | 1 | | | | 1 | 2 |
| *Bacillus lentus* | LS35/LS37 | | | | 2 | 2 | 1 to 3 |
| | LS10 | 1 | | | | 1 | 2 |
| *B. hackensackii* | LS40 | | | | 1 | 1 | 3 |
| **Totals:** | **19** | **6** | **4** | **10** | **17** | **37** | **1 to 5** |

0.1 mL of indicated decade dilution plated to yield specific strain shown
All strains urease positive, unless noted
*Distinct from ATCC 11859
**Urease negative
***Single datum, day 13 not day 12
Cluster A = LS19, 20, 22-24, 27, 28, 36, 39 (n=9)
Cluster B = LS14, 15, 18, 41-44 (n=7)

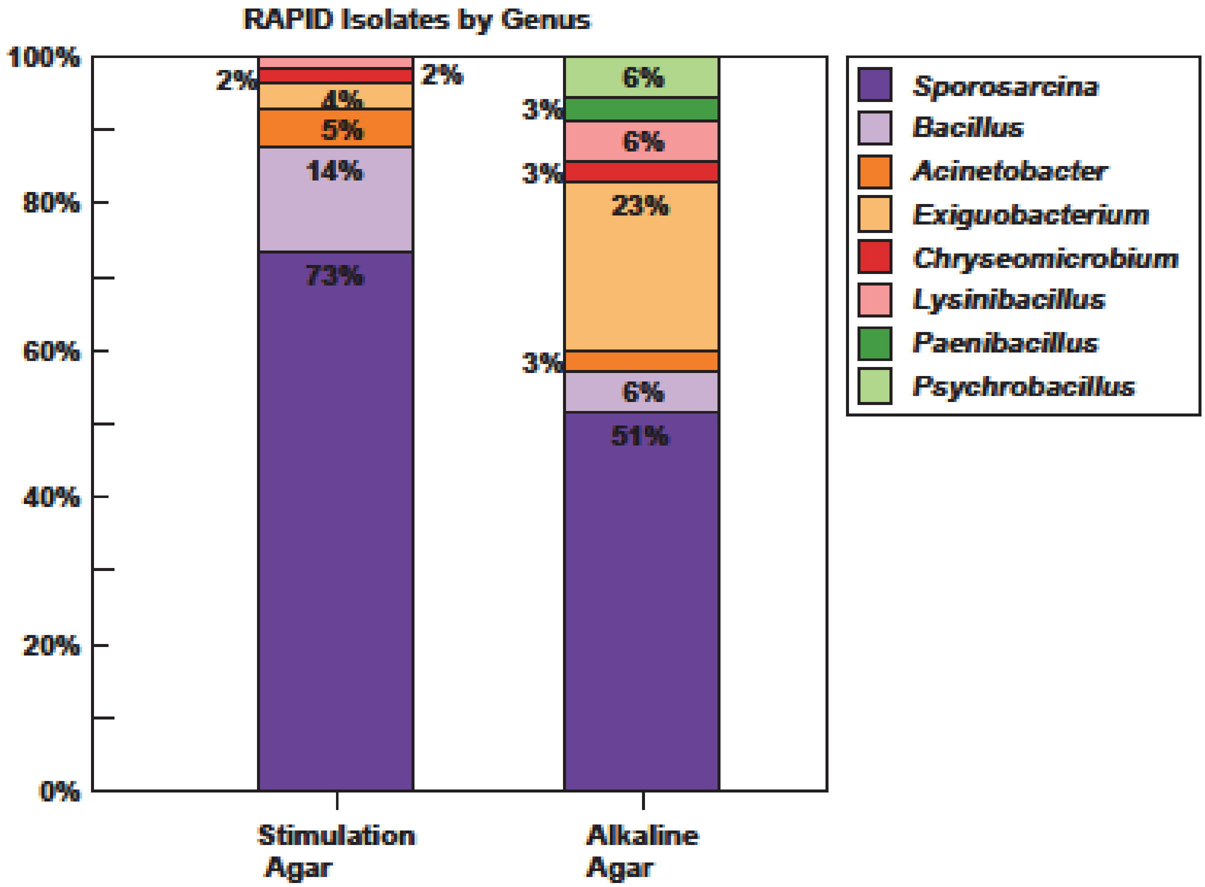


Figure 8. Isolates, by genus, from RAPID experiment. Separate columns reflect culturing results on different agar-gelled media.

Microbiological Support for Other CBBG Projects. PhD student, Charles Graddy, prepared diverse liquid media and provided large volumes of inoculating cultures at specific cell densities for a series of MICP tests performed by others at UCD. Bacteria culture ATCC 11859 was provided in bulk for the ongoing experiments of Kate Darby and Gabby Hernandez, which are testing MICP treatment uniformity for centrifuge modeling, and for the ongoing experiments of Dr. Alejandro Martinez and his students, which are investigating the effect of MICP on thermal conductivity and heat dissipation in soil. Finally, three *Sporosarcina* strains obtained in pure culture from our Large Tank study were provided in bulk to Dr. Michael Gomez and Alexandra San Pablo to assess the changes in material properties that result from large differences in calcite precipitation rates. Charles has also been providing the media to Dr. Parales and Jordan Greer for biofilm treatments and providing general microbiology advising on all the above projects.

**Summary of other relevant work being conducted within and outside of the ERC and how this project is different**

Related work being conducted within the ERC includes research on ground improvement via denitrification (bacterial conversion of soluble nitrate ions to $N_2$ gas), by native and introduced bacteria, and research on ground improvement via enzyme induced carbonate precipitation (EICP).

Sharing of findings on the three projects is the norm. Physiological properties of key ureolytic isolates from the "Patch On" and RAPID experiments will be made available to other projects as soon as they are identified as "dominants" by the above detailed methodology.

**Plans for the next year**

Plans on this project for the next year include:

- Focus on extending success with bulk DNA from " Patch On" experiment to aqueous bacterial samples from RAPID experiment. In parallel with discussion above, this will allow identification of the relative occurrences of the most abundant bacterial types in these samples from three depths. These data will broaden our understanding of whether bio-stimulated ureolytic MICP converges to a single endpoint set of strains. Furthermore, information about the relative abundance in soils of strains having high versus low maximum rates of urea hydrolysis, as well as high versus low half-saturation constants for this process, will provide insights about which properties leverage dominance both early and late in enrichments for MICP bio-stimulation.

- Expand interactions and collaborations with Joint Genome Institute to secure support for metagenomic and transcriptomic characterization of bacterial communities through various stages of bio-stimulated MICP. Take advantage of ongoing sequencing projects there to obtain full genomes of representative *S. pasteurii* and *S. soli* strains.

- Extend studies on the influence of pH and urea concentration on whole cell rates of urea hydrolysis to representative strains in our culture collection that are close relatives of *S. pasteurii*, which have emerged from RAPID and "Patch On" experiments. Five additional species of *Sporosarcina* and additional novel strains of already cultured species have emerged from our RAPID and "Patch On" sequencing efforts, which are less than half complete.

- Optimize our current bio-stimulation solution formulation by determining which component, including lack of key specific elements, limits growth yield for representative strains of Sporosarcina and relatives. Recent insights suggest that phosphorus and/or potassium may be limiting. This was previously unexpected.

- Begin experiments using an anaerobic chamber to study impact of urea hydrolysis on differential survival and growth of *S. pasteurii* and relatives under anoxic conditions. There is literature evidence supporting the view that urea hydrolysis by *S. pasteurii* under condition that mimic those present in our bio-stimulation columns enables production of a proton motive force and ATP even in the absence of an organic energy source or oxygen. If this can be demonstrated it would add significantly to our understanding of why this bacterium, and by inference its close relatives, flourishes under our stimulation conditions.

- Continue to provide diverse cultures, including those grown to high density for experiments of other UC Davis CBBG researchers.

**Expected milestones and deliverables for the project**

It is anticipated that demonstration of the effectiveness of this technology will occur in a large-scale test in Year 3. Refinement of bio-stimulation medium for that field test, with a strong emphasis on lowest cost for maximally effective medium, will continue to be informed by our pure culture studies. As part of this project, soil and aqueous samples will be collected for pure culture and molecular screening, which should allow valuable linkages between our pure culture studies and analysis of field-deployment outcomes.

**Member company benefits**

A practical technique for liquefaction mitigation beneath and around existing infrastructure facilities is of significant interest and great benefit to member companies engaged in specialty contracting for ground improvement, including Hayward Baker, Nicholson Construction, Schnabel Construction and GeoPier, who could market the technology nationally and internationally. It is also of interest to the public agencies that are Associate members, as they all work on facilities at risk from this phenomenon.

**If relevant, commercialization impacts or course implementation information**

Lessons learned about optimization of bio-stimulated MICP, from a microbiological perspective, will be shared and, as approoriate, incorporated into graduate courses in Geotechnical Engineering that are taught by PI DeJong. Commercialization will likely be achieved by making the latest best practices available through expertise residing in UC Davis graduates as they move into industry.

### 2.1.3 Thrust 1: Microscale Modeling of Carbonate Precipitation

**ERC Team Members**

*CBBG Faculty*
Narayanan Neithalath, ASU
Edward Kavazanjian ASU

*Graduate Students*
Pu Yang

*Other Research Staff*
Nasser Hamdan

**Project Goals**
The goal of this project is to model the improvements in soil properties as a function of carbonate precipitation under different conditions, so as to design pathways of carbonate precipitation, and the amounts of strengthening needed for several applications.

**The project's role in support of the strategic plan**
A proper understanding of carbonate precipitation in sands helps to advance several focus areas that are of importance to this ERC including: Mitigation of Earthquake-Induced Liquefaction, Geologic Hazard Mitigation, Mitigation of Fugitive Dust; Ground Improvement for Infrastructure Construction; and Infrastructure Construction Materials. Thus this project serves several related areas in the CBBG family. Efficient and cost-effective means of accomplishing these goals would be a major step toward enhancing the resiliency of trillions of dollars of civil infrastructure at risk. This project provides a fundamental understanding of the mode of carbonate precipitation (e.g., cladding of soil particles, bridging at soil particle contacts, precipitation in the void spaces) on soil behavior, along with novel and efficient modeling strategies to predict the response of particulate systems under different testing conditions. The models will help the development and optimization of bio-based soil strengthening methods for various applications.

**Fundamental Research, Education, or Technology Advancement Barriers**
Fundamental research and technology advancement questions that must be answered include: 1) what is the influence of calcite precipitation mode (around the sand particles, or as sand contacts) on the resultant engineering properties, 2) what types of microstructural models are adequate to predict the response of bio-cemented sands under different test conditions, 3) what is the impact of calcite content and method of precipitation on several important properties such as the capability to mitigate earthquake induced liquefaction, improve soil strength for foundations etc. Currently, there is a lack of understanding of the contributions of various modes of precipitation to soil improvement, lack of predictive models to estimate the degree of carbonation and their influence on soil strengthening.

**Any research aspect that involves foreign collaborations, especially indicating the length of time US faculty or students spent abroad conducting their work, and vice versa, and the value added of that work to the student's/faculty' work.**
N.A.

**Achievements in the previous years**

Achievements during the first year of CBBG operation on this project included: 1) identification of a discrete element method (DEM)-based numerical scheme for the tri-axial compression response of sands, 2) proper computational scheme to obtain the desired particle packing and void ratio, 3) modeling of type of carbonate precipitation based on the volume of carbonates precipitated, and 4) use of the DEM model to predict the tri-axial response of sands under drained conditions. These were summarized in the previous year's report, and formed part of a refereed journal publication.

In Year 2, research efforts focused on building on the work in Year 1 to better elucidate the mechanisms responsible for the obtained response of bio-cemented sands, and thus to define better material design and treatment procedures. The specific tasks included: 1) refinement of the DEM model to predict the undrained triaxial response of sands, 2) development of a methodology to simulate the actual response of sands under undrained conditions, 3) outlining the differences in modeling methodology for different response conditions, and developing suitable testing schemes, and 4) evaluating a modeling scheme for unconfined compression tests on bio-cemented sands. A summary of the research efforts and results is provided below.

The constitutive response of untreated and MICP-modified sands under consolidated isotopically undrained triaxial compression (CIUC) is numerically modeled using the constant volume method. Rigid boundaries, the most commonly employed boundary type in DEM simulations were used in the first set of simulations. The tests being modelled were fully saturated ($B > 0.95$, where B is the ratio of the increase in pore water pressure to the increase in isotropic confining pressure; samples with $B > 0.95$ are assumed to be fully saturated). The methodology adopted for simulations have been described in our publications, and in the previous year's report. Figure 9 shows the comparison of the experimental and simulated deviator stress and excess pore pressure as functions of axial strain. It can be noticed from Figure 9 that while both the deviator stress and excess pore pressure predicted by the numerical model for the untreated sand specimen are in good agreement with the experimental results, the model fails to predict the response of MICP strengthened sand specimen, particularly with respect to pore pressure at strains greater than 1 percent. Both the deviator stress and excess pore pressure are incorrectly estimated at strains greater than 5% for the MICP strengthened sample; the excess pore pressure more so. The simulation for the cemented sand indicates a strain hardening type behavior while the experimental data shows a strain softening behavior as the cementation degrades within a zone of strain localization (i.e., within a shear band). The rigid boundary does not apply a uniform lateral pressure and thus hinders the onset and growth of strain localization in numerical simulation. Thus, while this boundary condition is acceptable in the case of untreated, loose sands where strain localization was not very pronounced, it is clearly an improper approach to simulate heavily cemented granular media which develop prominent shear bands. Thus instead of the rigid wall boundary, a flexible boundary is needed to enable accurate representation of the stress-strain relationships and the prediction of strain localization in cemented media.

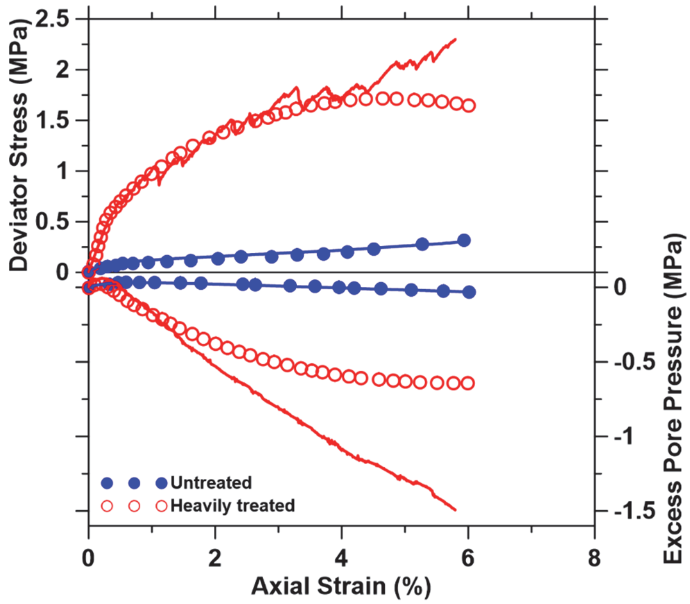


Figure 9. Deviator stress and excess pore pressure predicted by the DEM model (continuous lines) for uncemented sand and heavily cemented sand and its comparison with experimental data (symbols).

A new element called PFacet (particle facet), which is geometrically constructed by the Minkowski sum of a triangular facet and a sphere, is used as the fundamental element to model a flexible boundary. The PFacet element, shown in Figure 10(a), is composed of three nodes (spheres) and three connections (cylinders). The introduction of PFacet element accounts for sphere-PFacet, cylinder-PFacet, and PFacet-PFacet interactions. Both the facets and the cylinders are deformable and can be connected to form membrane-like structures. These discrete elements have been developed in YADE to simulate deformable objects such as membranes within the DEM framework. A schematic view of a flexible membrane boundary constructed by PFacet elements is shown in Figure 10(b).

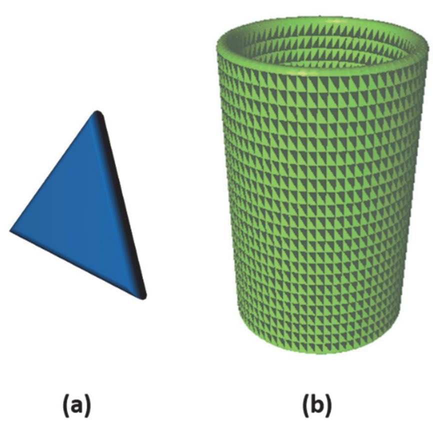


Figure 10. (a) PFacet element, and (b) cylindrical membrane created using PFacet elements. Spheres form the vertices of the triangular facet and deformable cylinders, the sides.

Four main steps are required to simulate the CIUC triaxial test using a flexible membrane boundary: (1) generation of the packed particles for the desired void ratio under rigid boundaries,

(2) replacement of rigid lateral walls with the flexible membrane, (3) isotropic compression of the specimen until the desired confining stress is reached, and (4) axial compression of the specimen. Figure 11 demonstrates the sequence of virtual CIUC experiments.

Figure 12 shows the deviator stress-axial strain, and excess pore pressure-axial strain relationships when rigid or flexible boundaries are used. Better agreement between the numerical simulation and the experimental data was achieved for both uncemented and cemented specimens than achieved using the constant volume method. In simulations of triaxial compression tests, the elastic stage of the deviator stress-axial strain relationship is predicted well, irrespective of the boundary conditions. The rigid wall boundary condition is found to result in a higher strength than the membrane boundary. Beyond the initial elastic stage, which is similar under both boundary conditions, the material stiffness degrades faster for the flexible membrane boundary case. Both these observations can be linked to the overly constraining nature of the rigid boundary (that does not allow shape change) that introduces an inhomogeneous state of stress in the material.

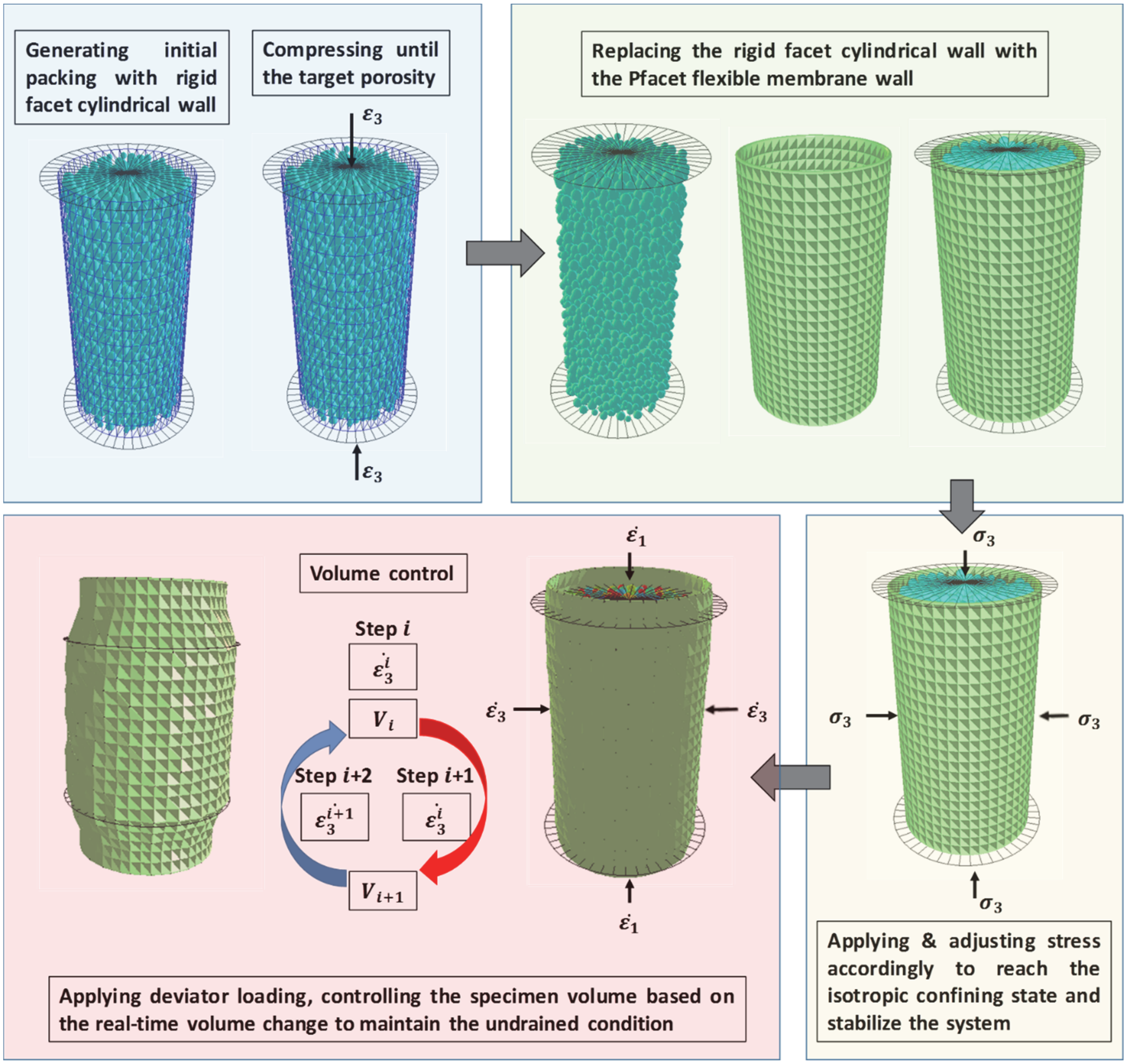


Figure 11. Flowchart depicting numerical simulation of undrained compression test using a flexible membrane boundary

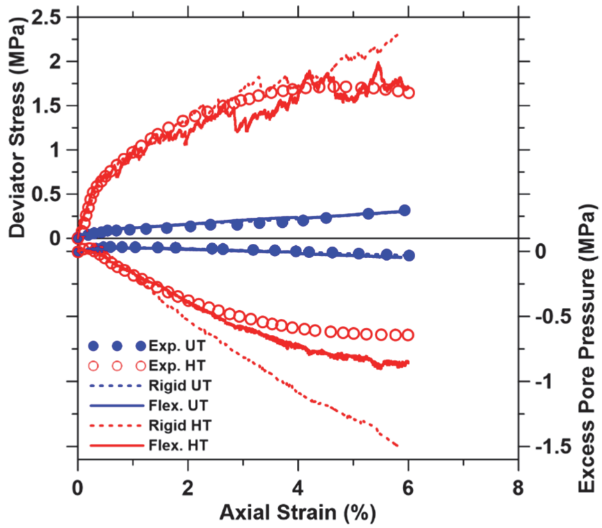


Figure 12. Deviator stress and excess pore pressure predicted by the DEM models employing rigid or flexible boundaries, for uncemented sand and heavily cemented sand. In the legend, UT indicates untreated, and HT, heavily treated.

The DEM model adopting flexible membrane boundary conditions is used to simulate the response of MICP-treated sands with varying cementation levels under undrained triaxial compression. Four specimens treated by MICP via ureolysis with calcium carbonate contents varying from 1.01% to 5.31% by mass and one untreated specimen were simulated. Figure 13 shows the stress-strain responses of all the specimens from the simulation and compares them with the experimental data.

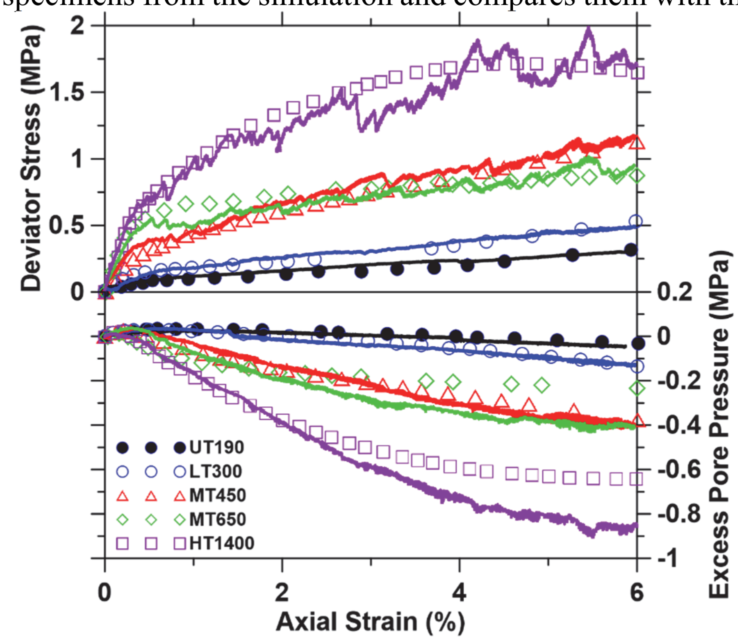


Figure 13. Simulation of constitutive response of sand strengthened using different amounts of carbonates through MICP. The symbols indicate the experimental results and the continuous lines, the simulated response. The numbers next to the legend indicates the shear wave velocity through the samples.

To further examine the stress-strain response of the cemented sands, particle rotation during CIUC simulations was monitored for the virtual samples. High particle rotations occur within the zones of strain localization and large voids appear in the shear band. Figure 14 shows the cross-sectional view of the five virtual samples at an axial strain of 10%. This relatively high axial strain was used to increase the chances of strain localization, especially for the cemented sands. The sand particles are colored in accordance with their rotation degrees, with dark blue indicating the lowest level of rotation and dark red representing the highest level of rotation. Figure 14 shows that the chances for shear band formation and preferential failure zones increase with increase in cementation.

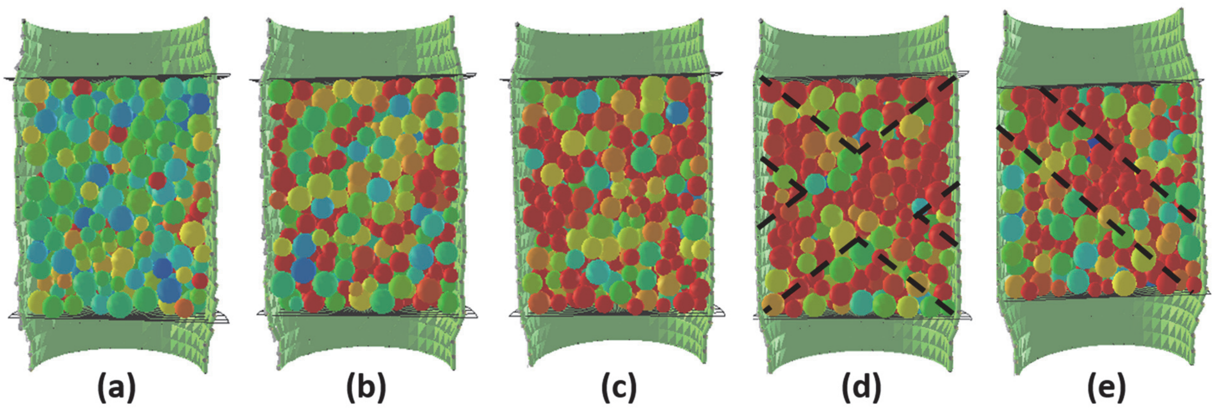


Figure 14. Particle rotations obtained from DEM simulations at different cementation levels: (a) untreated (UT190), (b) lightly treated (LT300), (c) moderately treated (MT450), (d) moderately treated (MT650), with likely conjugate shear banding and (e) heavily treated (HT1400), with a narrow shear band

To simulate the unconfined compressive strength test, 5,000 particles were used to assemble the numerical sample with a target porosity of 0.38. After the consolidation stage, the lateral wall was removed and all the existing contacts were assigned a cohesive strength. The top and bottom platens were then assigned a constant velocity to represent the strain-controlled testing condition. The particle rotations and the prediction of the stress-strain response are shown in Figure 15.

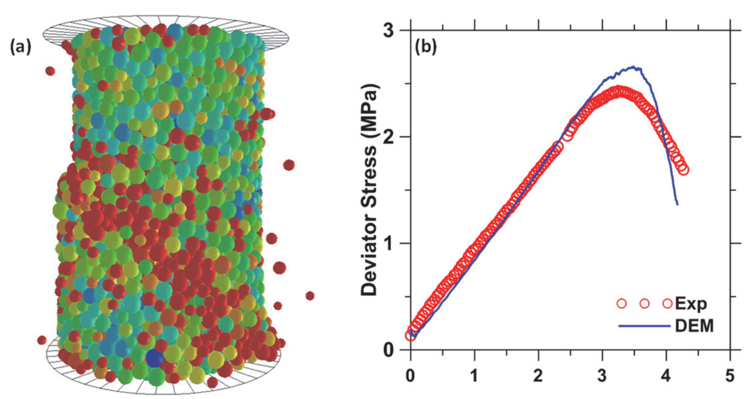


Figure 15. (a) 3D visualization of particle rotations and sample deformation @ 4% axial strain and (b) deviator stress predicted by DEM model and its comparison with experimental result

**Summary of other relevant work being conducted within and outside of the ERC and how this project is different**

Related work being conducted within the ERC includes research on ground improvement via microbially induced carbonate precipitation (MICP) and research on ground improvement via enzyme induced carbonate precipitation (EICP). Potential applications of both techniques include mitigation of earthquake-induced liquefaction. Also, as part of CBBG infrastructure development, a large test pit is currently being constructed on the ASU Polytechnic campus that will serve as a test bed for field scale development of all three carbonate precipitation technologies (MIDP, MICP, and EICP).

**Plans for the next year**

Plans on this project for next year include refining the models developed thus far using actual data from x-ray tomography and nanoindentation of the several phases to provide accurate indicators on the development of cohesive strength, and thereby enhancements in properties. Also anticipated is a study that considers crushing failure of soil particles or calcite grains to ensure that different soil treatments are accounted for adequately. Finally, we will move into simulation of liquefaction using direct shear tests, and also consider simulating liquefaction tests in the centrifuge to provide real-life simulations of the ability of bio-cemented sands to enhance the resistance to hazards.

**Transformative aspects and benefits**

This study is among the first one to systematically approach the issue of modeling the response of carbonated sands and aid in predictive tools for performance of such improved systems. The methodology adopted for this work can be applied to other cemented systems, and thus is a rational, generalized framework for modeling cemented sands. The novel method adopted to simulate the undrained response of sands under triaxial compression is quite unique, and can be extended to several applications were particulates are confined in flexible membranes for testing. Application of the modeling tools developed here for soil strengthening and liquefaction-induced damage mitigation, and its validation and verification will help agencies rapidly adopt these techniques. These tools also will save time and cost involved with extensive experimentation.

**Potential contribution(s) to resilience and sustainability:**

The project contributes significantly to resilience by contributing to our understanding of liquefaction-induced damage mitigation, and providing efficient strengthening methods against such damage. Cementation levels can be optimized through appropriate implementation of the models. The application of the developed models to better understand ground improvement techniques and design infrastructure materials, along with the implementation of optimization schemes are examples of the contribution of this work to sustainability. Fundamental information on the mechanisms at particle scale that contribute to the enhanced resiliency of geotechnical systems are gleaned from these models, which is a major technical contribution of this work.

### 2.1.4 Thrust 1: Stimulation of Native Bacteria for Bio-cementation at Field-Scale Treatment Depths

**ERC Team Members**

*CBBG Faculty*
Jason DeJong, UC Davis
Douglas Nelson, UC Davis

*Graduate Students*
Michael Gomez
Charles Graddy
Gabby Hernandez

*Undergraduate Students*
Alex San Pablo

**Project Goals**

The overarching goal of this project is to develop an environmentally-conscious in situ treatment technique that can reliably stimulate native bacteria in the subsurface to complete the reactions necessary for the bio-cementation of liquefiable sands. In Year 2, research focused on improving our understanding of biological and chemical changes that occur during bio-stimulated MICP including relationships between calcite precipitation and ureolysis reaction kinetics, identification of indirect strategies for field monitoring of reaction progression, and exploring the influence of biological and chemical factors (including differences in strain-specific enzymatic properties and solution composition) on reaction progression, material consumption, by-product generation, distribution of precipitation at the pore-scale, and ureolytic enrichment. In addition to these efforts, synthesis of small and large-strain measurements from the previously completed large-scale bio-cementation tank experiment were revisited to further identify approaches for bio-cementation detection and assessment in support of future up-scaling efforts.

**The project's role in support of the strategic plan**

The main motivation for this project is the reduction of materials and energy required to complete bio-cementation soil improvement using microbial ureolysis. The stimulation of native ureolytic bacteria was first considered to eliminate detrimental environmental impacts associated with the culture, transport, and injection of non-native microbial cells required in the bio-augmentation approach. Further refinement of ureolytic stimulation techniques considering more challenging enrichment conditions, such as soil depths near 15 meters, have improved the efficiency and performance of the technique through more selective microbial enrichments. The project considers a broad range of site conditions, including differences in soil types, groundwater chemistry, and initial microbial populations and will provide guidance for development of site-specific MICP treatment plans. An improved understanding of the effect of site-specific factors will enable higher confidence of improvement success during future up-scaling while simultaneously reducing environmental impacts. As a result, this work is linked to other MICP projects and directly aligns with the Hazard Mitigation and Infrastructure Construction thrust efforts to deploy MICP in field trials.

**Fundamental Research, Education, or Technology Advancement Barriers**

The research challenges stated above directly reflect the advancement barriers our work sought to address in Year 2. This included a practical barrier of developing guidance for using geophysical, in-situ penetration, and aqueous pore fluid samples to verify treatment delivery and reaction progression. It also included fundamental knowledge barriers related to understanding how biogeochemical conditions change in both time and spatially during and after treatment injections, how differences in enzymatic properties intrinsic to stimulated bacteria may affect the rate, location, and efficiency of bio-cementation, and how solution composition can be modified to yield reductions in material and energy consumption and ammonium by-product production while still achieving reliable cementation of sands.

**Any research aspect that involves foreign collaborations, especially indicating the length of time US faculty or students spent abroad conducting their work, and vice versa, and the value added of that work to the student's/faculty' work.**
None.

**Achievements in previous years**
This project builds on work performed by the PIs that was funded by NSF prior to, and in parallel with, the NSF ERC award, and continues to build on the Year 1 project achievements, which included successful sterile sampling of soils at depth, investigation of the changes in cone tip resistance with bio-cementation, and the development of an 'enhanced' stimulation technique that was shown to be effective at soil depths wherein low initial bacterial densities were encountered. This suite of work has matured over the last year and resulted in one doctoral dissertation, a series of three journal publications (2 of which have been accepted and 1 that is under review) and one conference publication.

- Gomez, M.G. (2017). *Up-scaling of Bio-cementation Soil Improvement Using Native Soil Microorganisms.* Doctoral dissertation, Department of Civil and Environmental Engineering, University of California, Davis, 334 pp.
- Gomez, M.G. and DeJong, J.T. (2017). "Engineering Properties of Bio-cemented Sandy Soils." *Grouting 2017 Technical Papers*, ASCE, Reston, VA. 11 pp. http://ascelibrary.org/doi/pdf/10.1061/9780784480793.003
- Gomez, M.G., Anderson, C.M., Graddy, C.M.R., DeJong, J.T., Nelson, D.C., & Ginn, T.R. (2017). "Large-scale Comparison of Bioaugmentation and Biostimulation Approaches for Bio-cementation of Sands", *Journal of Geotechnical and Geoenvironmental Engineering*, 143(5): 04016124. 13 pp. http://ascelibrary.org/doi/abs/10.1061/(ASCE)GT.1943-5606.0001640
- Gomez, M.G., Graddy, C.M.R., DeJong, J.T., Nelson, D.C., Tsesarsky, M. (2017). "Stimulation of Native Microorganisms for Bio-cementation in Samples Recovered from Field Scale Treatment Depths." *Journal of Geotechnical and Geoenvironmental Engineering*, (Accepted).
- DeJong, J.T., Gomez, M.G., Anderson, C.M., (2017). "Effect of Bio-cementation on Geophysical and Cone Penetration Measurements in Sands." *Canadian Geotechnical Journal*, (Under Review).

## Achievements in past year

Achievements in the past year include maturation of the prior year's work into journal publications, as detailed above, as well as integrated achievements in the following four areas:

***QA/QC Monitoring Using In-situ and Geophysical Measurements***

Strategies for bio-cementation improvement assessment have been identified following comprehensive analysis of cone penetration, shear wave velocity, and direct chemical measurements obtained from the large-scale bio-cementation tank test. Prior to synthesis of results, uncertainty regarding small differences in initial penetration resistances between tanks, the potential for cementation non-uniformity with depth, and the presence of thin-layer penetration effects were investigated and accounted for. It was concluded that penetration measurements obtained at mid-depth in the sand layer were representative of steady-state conditions and that cementation was relatively uniform at all sounding locations. All results were compared at mid-depth to understand differences in the abilities of small-strain geophysical and large-strain penetration measurements to successfully detect changes in bio-cementation. As shown in Figure 16, $V_s$ improvements were nearly identical between tank specimens for all tested calcite contents. At calcite contents near 1.0%, $V_s$ improvements approached 100% suggesting that the method may be able to effectively detect low levels of bio-cementation. At more highly cemented locations, $V_s$ improvements remained comparable between tanks and approached values near 500%. $q_c$ improvements were again similar between tanks at all bio-cementation levels. At calcite contents below 3.0%, however, $q_c$ improvements at several soundings plotted near 0% suggesting that $q_c$ may not reliably detect bio-cementation below calcite contents of 3.0%. At highly cemented locations, $q_c$ values increases significantly and improvement values approached 500%. Assessment of bio-cementation using other cone parameters (including $f_s$, $R_f$, and $I_c$) suggested that a $K_G$ parameter developed by Schneider and Moss (2011) could effectively detect low calcite contents near 0.5% through a comparison of both $V_s$ and $q_c$ values at similar locations. Although cone penetrometer measurements were able to identify moderate levels of bio-cementation, these results suggested that the addition of geophysical $V_s$ measurements may be essential for successful verification of MICP improvement at low levels of cementation.

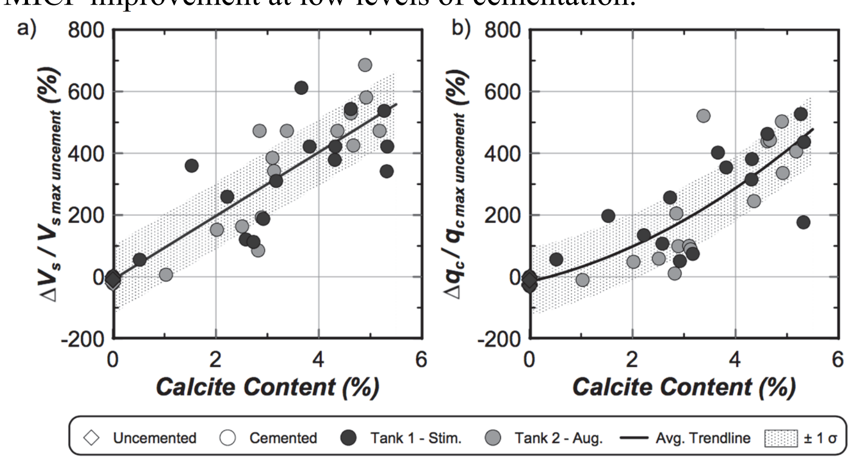


Figure 16. Normalized improvements in (a) shear wave velocity ($\Delta V_s/V_{s\ max\ uncement}$) and (b) cone tip resistance ($\Delta q_c/q_{c\ max\ uncement}$) versus soil calcite content for all measurement locations with average trend lines and a hatched range of one standard deviation provided.

***Temporal Progression of Biogeochemical Changes and Role of Ureolysis in Precipitation***

The temporal progression of calcite precipitation reactions in the large-scale bio-cementation experiment was investigated using an activity ratio framework conventionally used to evaluate the thermodynamic stability of minerals in contact with an aqueous phase. Figure 17 presents activity ratio plots for solution measurements obtained in both the stimulation and augmentation tanks at various points in time during stimulation/augmentation and cementation treatments. In these plots, measurements existing above the $\Omega$=1 line were thermodynamically favorable to precipitate calcite, and those existing below the $\Omega$=1 line were thermodynamically favorable to dissolve. The results suggest that urea hydrolysis during augmentation and stimulation may significantly increase solution carbonate concentrations, however, during stimulation/augmentation calcium is not provided and therefore concentrations do not change significantly. Instead of experiencing precipitation and approaching equilibrium, however, solutions after simulation/augmentation remain highly super-saturated with respect to calcite. Following the addition of calcium during cementation treatment injections, chemical conditions change significantly, and immediately prior to cementation injections most tank locations were close to equilibrium with calcite suggesting that the addition of calcium had consumed a large fraction of produce carbonate during precipitation. Following non-uniform injections, large increases in calcium occurred within the treatment path with correspondingly large reductions in solution carbonate resulting from solution replacement. In time following injections, calcium concentrations reduced at nearly constant carbonate concentrations until the equilibrium ($\Omega$=1) line was approached. At this point, increases in carbonate from microbial ureolysis were required to maintain super-saturation and continue the reduction of calcium concentrations through precipitation. These results suggest that although solutions are highly super-saturated with respect to calcite immediately after injection, solutions quickly approach equilibrium (~4 hours in this experiment) through reductions in calcium at constant carbonate activities. After equilibrium is approached, all further precipitation results from continued urea hydrolysis, which allows for slightly super-saturated conditions to be maintained. Although the largest reductions in calcium occurred within 4 hours after injections, 22 hours after treatments nearly all measurements were at equilibrium with calcite. Slower precipitation reactions observed at slotted well locations when compared to internal soil locations further suggested that the presence of soil material may significantly increase participating ureolytic microorganisms and therefore bulk ureolytic rates.

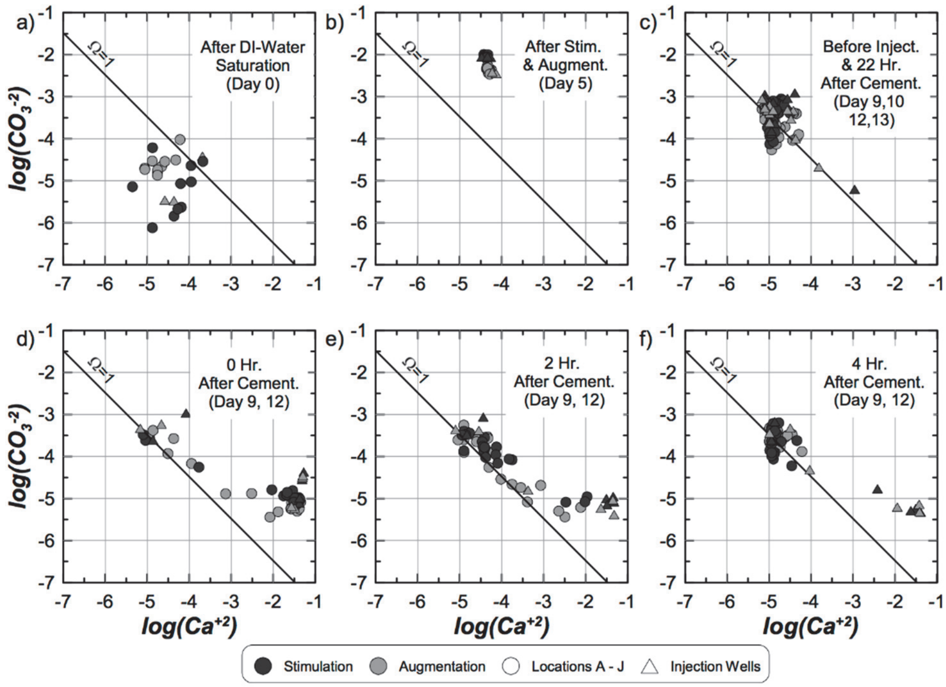


Figure 17. Activity ratio plots presenting log($CO_3^{-2}$) versus log($Ca^{+2}$) values for all sampling locations in the stimulation and augmentation tanks (a) after deionized water saturation, (b) after stimulation and augmentation treatments, (c) before treatment injections (and after 22 hr. treatment residence times), (d) immediately after cementation injections, (e) 2 hours after cementation injections, and (f) 4 hours after cementation injections.

***Indirect Measurement Approaches for Monitoring of Reaction Progression***

The ability to complete real-time chemical reaction monitoring is desirable for field-scale bio-cementation applications in order to optimize treatment injection rest intervals and achieve greater control of cementation spatial distribution. Although probe-based ion selective and pH measurements offer the ability to complete quick, low cost, and portable measurements, their ability to provide a comprehensive suite of chemical measurements is limited. At the same time, direct chemical measurements, used to verify reaction progression in the large-scale tank experiment, cannot likely be used in field applications to provide information within a limited timeframe for treatment decision making. A comprehensive analysis of past chemical data was completed to identify the potential for indirect measurements to be used wherein one parameter is measured and used to infer changes in other reaction species, therefore eliminating the need for more complicated assays and maximizing the information that can be generated from a single measurement. As shown in Figure 18, aqueous samples obtained during cementation injections in the augmentation and stimulation tanks were analyzed to explore relationships between solution pH, saturation ratio, and calcium, urea, and ammonium concentrations. These results provided new insights regarding the potential use of indirect measurements for reaction monitoring during up-scaling applications. In particular, solution pH measurements were shown to indicate the end of precipitation reactions and the depletion of calcium through a rapid rise. Despite this, incremental changes in calcium and urea concentrations during cementation could not be inferred from solution pH alone. In addition, although additional complexities were present in the experiment resulting from solution mixing and the potential for reactions during transport, a comparison of calcium and urea concentrations suggested that the concentration of one species could be reliably estimated from the other. Similar results were also observed for the relationship between urea and ammonium, however, values below the 2:1 ratio expected by reaction stoichiometry were encountered at high ammonium concentrations and may reflect ammonia losses from volatility or sorption. Lastly, solution pH appeared to be relatively insensitive to increases in ammonium, until calcium was depleted, after which increases in pH tracked well with incremental increases in ammonium. The results suggest that rapid increases in solution pH occurring towards the end of treatment residence periods may provide confirmation that calcium has been depleted and that urea and ammonium are present at concentrations specific to the applied solution composition. Similar relationships developed for different solution formulations may further increase our ability to indirectly monitor reaction progression.

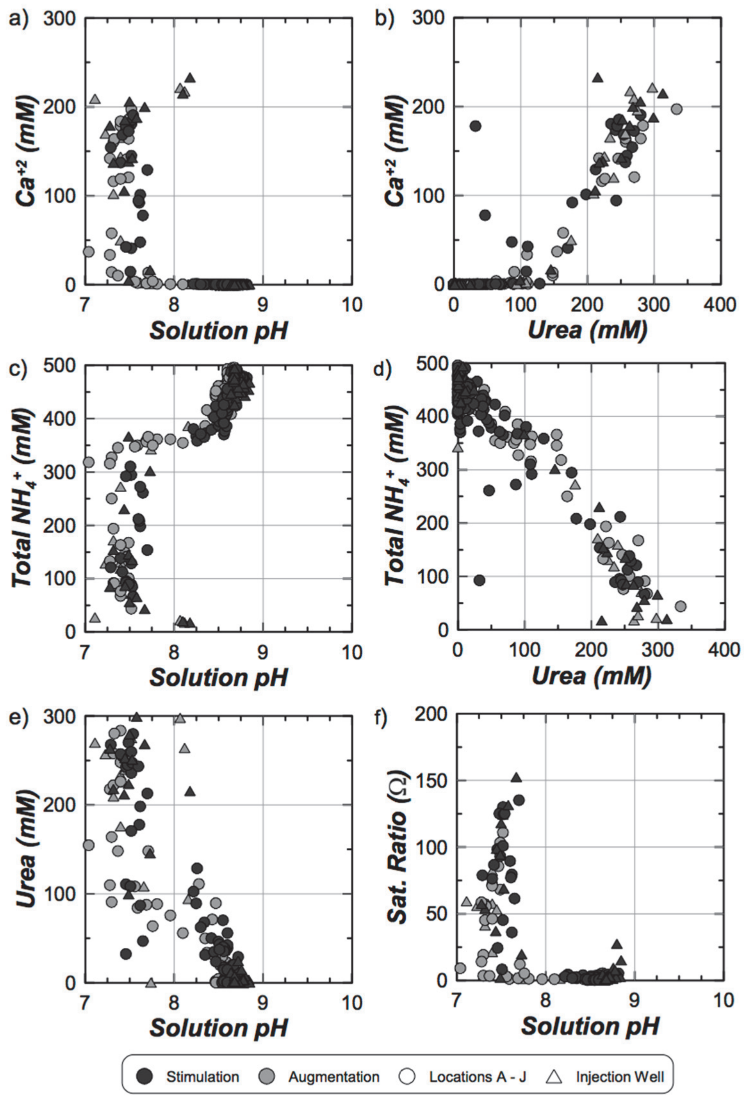


Figure 18. Relationships between (a) $Ca^{+2}$ and solution pH, (b) $Ca^{+2}$ and urea, (c) total-$NH_4^+$ and solution pH, (d) total-$NH_4^+$ and urea, (e) urea and solution pH, and (f) saturation ratio and solution pH measurements for both tank specimens during cementation treatments.

***Effect of Changes in Ureolytic Cell Densities, Strain-Specific Activities, and Solution Chemical Composition on Bio-cementation Efficacy and Material Usage***

Research examining the effect of changes in cell-specific urease activity, ureolytic cell densities, and solution chemical concentrations on bio-cementation was initiated to understand how the engineering properties of bio-cementation could be improved and while reducing chemical reagent consumption and by-product production. Researchers examining bio-cementation using microbial ureolysis have almost always provided urea in cementation solutions at concentrations that exceed calcium concentrations. This allows calcite precipitation reactions to proceed until calcium concentrations become limiting and additional carbonate is generated. Aqueous chemical data and preliminary biogeochemical modeling results have suggested that urea to calcium ratios near 1:1 may provide optimal efficiency with respect to chemical reagent usage and calcite mineral yield. As shown in Figure 19, soil column experiments have been completed examining urea to calcium ratios ranging from 1.5:1 to 0.5:1. The tested spectrum of solution compositions considered both reactions limited by calcium and those limited by carbonate from reduced urea hydrolysis. Although it is hypothesized that applied urea concentrations can be reduced, the effect of excess residual carbonate on the microstructure and engineering properties of bio-cementation remains unknown. In addition to investigating chemical factors, it was unknown what effect if any changes in the biological catalyst in the stimulation approach might have on chemical reactions at the pore-scale and bulk soil engineering properties. Initial investigations on the effect of changes in strain-specific enzymatic properties has been completed using ureolytic isolates obtained from previous bio-stimulation experiments. Although previous stimulation efforts have targeted fast ureolytic rates, it is unknown if additional advantages may be realized from slower reaction progression. The results of this scope of work are expected to enable significant reductions in process energy and material usage and may inspire future modification of the stimulation protocol to target and enrich select ureolytic microorganisms with desirable enzymatic properties determined from these studies.

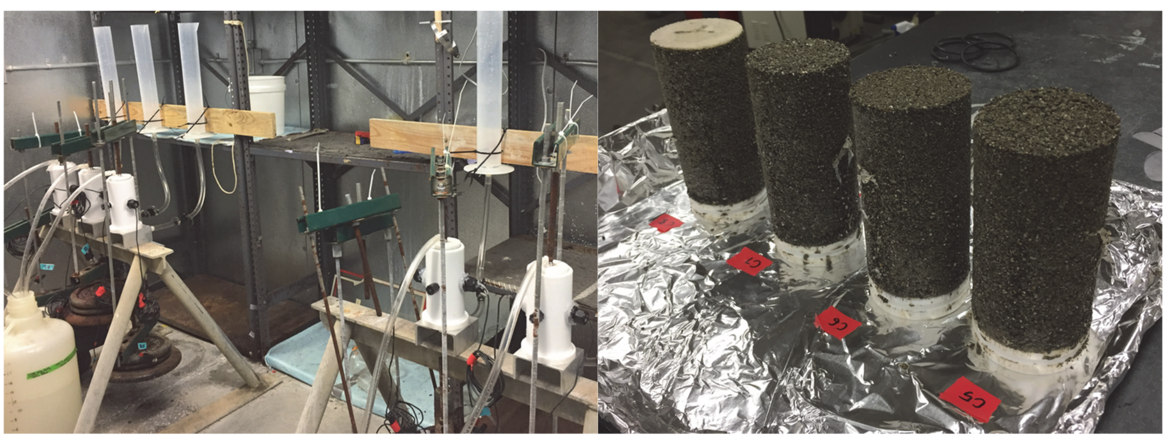

Figure 19. Soil column experiments were completed to examine the effect of changes in urea to calcium ratios and biological factors for similar soils using ureolytic bio-stimulation.

**Plans for the next year**

The work scope for Year 3 will include continuation of the final two tasks described above as well as two new tasks focused on handling of reaction byproducts and reducing environmental impacts of the treatment process. These can be summarized as follows:

- Minimizing by-product generation and improving treatment uniformity are competing factors that make determination of an optimal treatment formulation difficult. A suite of initial experiments and chemical modeling has been performed and suggest that equimolar calcium to urea ratios can produce similar magnitudes of calcite precipitation as previously employed approaches with reductions in urea usage. Spatial distributions of cementation using this treatment formulation, however, may be more sensitive to bacterial spatial distribution and activity. As a result, additional tests will be performed to determine the ratio of urea to calcium needed to reliably produce bio-cementation in a controlled manner.

- A lack of fundamental understanding remains with respect how bacterial concentration, cell specific ureolytic rate, and chemical concentration effects the number of precipitation nucleation sites, crystal structure, and improvement of engineering properties. This issue becomes particularly important for bio-stimulation as the type and population of enriched bacteria is diverse and potentially controllable (see report by UC PI Nelson). A pilot experiment near the end of Year 2 indicated the complexity of this issue, and a follow up experiment is planned for fall 2017.
- Handling of total ammonium byproducts from MICP (as well as EICP) has been a long-standing issue that the ERC will now begin addressing. A literature review of water treatment, a series of experiments, and collaboration with the LCSA project team (PI Kendall) and industry partners (e.g. Geosyntec) will explore different alternatives and work to identify effective, practical solutions for total ammonium removal and or in-situ remediation.
- The cost and environmental impacts of MICP treatment is largely dependent on the constituents used for bio-stimulation and subsequent cementation. We will work with industry collaborators and the LCSA project team to identify alternative recycled, waste, or industrial products that can be used to replace high-quality chemical reagent sources. Candidate options will be first evaluated for their ability to reduce relative environmental impacts and practical feasibility will be assessed through a series of soil column experiments.

It is noted that the project has been re-structured for Year 3 in order to include Assistant Professor Michael Gomez from the University of Washington as a Co-PI on the project. In addition, the insights generated from the above tasks over the first 9 months of Year 3 will be directly incorporated into the new, 1 year large ~3m MICP tank experiment expected to be performed in the summer/fall of 2018.

**Expected milestones and deliverables for the project**

The work performed in Year 3 is expected to mature such that practical guidance for the first two tasks above will be completed. The leading options for by-product treatment will be identified, tested at the column scale, and then implemented in the large tank experiment in summer/fall of 2018. Similarly, identification of more cost effective and/or environmentally friendly chemical reagents for MICP treatment will be identified, tested in the laboratory, and then incorporated into the large tank experiment.

**Member company benefits**

The outcomes of the above tasks, while largely fundamental in nature, map directly to some of the most critical aspects relevant to minimizing cost and reducing detrimental environmental impacts when upscaling bio-cementation to the field scale. Consequently, the results are expected to be of interest to member companies engaged in specialty contracting for ground improvement, including Hayward Baker, Nicholson Construction, Schnabel Construction, Biocement, and for consultants such as Geosyntec that utilize bioremediation technologies.

**If relevant, commercialization impacts or course implementation information**

Fundamental knowledge obtained during the optimization of bio-stimulated MICP, particularly as it pertains to the behavior of artificially and naturally cemented soils, has been introduced in the graduate level site characterization class at UCD. The content is also planned to be incorporated into the graduate physio-chemical soil properties course at UCD and will be included in a similar course to be developed at UW. Commercialization will likely be achieved, not through patents, but rather by making the latest best practices available through expertise residing in UC Davis graduates as they move into industry.

### 2.1.5 Thrust 1: Upscaled Modeling of MICP for Field Deployment

**ERC Team Members**

*UCD CBBG Faculty (Year 2)*
Tim Ginn, UCD/WSU
Jason DeJong UCD
Doug Nelson UCD

*Graduate Students (Year 2)*
Mohamed Nassar UCD
Mehrdad Bastani UCD
Deviyani Gurung UCD
Michael Gomez UCD
Charles Graddy UCD

*UCD CBBG Faculty (Year 3)*
Katerina Ziotopoulou UCD
Jason DeJong UCD
Ross Boulanger UCD

*Graduate Students (Year 3)*
Gabby Hernandez UCD
Kate Darby UCD

**Project Goals**

The goal of the project is to develop a mathematical modeling framework to support field deployment of *in situ* microbial induced calcite precipitation, for the purpose of controlling calcite precipitation over a specific treatment domain.

**The project's role in support of the strategic plan**

This project provides a primary support tool for "ecologically friendly, cost-effective solutions, inspired by nature, for development and rehabilitation of resilient and sustainable civil infrastructure systems" that quantifies the subsurface hydraulics, transport, and biogeochemical reactions, within one cohesive framework that allows engineering design of field deployment strategies through predictive simulation of the results of those strategies prior to expensive employment.

**Fundamental Research, Education, or Technology Advancement Barriers**

The planning and design of engineering applications using MICP at the field scale requires accurate field-scale modeling approaches. The complexity of modeling MICP is compounded by a number of complex interacting processes. Ureolysis driven MICP involves a microbially-catalysed reaction, which can be modeled if the reaction kinetics are known [Mobley and Hausinger 1989; Lauchnor et al., 2015]. However, the quantification of the impact of flow and transport on the bacterial population activity is not currently possible because bacterial transport in natural porous media is still not well understood. Most of the modeling work reported previously focuses on small to medium-scale column processes (e.g., Lauchner et al. (2015) used suspended cell batch experiments). It is well known that parameters important in small scale studies might not be relevant when modeling larger scale field processes [e.g., Meile and Tuncay, 2006]. Here we focus on modeling meter-scale experiments with transient nonuniform flow and transport to evaluate the minimum modeling parameters required to provide accurate prediction of field behavior of MICP processes. Of particular importance is our hypothesis that the microbial population under either stimulation or bioaugmentation can be treated as a steady-state solid-phase catalyst. This dramatically simplifies the modeling because it condenses the microbial processes of attachment, substrate-dependent growth, decay, and detachment due to shear stress, into the determination of one single rate parameter for catalyzed ureolysis. While this seems to work for our modeling of the controlled meter-scale experiment, the challenge of understanding bacterial community dynamics in moving groundwater remains a Technology Advancement Barrier for extending the modeling technology to less controlled conditions.

**Achievements in previous years**

Research last year focused on the construction and testing of the reactive transport model in two separate platforms (for cross-validation study), COMSOL-iCP [Nardi et al., 2014], and PHT3D [Prommer et al., 2003; Prommer and Post, 2010], in application to modeling large scale tank experiments with transient nonuniform flow and transport. The summary of the experiment and the basic assumptions underlying the modeling are presented in the Report for last year, and involved the following tasks:

1. Comparative analyses of methodologies for fitting mathematical models of biogeochemical kinetic reaction rates ("kinetics") to laboratory data resulting in a draft manuscript recommending nonuniform sampling frequencies in time, as well as particular parameter fitting approaches, customized to the particularities of the lab experiments.

2. Completed and incorporated kinetic rate model for ureolysis based directly on bulk ureolytic activity measured in column experiments performed by Michael Gomez and Charles Graddy at UCD.

3. Tested model prediction of bromide tracer test breakthrough curves by fitting only one parameter (porosity) while implementing transient flow and reagent injection boundary conditions.

4. Confirmed hypothesis that the bulk activity of the attached bacteria phase can be modeled as stationary during the MICP cementation process, despite strong transients in the treatment flowrates and microbial nutrient delivery. This hypothesis, when incorporated into mathematical models of controlled large-scale MICP experiments, led to good simulation of collected data. This assumption includes the corollary notion that all bacterial growth and/or activity change is essentially flushed out with subsequent treatment injections. This corollary was found consistent with subsequent estimates of total effluxed biomass.

5. Completed modeling of entire biostimulation and bioaugmentation tank experiments, including initial tracer flushing, biostimulation treatments, cementation treatments, and final groundwater flushing injections within both PHT3D and COMSOL numerical platforms.

Primary results from the modeling study are:

6. Successful prediction of precipitated calcite as well as degradation/generation of chemical constituents in the aqueous phase during each injection stage.
7. Formalized collaboration and planned meetings with Geosyntec Consultants to transfer modeling technology (via the USGS computer program PHT3D, Prommer et al., 2003; Prommer and Post, 2010) for eventual use in assisting with design of MICP treatments in situ at the field scale.

**Achievements in past year**

Activity this past year tapered down and terminated in January 2017 and this project is complete. Item 1 from last year has been pursued to development of a draft manuscript planned for submission in October 2017. Items 2-5 were completed in form of a manuscript submitted for publication in the journal *Water Resources Research*. The manuscript focuses on the PHT3D modeling and the biostimulation tank experiment only. The workshop prepared and delivered 8-9 August of 2017 was followed up with technology transfer as directed by Geosyntec Inc. personnel.

**Summary of other relevant work being conducted within and outside of the ERC and how this project is different**

None in past year. In coming year it will be linked with other MICP microbiology (Nelson) and upscaling (DeJong/Gomez) projects at UCD as well as with MIDP project at ASU (Kavazanjian / van Paassen).

**Plans for the next year**

The participation of Dr. Tim Ginn and his graduate students on biogeochemical transport modeling of the MICP treatment process has been terminated as of January 2017. This was in part due to Dr. Ginn's move to Washington State University. Technology transfer of the code to Geosyntec Consultants resulted in the capabilities developed being available to an industry partner and available for use in future upscaling MICP projects (such as the new large tank experiment to be performed in summer of 2018). At the mid-year meeting in April 2017 the ERC leadership team agreed to redirect the scope of the modeling work from biogeochemical transport modeling and to split it into numerical constitutive modeling of cemented sands and into physical centrifuge modeling of MICP cemented soils. The numerical constitutive modeling effort will be led by new Assistant Professor Katerina Ziotopoulou and the physical centrifuge modeling effort will be led by Professors DeJong and Boulanger. The numerical constitutive modeling component will be focused on (1) collecting past element laboratory test results on biocemented sands, (2) identifying critical aspects of behavior that different significantly from uncemented soils, (3) evaluate how different existing constitutive models capture cemented sand behavior, (4) select constitutive model that will be used, and (5) begin modification of the constitutive code. The physical centrifuge modeling tests have been designed in collaboration with ASU in order to perform a suite of comparative test bed experiments in which the performance, advantages, and disadvantages of MICP and MICP can be compared side-by-side. In the coming year this will include about 12 small centrifuge tests performed at the UCD NEHRI facility. A baseline set of tests will be performed to established the performance of uncemented sand deposits, followed by a suite of tests evaluating the effect of different levels of cementation and desaturation. It is noted that next year this project will be presented as two distinct projects.

**Expected milestones and deliverables for the project**

The expected deliverables for Year 3 will be separate for the numerical and physical modeling components.

Numerical Modeling Project:

1. Synthesis of laboratory data that provide information on the strength and stress-strain response of MICP treated sands. Behaviors of immediate interest include cyclic strength and cyclic strength degradation with progressive loading, stress-strain response, stiffness degradation, damping, and critical state. The goal is to summarize the key fundamental mechanical responses, delineate the constitutive responses that they correspond to, and identify any gaps that warrant further lab testing.
2. Results of a validation study of the capabilities and limitations of selected existing constitutive models in capturing key mechanical responses of MICP treated soils, as informed by the collated laboratory results. A commercial numerical platform will be utilized to ensure that results and contributions can at all times have a direct pathway to practice. This will provide a baseline of constitutive components that warrant further work and a plan will be developed for moving forward with the identified constitutive formulation components and their implementation.

Physical Modeling Project:

1. Design and complete equipment/sensor development required for initial set of small centrifuge tests in collaboration with ASU. Design will consider the following variables: cementation level, initial relative density, and shaking intensity. Developments include treatment method, shear wave and P-wave velocity measurement system.
2. Report summarizing the results of initial set of 12 small centrifuge tests. It will include evaluation of how results map onto current triggering and 1-D volumetric strain (settlement) relationships, with modifications and/or reformulation of relationships as necessary to incorporate effects of cementation.
3. Design select set of large centrifuge tests necessary for testing late in Year 3 or early in Year 4.

**Member company benefits**

The technology transfer of the biogeochemical code to Geosyntec Consultants was significant. They now have in-house capability of modeling the MICP treatment process at larger scales. The future research on constitutive and physical modeling of biocemented soils will, in the future, enable member companies to appropriately model cemented soils in their numerical simulations and the physical modeling results will provide guidance for designing biocement ground improvement for seismic loading.

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## 2.2 Thrust 2: Environmental Protection and Restoration

### 2.2.1 Thrust 2: Activated Landfill for Rapid Organic Degradation

**ERC Team Members**

| *CBBG Faculty* | *Graduate Students* |
| --- | --- |
| Zohrab Samani, NMSU | Saman Mostafazadeh-Fard |
| Paola Bandini, NMSU | Peter Zelkowski (through March 2017) |

**Project Goal**

Landfills represent a long-term environmental, legal and economic liability for municipalities and a contamination threat to the soil, water and air. A conventional landfill may continue to degrade and potentially affect the environment for hundreds of years after closure. The slow degradation of organic waste is mainly due to the low water content and low level of cellulosic and methanogenic bacteria in a typical municipal solid waste (MSW) landfill. This research addresses the problem of the long time required for MSW landfills to stop producing methane gas.

The main goal of this project is to demonstrate an alternative engineered activated landfill concept that can degrade the organic matter very quickly. Based on prior results of a small pilot experiment, the activated landfill consists of building a layered landfill in which the organic waste is alternatively placed with another organic medium that contains cellulosic and methanogenic bacteria (fresh cow manure) in conjunction with a layer of growth medium with the addition of a leachate recirculating system and a gas collection system. The main objectives of the proposed research are:

1. To design, setup and run a small-scale activated landfill experiment (testbed 1) for evaluating the technical feasibility of the proposed activated landfill concept and for developing the design parameters to build a pilot-scale landfill for testing and demonstration.
2. To design, construct and monitor a pilot-scale activated landfill (testbed 2), in which the landfill is enriched with cellulosic and methanogens (methanogenic bacteria) and sufficient moisture so that an accelerated bio-leaching process will convert the landfill into a source of methane and soil amendment in a short time (about a year) instead of hundreds of years of slow degradation.

**The Project's Role in Support of the Strategic Plan**

This research is under the Environmental Protection thrust. The project contributes to sustainable waste management and landfill infrastructure by making MSW management more economical. The societal benefit of this technology is the significant reduction in cost of MSW management and additional economic benefit for municipalities through capturing biogas for energy production and soil amendment (residual). Additional societal benefit would be reduced landfill space.

This project started in January 2017. Based on feedback from the Site Visit Team report that landfill research should not be part of the CBBG research portfolio supported with NSF funds, CBBG leadership decided to phase-out this project in Year 3 and provide partial support through May 2018 (student support).

**Fundamental Research, Education, or Technology Advancement Barriers**

Research Advancement Barriers include:

- The proposed technology has never been implemented and, therefore, design parameters to upscale from small-scale to pilot-scale to field-scale are not available.
- The scale of environmental and economic benefits is not known.
- The disposal of non-beneficial residuals.

**Any research aspect that involves foreign collaborations, especially indicating the length of time US faculty or students spent abroad conducting their work, and vice versa, and the value added of that work to the student's/faculty' work**

N.A.

**Achievements in previous years**

N.A.

**Achievements in past year (January-July 2017)**

**1. Design of experiment and construction of columns**

The small-scale experiment (testbed 1) consists of four 7.5-ft tall columns. In each column, the organic waste is placed in two 3-ft layers; each organic layer is underlain by the bacteria medium and growth medium layers, as illustrated in Figure 20. Fresh cow manure will be used as the natural bacteria medium. The column will be brought to field capacity with an addition 10% of leachate for re-circulation. The leachate is recirculated daily (with a small pump) and sampled. Chemical analyses and temperature and pH measurements of the leachate samples will be carried out during the experiment. The gas produced will be collected, measured, and regularly sampled for testing. The experiment will last until the produced gas is insignificant indicating that no more degradation of the organic material is taking place. It is expected that the test will last 4-5 weeks. Characterization of the bacteria in the input (cow manure) and residual is being considered.

The experiment includes three identical columns (triplicates) and one column in which the thickness of the organic waste layer is varied to observe the effect of layer thickness and obtain additional information that can guide the design of future experiments. The residual will be described and analyzed to assess its potential beneficial uses. The columns will be placed outdoors on a raised floor under a canopy to prevent the direct sunlight on the columns.

**2. Search for an industry collaborator and sponsor**

The senior investigator (Prof. Zohrab Samani) has discussed this research with Patrick Peck, Director of the South Central Solid Waste Authority (SCSWA). The SCSWA is the agency responsible for managing waste and recyclables for the City of Las Cruces and Doña Ana County (located in Southern New Mexico). The SCSWA has expressed interest in collaborating by providing in-kind services and materials for the field-scale testbed (test site, construction, liner and other materials). Funding sources for the other research components remain to be identified (e.g., personnel salaries, chemical analyses, field instrumentation or sensors).

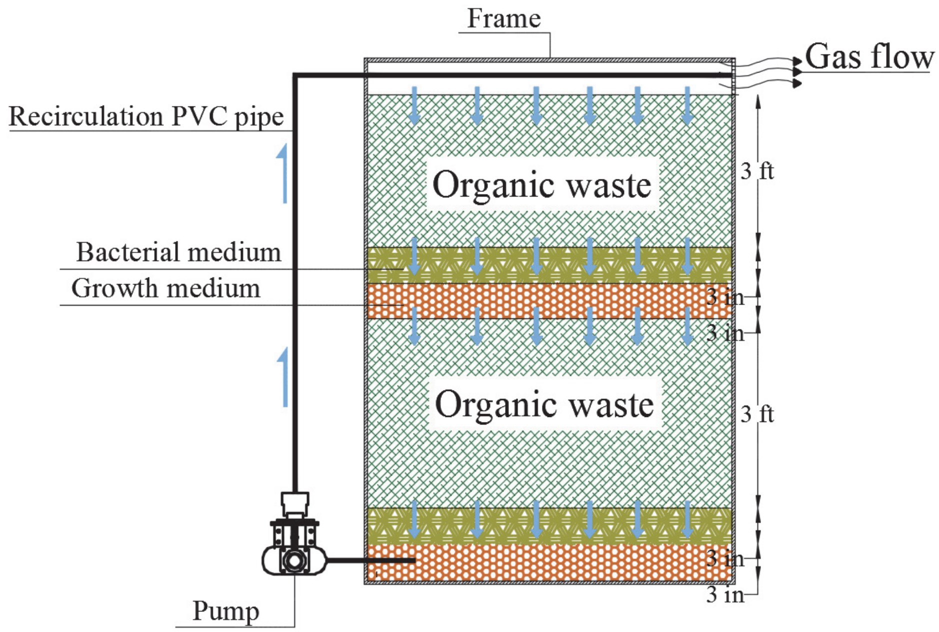


Figure 20. Illustration of the column test

**Plans for the next year (August 2017-May 2018)**
The team will complete the column test setup and conduct at least one batch of column experiments (Fall 2017) on NMSU campus. The results of the column tests will be analyzed and a paper will be prepared and submitted to a conference or journal publication.

**Expected milestones and deliverables for the project (Year 3)**
A paper (May 2018) with the results of the column tests with design parameters that can be used in field-scale pilot test.

**Member company benefits**
Some CBBG industry partners are interested in new landfill construction and management approaches. New industry partners or collaborators can be attracted with this research.

**If relevant, commercialization impacts or course implementation information**
N.A.

### 2.2.2 Thrust 2: Electro-kinetic Transport for Mineral Precipitation and Soil Remediation

**ERC Team Members**

*CBBG Faculty*
César Torres, ASU
Rosa Krajmalnik-Brown, ASU
Anca Delgado, ASU

*Graduate Students*
Megan Altizer, PhD student, ASU
Eric Traichal, Master's student, ASU

*Undergraduate Students*
Marisol Luna-Aguero, ASU
Samuel Aguiar, ASU
Erick Ruiz, REU, UC Irvine

**Project Goals**
The goal of this project is to leverage electro-kinetic transport to overcome limitations that hinder geoenvironmental technologies. This application will be particularly effective in extending the application of bioremediation and stabilization technologies to silt and clay soils, which previously required expensive and disruptive ex-situ remediation and environmentally taxing grouts. Specifically, we aim to use electro-kinetic transport to aid in trichloroethene bioremediation approaches and carbonate precipitation studies.

**The project's role in support of the strategic plan**
Fugitive dust emissions, soil contamination and soil instability all pose a serious threat to human and environmental health and are important focci of the environmental protection and restoration thrust. This research focuses on applying electro-kinetics to a variety of environmental issues, like chlorinated solvent contamination, while thoroughly investigating the long-term soil ecology impacts of the technology. The many functions of electro-kinetics in treating environmental issues will provide significant contributions to environmental resilience and sustainability and provide a reliable way to increase transport rates in many geotechnical applications.

**Fundamental Research, Education, or Technology Advancement Barriers**
Fundamental research and technology advancement questions that must be answered to develop and commercialize this technique include: 1) what are expected electro-kinetic transport rates for essential molecules like nanoparticles, electron donors, electron acceptors and microbes; 2) how effective is electro-kinetic bioremediation for remediation of organic contaminants, as compared to abiotic techniques; 3) what is the impact of electro-kinetics on microbial communities, including dehalogenating microbes; 4) how can electro-kinetics be effectively combined with other remediation technologies?

**Any research aspect that involves foreign collaborations, especially indicating the length of time US faculty or students spent abroad conducting their work, and vice versa, and the value added of that work to the student's/faculty' work.**
N/A.

**Achievements in previous years**
Prior to initiation of the CBBG, the Krajmalnik-Brown lab group did significant research on optimizing production of dechlorinating cultures at large scale and testing them *in-situ*. The lab

created a continuous flow stirred tank reactor (CSTR) of 10L able to continuously produce a mixed dechlorinating culture. In lab tests, this culture demonstrated complete dechlorination of trichloroethylene (TCE) to ethene at hydraulic retention times of 3-8 days. A tetrachloroethylene (PCE) contaminated site amended with the culture saw remediation from 2000 μg/L to non-detect in 6-12 months. This experience with bioaugmentation in the field will help facilitate large scale application of electro-kinetic bioremediation in the future.

During the first year of CBBG operation, notable achievement for electro-kinetic mitigation of fugitive dust included 1) Measuring the detachment velocity in wind tunnel tests of soil treated with electro-kinetic calcium carbonate precipitation compared to traditional wetted soil and calcium carbonate controls; 2) Quantifying amount of calcium carbonate precipitated with electro-kinetics as compared to traditional methods; 3) Designing and fabricating column for future strength testing of electrokinetically treated soil. Achievements for electro-kinetic remediation of organic contaminant included 1) Meeting with industry partners to discuss potential applications to sites contaminated with chlorinated solvents; 2) Determining electron distribution and microbial community changes in soil systems under excess hydrogen; a baseline for future studies on microbial community changes in electro-kinetic treatment of chlorinated solvents.

**Achievements in past year**

**A.** We performed a standard test of $CaCO_3$ for dust mitigation to expand previous studies with electro-kinetics. In these studies, solutions of $CaCl_2$ and $NaHCO_3$ were added to soil pans containing either AZ top soil or F-60 sand samples. The addition of the solutions at different concentrations were tested against a dry control, water only (0 M concentration) and a wet sample to test soil detachment velocities using ASU's wind tunnel facility.

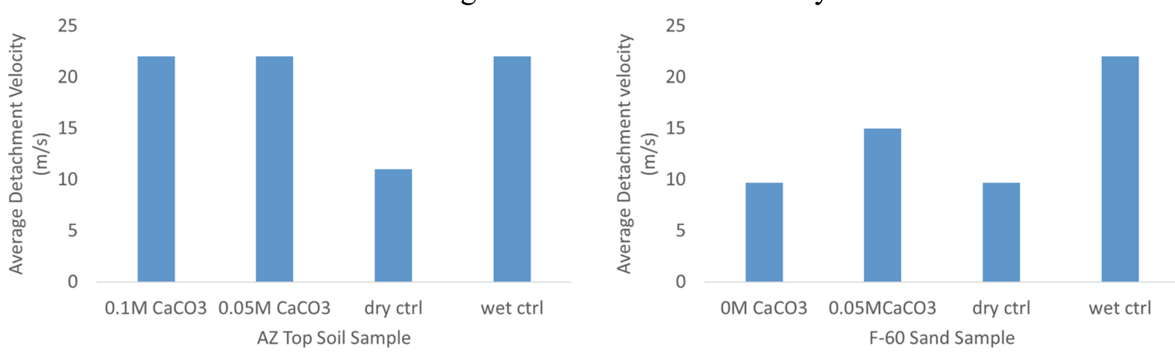


Figure 21. Detachment velocities of AZ Top Soil and F-60 Sand after addition of solutions containing $Ca^{+2}$ and $HCO_3^-$. Maximum testing velocity is 22 m/s.

For AZ top soil, the addition as low as 0.05 M resulted in a significant increase in detachment velocity, suggesting an improvement in dust mitigation. For a smaller particle size sand, F-60, the addition of similar concentrations significantly increased the detachment velocity, but were not as high as the wet sand sample. Further studies will determine optimum concentrations and the possibility of electro-kinetic transport to improve $CaCO_3$ precipitation.

**B.** Achievements for electro-kinetic remediation of organic contaminant included 1) Collaborating with an industry partner on pilot scale test site to investigate the long-term impacts of electro-kinetic bioremediation on soil microbial ecology; 2) Determining transport rates of ions and soil amendments in a standard sandy soil; 3) Publishing a paper on previous baseline studies investigating electron distribution and microbial community changes in soil systems under excess hydrogen (expected to be submitted Fall 2017);

Figure 22A displays the relative abundance of different bacterial families in groundwater and soil from an industry partner pilot scale test site treated with electro-kinetic bioremediation. Most notably, microbes capable of dechlorination, metal, and sulfate reduction are enriched throughout the test zone, a possible “side effect” of the treatment. This requires further investigation to confirm if enrichments were due to electro-kinetic transport of substrates and consideration of how this may effect microbial competition at the site as well as long term soil microbial ecology.

Figure 22B displays the alpha diversity (mean local species diversity) of soil samples up and down gradient as well as within the test zone. The increase in diversity in samples within the test zone suggest the treatment does not have a long-term effect on the diversity of the soil, a good indicator of a healthy ecosystem. This is a positive outcome for the wider application of the technology.

Overall, this investigation into the effect of electro-kinetic bioremediation on soil microbial ecology was, to the best of our knowledge, the first of its kind and an important step in approving the technology for larger applications.

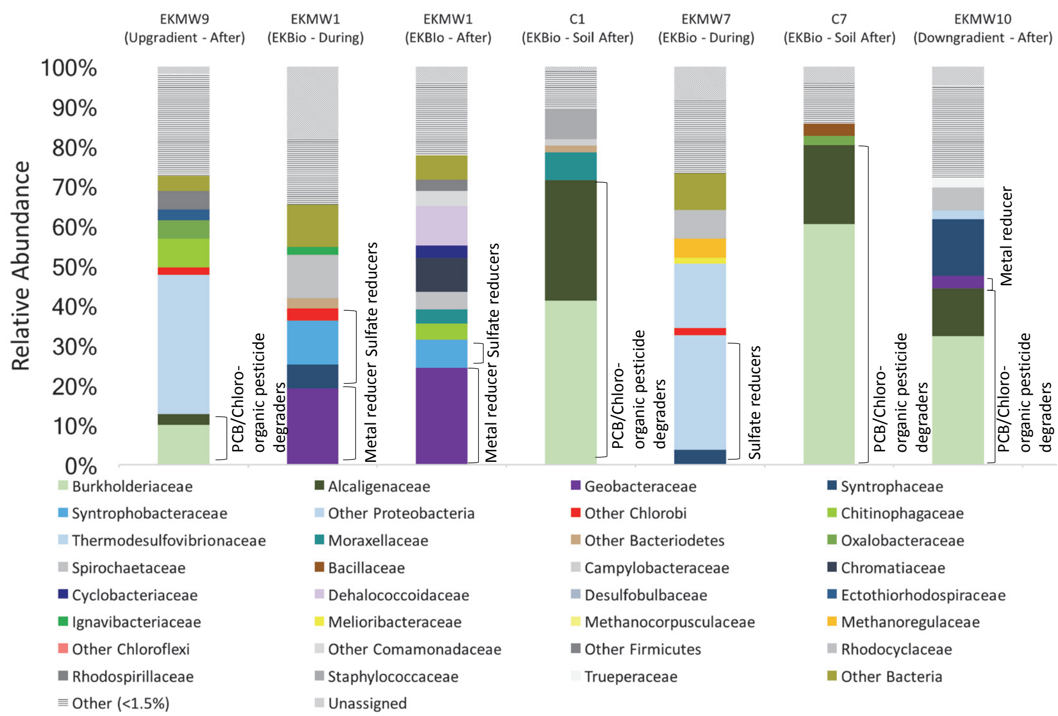


Figure 22A. The relative abundances of different bacterial families in soil samples from pilot site treated with electrokinetic bioremediation from wells upgradient (EKMW9), in the treatment zone (EKMW1, C1, EKMW7, C7) and downgradient (EKMW10 from the site).

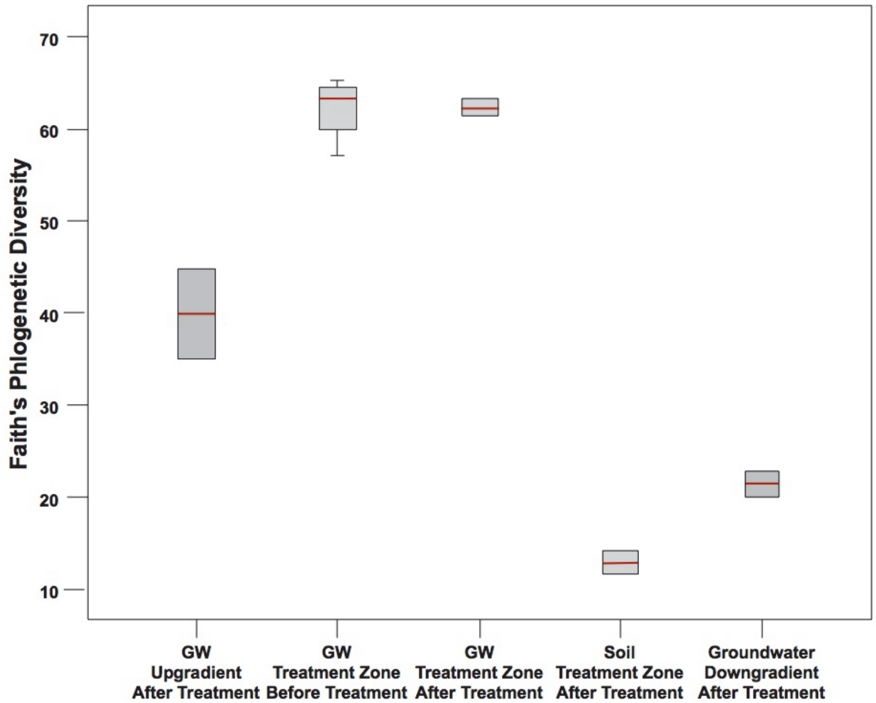


Figure 22B. The alpha diversity (mean local species diversity) of soil samples in pilot site treated with electro-kinetic bioremediation.

Figure 23A depicts the transport of nitrate ions via electro-kinetics, as compared to a control test where transport was governed by diffusion. This data was used as a comparison for the transport of other molecules (i.e. zero valent iron). We can see that nitrate was successfully transported in this experiment as the results. This validates the success of our experimental set-up and is can also be applied to other applications of electro-kinetics within CBBG, like addition of nitrate to soil for calcium carbonate precipitation via denitrification.

Figure 23B depicts transport of zero valent iron (ZVI) via electro-kinetics as compared to a control pan governed by diffusion. Electro-kinetic transport of this common abiotic remediation amendment was not significant, indicating the need to focus on surface modified particles in year 3 if ZVI is to be used for remediation.

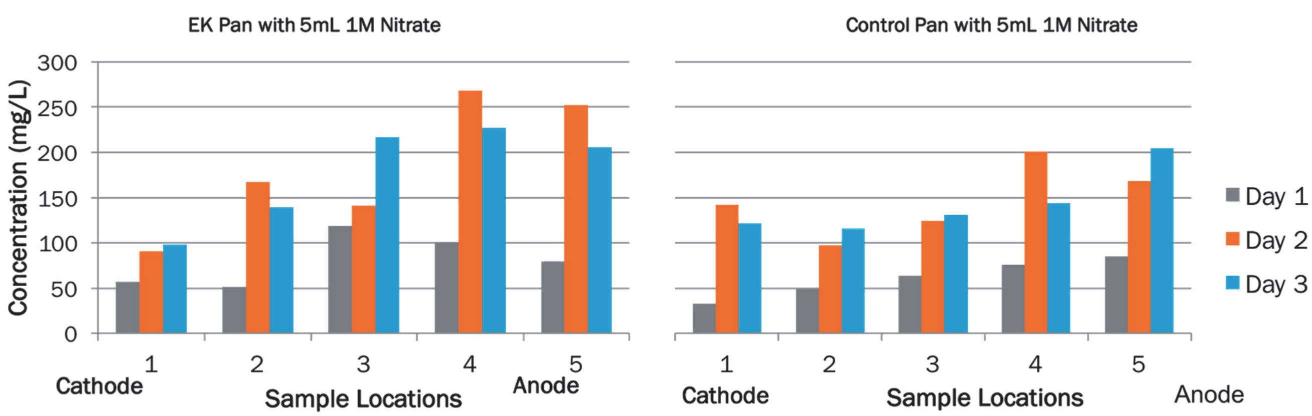


Figure 23A. Measured transport of nitrate ions in soil by electrokinetics (EK pan) vs diffusion (control pan) in soil.

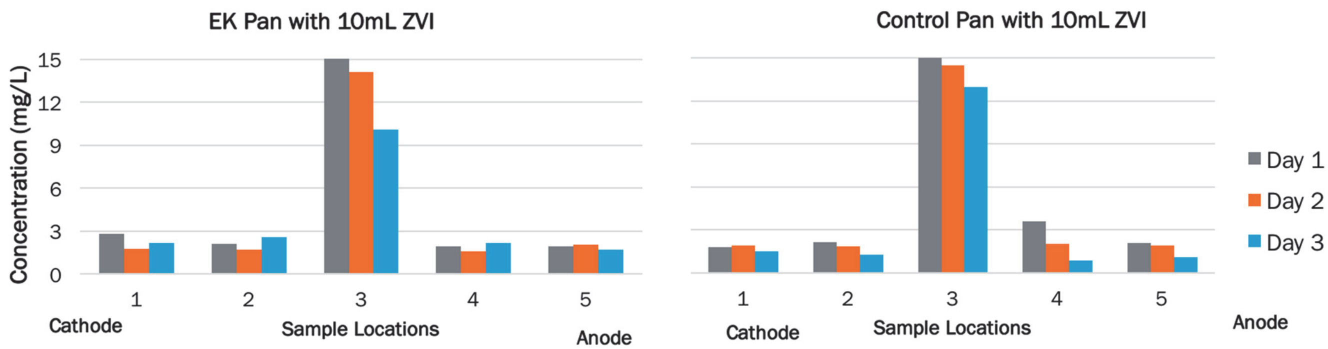


Figure 23B. Measured transport of zero valent iron species in soil by electrokinetics vs diffusion in soil.

**Summary of other relevant work being conducted within and outside of the ERC and how this project is different**

Related work being conducted within the ERC includes microbially induced carbonate precipitation (MICP), enzyme induced carbonate precipitation (EICP), carbonate precipitation via denitrification, and bioremediation of chlorinated solvents with ZVI. Fundamental knowledge from work will be relevant for other applications of electro-kinetics, including ground improvement via MICP and EICP.

Relevant work to the bioremediation section of this project is being done in the industrially funded project "Groundwater detoxification through combined bioremediation & zero-valent iron reduction" Close communication and interaction with this project occurs often.

**Plans for the next year**

Plans for this project for next year for dust mitigation and ground improvement include 1) Provide a more comprehensive study on the effect of $Ca^{2+}$ and $HCO_3^-$ salts on soil detachment velocities; 2) Perform first preliminary studies on $CaCO_3$ precipitation for ground improvement.

Plans for this project for next year for electro-kinetic bioremediation of organic contaminants include 1) Completing a paper and conference presentation (Battelle Chlorinated Solvent Symposium 2018) co-authored with industry partner (anticipated Spring 2018); 2) determine feasibility of using electro-kinetics to transport special molecules designed to improve anoxic site conditions and serve as electron donors, including carbon coated surface modified zero valent iron nanoparticles, formate and citrate; 3) determine efficacy of pairing electro-kinetic bioremediation with each of these special molecules.

**Expected milestones and deliverables for the project**

It is anticipated that demonstration of the effectiveness of this technology at a field site will take place by the end of year 5 and by the end of year 6 the technology will be available for deployment.

**Member company benefits**

A practical technique for ground improvement is of interest to member companies engaged in ground improvement specialty contracting, including Hayward Baker, Nicholson Construction, Schnabel Construction and GeoPier. *In situ* remediation of chlorinated solvents is of significant interest and great benefit to member companies engaged in site remediation, including Geosyntec.

**If relevant, commercialization impacts or course implementation information**
N.A.

### 2.2.3 Thrust 2: Enhancing Methane Production from Landfills

**ERC Team Members**

*CBBG Faculty*
Hinsby Cadillo-Quiroz, ASU, Project Leader
Rosa Krajmalnik-Brown, ASU
Ed Kavazanjian, ASU
Leon van Paassen, ASU

*Other Research Staff*
N.A.

*Graduate Students*
Mark Reynolds

*Undergraduate Students*
Jaime Lopez (graduated)

**Statement of Project Goals**

The goal of this project is to identify and use alternative mechanisms to enhance municipal solid waste (MSW) transformation and stabilization in landfills using proven stimulation treatments. We envision the final deliverable of this project (and related internal projects) to provide a cost-effective treatment scheme to enhance methane production using biogeochemical characterization of methane production rates in combination with microbiological community composition and activity monitoring. We seek to manipulate these two parameters within a geotechnical and/or geophysical context in landfills as part of the regular management activities.

**The project's role in support of CBBG's strategic plan**

Methane ($CH_4$) gas is the terminal output of MSW stabilization, due to the initial composition of MSW (i.e. containing "cellulose-like" material) which is prone to biodegradation. Enhancing methane ($CH_4$) production (also generally referred to as "biomethanation" throughout this report) for biogas recovery in MSW landfills supports the strategic plan through efforts to promote alternative and sustainable energy systems in the (former) thrust dedicated to resource development and recovery. Specifically, our project addresses efforts to promote biogas upgrading *in-situ*, rather than *ex-situ* which requires costly infrastructure and extensive operation/maintenance. The majority of landfills in the United States are not linked to a waste-to-energy facility, although have the potential to when forecasting available space and gas generation rate in future years given current operation statistics. As a result, operators often flare the gas produced from a landfill (LFG) to prevent potent greenhouse emissions. Landfill operators can help relieve fossil fuel dependence by working more closely alongside microbiologists, environmental engineers, biogeochemists, etc. and vice versa to optimize microbiological performance and gas capture efficiency in landfills. The efforts conceived in this project aim to develop management approaches to enhance biomethanation rates and identify/select a microbiome that is optimized for MSW stabilization in a region, despite inherent variations given the source of waste and/or differing climatic influences.

**Fundamental Research, Education, or Technology Advancement Barriers**

Fundamental research barriers exist (i) regarding how efforts to increase biomethanation will affect the geotechnical properties of both the existing soil, gas recovery infrastructure, or MSW itself. Primarily relevant to landfills are properties such as slope stability, mechanical creep, compression ratio, and total unit weights; all of which, impact the resilience of the High-Density Polyethylene (HDPE) geomembrane that is the current standard for landfill lining. Other barriers are of technological concern and include how current monitoring practices cannot tease out specific locations of a landfill that are impacted by biogeotechnical stresses, due to leachate inherently acting as an aggregate of all MSW it passed prior to collecting in a leachate sump, or leachate selectively traveling in the path of least resistance and not uniformly across a cell.

**Foreign collaborations**. Dr. Cadillo-Quiroz has started efforts to expand the use of landfill technologies in South America with current focus in Tropical landfills. In December 2016 and July 2017, PI has held working meeting in Lima Peru with faculty of the Servicio Nacional de Adiestramiento en Trabajo Industrial (SENATI), CATOLICA University, and NGO SNV Netherlands Development Organization all located in Peru. An agreement to seek financial support to develop landfill-reactors for Solid Municipal Waste to maximize soil stabilization and bioenergy has been developed for future work in this project. Similar efforts can be expanded to Colombia, Ecuador and Bolivia all with pressing issues on soil stabilization and waste management.

**Achievements in previous years**

Our group initially focused on assessing any variation in efficiency of biomethanation *in-situ* during year 1, to assess 1) how efficient a landfill was in terms of its biomethantion capacity (as evidenced by stable isotopes) and 2) whether any variation would manifest across landfill cells within an entire landfill and/or potentially even within a single landfill cell. *In-situ* work performed by the graduate student in the first year as advised by co-lead PIs demonstrated that methanogenic activity is not uniform in a landfill, and can even be more dissimilar within a landfill than between. This was surprising and likely is the result of non-uniform leachate dispersal, potential inhibitory accumulations impacting downstream methanogenesis, and/or direct uncoupling of acetogenic bacteria and hydrogenotrphic bacteria/archaea. Also, *in-vitro* work performed in year 1 demonstrated that substrate-level treatments can be feasibly implemented into landfill practices to enhance methane production from MSW. The tested treatments are rooted in generating excess methanogenic precursors and/or to promote increased chances for bacterial/methanogen proliferation (e.g. promoting unfavorable syntrophic oxidation of short chain fatty acid or increased stress tolerance in a dynamic system such as MSW).

**Achievements in past year**

For the first half of year 2, we planned to further optimize the above described small *in-vitro* treatments (i.e. concentration-wise, delivery mechanisms, aerobic vs. anaerobic pre-incubation, etc.) in addition to seeking out additional biomethanation stimulants. Moreover, employing and monitoring the long-term biogeochemistry of a demo 5L PVC-based bioreactor using synthetic MSW representative of the City of Phoenix also occurred in late 2016 (data not shown). The demo 5L bioreactor was used primarily to attempt culturing-dependent isolation of novel bacterial and/or archaeal functional groups from MSW, identify bioreactor design flaws, deduce volume of liquid delivery needed to reach 40% moisture content, and optimize time point scheduling (data not shown).

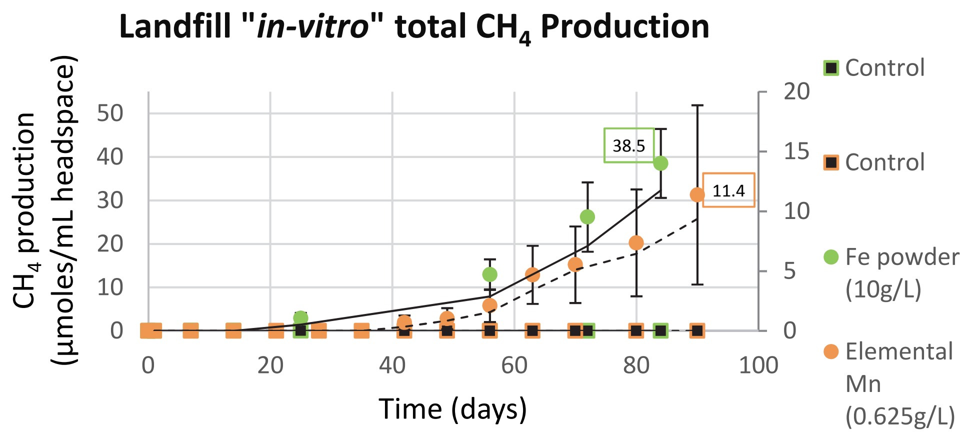


Figure 24. Summary of results from biomethanation stimulant concentration optimization trials in 1:10 MSW "slurry" microcosms using solid waste from a depth of 50-55ft in Southwest Regional Landfill, Buckeye AZ. Note: These results are from two separate experiments and were completed upon reaching stable methanogenesis phase.

Figure 24 shows the *in-vitro* $CH_4$ molar gas dynamics of (2) unique biomethanation stimulation treatments involving metals: commercial iron powder (Fe) and elemental manganese ($Mn^0$). For Fe addition upon starting the incubation anaerobic, that data suggests both 1x (5g/L) and 2x (10g/L) treatments strongly stimulates biomethanation relative to control, which is an indication that MSW is an Fe-depleted system. This $CH_4$ production rate increase has been observed several times in numerous repeat microcosms, additionally. Comparing the $CH_4$ production rates between the 1x and 2x treatments (data not shown), a linear concentration response can be observed which perhaps can be interpreted as the various Fe species present in the commercial powder being utilized for critical enzymatic co-factors within the anaerobic community (e.g. as utilized in Fe-S clusters, a common catalytic protein moiety present in anaerobic microorganisms). Therefore, we infer from preliminary data that the excess Fe, rather than stimulating organometallic respiration, simply prevents Fe depletion and thereby prevents operation failure in anaerobic digester-like systems such as MSW landfills.

A similar experiment was conducted with $Mn^0$, except the experiment began after week-long aerobic pre-incubation to establish fermentative conditions prior to $Mn^0$ addition. This change in experimental execution was conducted because previous microcosms with $Mn^0$ informed that an abiotic transformation occurs resulting in a rapid reduction of protons in solution that occurs under water-logged, anoxic conditions. Ultimately, this produces temporary fluxes of cathodic hydrogen ($H_2$) production concurrent with a raise in pH; thus, addition of $Mn^0$ was performed upon confirmation of the microcosms transition from aerobic phase to fermentation phase (as evidenced by pH drop from 8.5 to 5.8; data not shown). Overall, this experiment determined that adding a minimal dosage of $Mn^0$ (0.625g/L – 0.125x) allowed for stable, circumneutral pH to develop alongside with complete $H_2$ consumption (as shown in Figure 24B), primarily through hydrogenotrophic methanogenesis. Data from the two experiments described above and others has informed the experimental design for the deployment of (8) 15L bioreactors with biomethanation stimulation treatments added through conventional leachate recirculation beginning in Year 3.

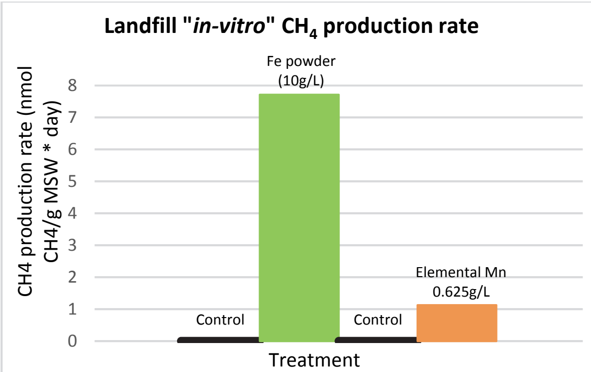


Figure 24A. Graphical summary of 1:10 MSW slurry microcosm methane ($CH_4$) production rate (in nmol $CH_4$ /g MSW * day) for the two described experiments.

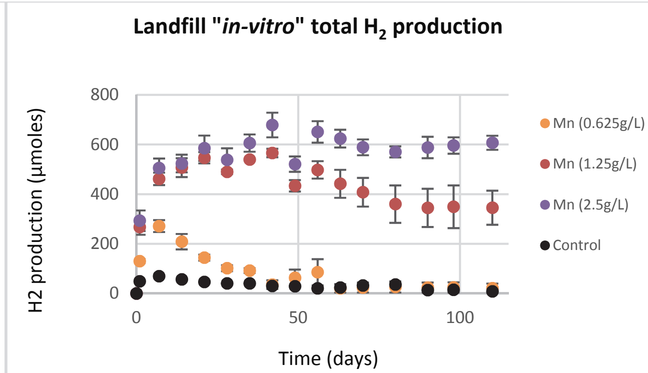


Figure 24B. Cumulative hydrogen ($H_2$) molar production in 1:10 MSW slurry $Mn^0$ concentration optimization microcosms.

In addition to bench scale observations limited to a 30ml serum vial and the initial 5L MSW PVC bioreactor, data was also continually obtained in the field at Salt River Landfill. Sample collection focus shifted from LFG to primarily leachate biomass in the recent sampling seasons. Our aim was to gain insight into the novel microbial community that has described minimally using current next generation sequencing technologies. With our initial sequencing efforts (16S rRNA gene and mcrA gene), we wanted to demonstrate whether this microbiome is stable or not. Preliminary taxa summary bar area graphs based on the 16S rRNA gene biomarker in Figure 25 depict what seems to be minimal variation in the Salt River Landfill microbiome across sampling seasons. The samples (i.e LPx – see figure) come from (2) different cells that display an age gradient. Across all sampling events, common phyla such as Proteobacteria, Firmicutes, and Chlorobi were consistently detected. Such a relative abundance distribution has been observed in other landfills. However, the presence of phyla with no culture-based representation (e.g. Candidate phyla OP3 and OP11, which were recently described from wastewater treatment systems) were dominant in the older of the two landfill cells (including samples LP8, LP9, LP11). This, along with previous isotopic data we obtained from this field site in year 1, affirms the presence of unaddressed variation in landfill microbial activity within and between cells, at least within the Salt River Landfill.

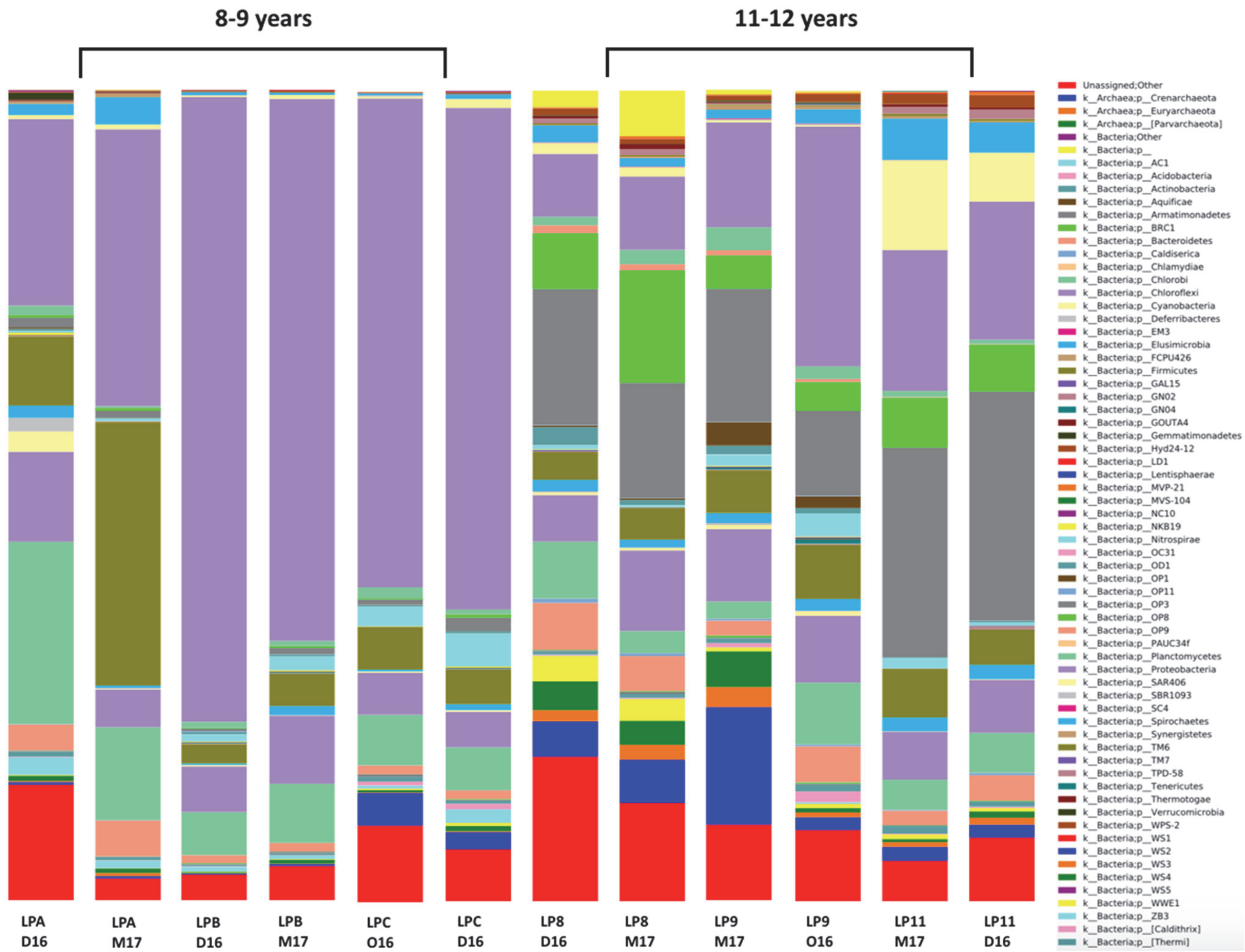


Figure 25. *In-situ* gas taxa bar chart summary of overall bacterial and archaeal community in Cell VI, Salt River Landfill, N. Scottsdale, AZ across several sampling seasons. ABBREVIATIONS: LPx = Leachate sump # sampled | O16=October 2016, D16=December 2016, M17=March 2017

**Summary of other relevant work being conducted within and outside of the ERC and how this project is different**

Related work being conducted within the ERC includes the project "Activated Landfill for Rapid Organic Degradation" from NMSU lead PI Dr. Zohrab Samani organic landfill, particularly because the envisioned landfill design their team plans to test involves using bioinspiration (e.g. bioaugementation of cellulolytic bacteria and porous vegetation waste for gas dispersal) instead of biostimulation (what is proposed in our work), which would also theoretically impact biomethanation of the MSW system.

**Plans for the next year**

Although project is entering a phase out stage from NSF sponsorship, the team is moving into an industrial partner sponsored model for subsequent year. Final approval is on the works at this stage.

Research plans on this project for next year includes deployment of (8) bench-scale 15L bioreactors that mirrors the design of the true *in-situ* operation of a bioreactor landfill cell beginning in August 2017. Specifically, it will resemble the *in-situ* landfill cell through the relative placement of injection and gas sampling ports along with the maintenance of 40% moisture via real time measurements of moisture content, temperature, and degree of compaction. We anticipate to obtain a clear understanding of how recirculation of leachate alongside (3) lab-verified biomethanation stimulants alter the MSW biogeochemical output and overall microbial diversity. Geochemical monitoring strategy will include measuring pH, conductivity, redox potential, short chain volatile fatty acids, dissolved organic carbon (DOC), chemical oxygen demand, (COD), and major metals. Additional, event-based metrics depending on measurement-determined phase transition will be performed such as isotopic analysis of gases, fluorescent characterization of dissolved organic pools, and/or *–omics* of total bacterial/archaeal community genetic transcription and translation. Furthermore, a similar workflow that was preliminarily presented in Figure 25 (alongside other techniques such as qPCR) to determine microbiological community variation will be executed both in the 15L bioreactors in addition to approximately (4-6) other landfills across the state of Arizona to determine the impact of drought on MSW biomethanation with additional thorough diversity and multi-variate statistical analyses within and between landfills. Lastly, geotechnical characterization of the waste prior to and after the duration of the bioreactor experiment will take place to determine what effects (if any) the biomethantion stimulants have on common geotechnical parameters relevant to a landfill such as degree of compaction (e.g. space available for more MSW), bulk density, compression ratio, organic matter quality, and particle size density. The two above described experiments are anticipated to yield (2) publications, overall.

**Expected milestones and deliverables for the project**

We will test two innovative technologies for enhancing CH4 production and model the process, hence we expect by the end of year 3 to contribute 2 research papers and a patent proposal.
The research stage of year 3 is the proof of concept stage for medium scale reactors; however, we also expect after year 3 a field test stage at large scale using a landfill bioreactor cell at Rio Salado Landfill. After the duration of the experiment planned for year 3, industrial partners at Salt River Landfill will develop a six-year leachate reinjection strategy, where we will test our treatment and monitor CH4 production as well as CH4 escape by GC and eddie tower monitoring. We expect to develop a geotechnical strategy and microbial monitoring for landfills that can have a broad use.

**Member company benefits**

In general, efforts to manipulate biomethanation are of general interest primarily to understand (1) the potential to harness the cleanest carbon fuel for combustion under relatively low-demand operating conditions (e.g. from landfills and wastewater treatment plants and (2) the implications $CH_4$ emissions poses as a potent greenhouse gas in a changing climate. We have been engaged with members of the Industrial Partner program (Republic Industries, Geosyntec Consultants, and Arizona Department for Environmental Quality) alongside others members (Salt River Landfill) that recently joined the Industrial Partner program after several meetings with our research group and CBBG leads. All partners described above have been made aware the landfill performance-based optimizations we are addressing throughout this project and efforts to attract other like-minded partners are currently ongoing.

**If relevant, commercialization impacts or course implementation information**

Information on the optimization of this geotechnology can be implemented into ERC-partner university coursework relevant to microbial biogeochemistry, biotechnology, and environmental/geotechnical engineering. Datasets including *in-situ* gas dynamics and 16s rRNA genes/select functional genes (e.g. mcrA) could be used in statistical projects and/or bioinformatics workshops. Additionally, the workflow can be adaptable to other man-made ecosystems with low-demand operating conditions, for example, municipal/industrial wastewater treatment.

### 2.2.4 Thrust 2: Microbial Effects on Mechanical and Geochemical Properties of Porous Media

**ERC Team Members**

*CBBG Faculty*
Joel Kostka, GT
Sheng Dai, GT

*Graduate Students*
Xiaoxu Sun

*Undergraduate Students*
Lena Chu
Elisa Mercando

**Project Goal**
The overall goals of this project was to characterize the diversity/ metabolic potential of indigenous microbial communities present in the subsurface using metagenomics and to develop a cultivation system for the testing the bio-mediated transformation of fluids and gases exposed to high pressure in the subsurface.

***Based on feedback from the NSF SVT after the Year 1 review, the Thrust that this project was part of "Resource Recovery" was eliminated and then this project was subsequently sunset during the review of Year 1 projects. The student is completing the research with partial funding from other sources and will no longer be supported by CBBG after May 2018.***

**The project's role in support of the strategic plan**
Geotechnical characterization of the subsurface is integral to the reliable and economic development, operation, and remediation of infrastructure related to water, energy, and waste. Microorganisms are abundant in the subsurface and their metabolism directly impacts the geochemistry and mechanical properties of subsurface porous media exposed to high pressures. This project can contribute to the fundamental understanding to support environmental protection and restoration as well as resource development projects.

**Fundamental Research, Education, or Technology Advancement Barriers**
This was initially a fundamental knowledge project. The objective was to determine the contribution of microorganisms to the thermo-hydro-chemo-bio-mechanical (THCBM) properties of subsurface environments that contain important hydrocarbon and metal resources. In particular, the impacts of pressure and temperature on the structure and function of microbial communities is critical to engineering strategies for hydrocarbon resource/ recovery, remediation of hydrocarbon contamination, and modeling of flow paths in porous media. Existing subsurface science generally does not include the impacts of pressure on microbial communities that are critical to the integrity of subsurface porous media. Modeling of reactive-transport of contaminants or flow in porous media often includes limited information about microbial communities and that information is limited to process rates from pure bacterial cultures or to Michaelis Menton kinetics.

Experimental work to verify and calibrate modeling has been conducted at pressures and temperatures that do not adequately reflect in situ subsurface conditions. We often don't know, for example, whether the high pressures found in the subsurface will enhance or diminish the rates of microbially-mediated hydrocarbon transformation. This research project was expected to provide inputs for technology development and modeling under close to in situ conditions.

**Any research aspect that involves foreign collaborations, especially indicating the length of time US faculty or students spent abroad conducting their work, and vice versa, and the value added of that work to the student's/faculty' work.**

Colleagues at the Technical University of Hamburg have incubation systems that utilize gas pressure rather than hydraulics. To further verify our results, Ph.D. student Xiaoxu Sun travelled to Hamburg to repeat our experiments using gas pressure incubation cells. Sun will also initiate experiments using DNA stable isotope probing to identify the metabolically active microbial populations mediating hydrocarbon transformation.

**Achievements in previous years**

In the first year of the project, it was proposed to review the published information on subsurface microbial communities and to develop a suitable cultivation system for high pressure conditions. These objectives were achieved. The literature review is complete and the cultivation system has been developed. We have been verifying and calibrating the cultivation system. For proof of principle, we chose to investigate bio-mediated hydrocarbon degradation in the pressure cells.

This project is funded equally by CBBG and the Gulf of Mexico Research Initiative (GoMRI). Through research cruises supported by GoMRI, we obtained subsurface samples from the Gulf of Mexico in environments exposed to ~ 10 MPa. From these sediment samples, we isolated hydrocarbon-degrading bacteria and performed experiments with the sediments. Replicate sediment slurries were incubated at 10 MPa as well as at atmospheric pressure with and without the addition of crude oil. Oxygen consumption was used as a proxy for biodegradation. After incubation, DNA was extracted from the sediments and microbial communities were characterized using next generation sequencing of SSU rRNA genes. Several iterations of experiments were performed using the high pressure cultivation system.

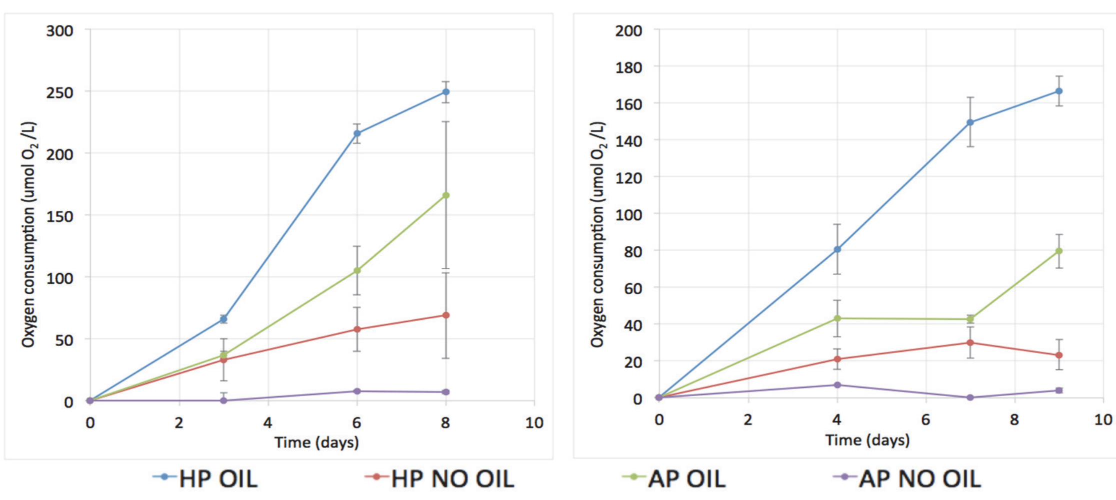


Figure 26. Biodegradation quantified by oxygen consumption in the high pressure cultivation system. Sediment samples were collected from subsurface sediments exposed to > 10 MPa. HP = high pressure of 10 MPa. AP = atmospheric pressure.

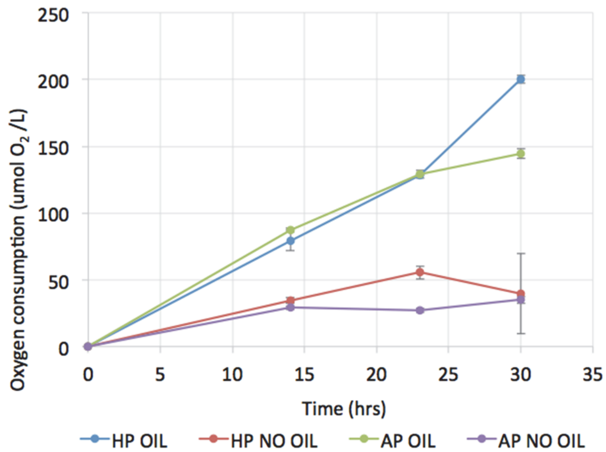


Figure 27. Biodegradation quantified by oxygen consumption in the high pressure cultivation system. Sediment samples were collected from shallow sediments exposed to near atmospheric pressures. HP = high pressure of 10 MPa. AP = atmospheric pressure.

Rates of hydrocarbon biodegradation were shown to be elevated at high pressure in subsurface sediments collected from high pressure environments, indicating that microbial communities are well adapted to high pressure conditions (Figure 26). In sediments collected from shallow environments exposed to much lower natural pressures, biodegradation rates were not substantially impacted by exposure to high pressure.

Analysis of microbial communities showed an enrichment of microbial groups known to carry out hydrocarbon degradation including members of the Colwelliaceae and Oceanospirillaceae taxa (Figure 28). However, at the DNA level, we did not observe the effects of pressure on the relative abundance of hydrocarbon degrading bacteria.

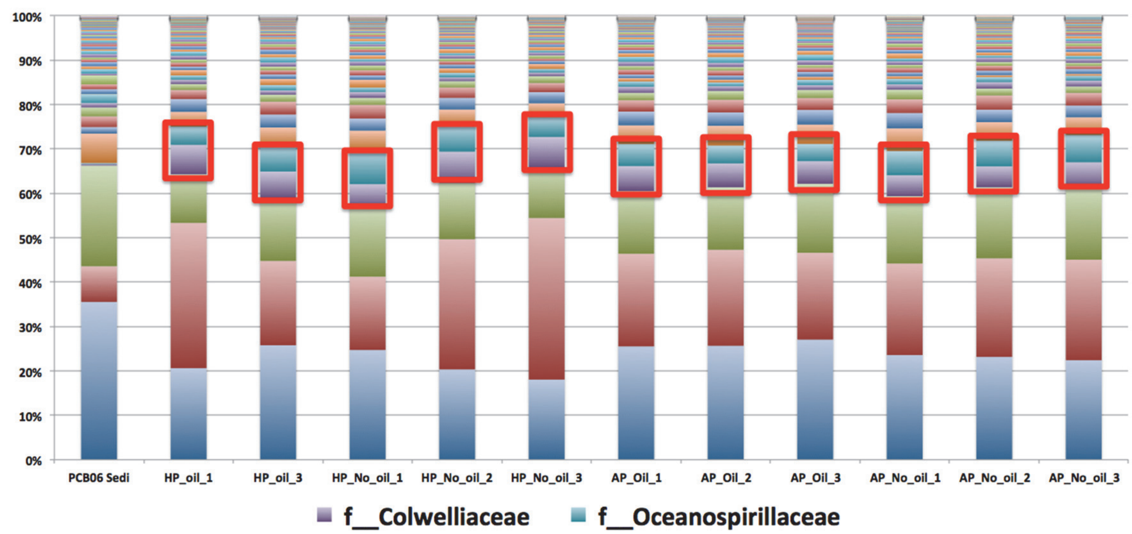


Figure 28. Characterization of microbial communities at the class level from the high pressure incubation system. Sediment samples were collected from subsurface sediments exposed to > 10 MPa. HP = high pressure of 10 MPa. AP = atmospheric pressure.

**Achievements in past year**

This project had achieved exciting results on the impacts of high pressure on subsurface sediment microbial communities. Our high pressure incubation system utilizes hydraulic pressure to mimic the in situ condition.

**Summary of other relevant work being conducted within and outside of the ERC and how this project is different**

N/A

**Plans for the next year**

***<u>Based on feedback from the NSF SVT after the Year 1 review, the Thrust that this project was part of "Resource Recovery" was eliminated and then this project was subsequently sunset during the review of Year 1 projects. The student is completing the research with partial funding from other sources and will no longer be supported by CBBG after May 2018.</u>***

Prior to this outcome, the research team had determined that to more effectively determine rates of microbial activity under close to in situ conditions, they had proposed to install sensors for the quantification of oxygen and carbon dioxide directly in the high pressure incubation cells. Ideally, microbial activities should be studied in subsurface sediments that are collected at high pressure and never depressurized. Nearly all previously published work has been conducted on samples that were depressurized. Faculty member Dai has developed a high pressure chamber to perform experiments on bio-mediated processes at high pressure without depressurization. They proposed to build a new chamber for the Georgia Tech high pressure lab facility. Through collaborations at the USGS and US DOE labs, we had written a proposal to obtain methane hydrate samples from the subsurface. These samples were collected on the continental slope of the Indian Ocean and have been maintained at in situ pressure and temperature. We proposed to build the new incubation system and perform experiments on the methane hydrate samples at Georgia Tech.

**Expected milestones and deliverables for the project**

This project serves as approximately half of the dissertation research of Ph.D. student, Xiaoxu Sun. Xiaoxu worked closely with CBBG faculty (Sheng, Kostka) to develop the pressure cells for the study of bio-mediated activities at high pressure. Two undergraduate students were recruited by Kostka and supervised by Sun to work on the project. One undergraduate student, Lena Chu, isolated hydrocarbon-degrading bacteria from deep-sea subsurface sediments. Another student, Elisa Mercando, participated in the quantification of biodegradation rates. Both of these students were awarded prestigious Presidential Undergraduate Research Awards (PURA) by Georgia Tech for the fall semester of 2016. By means of the PURA awards, Georgia Tech will support Chu and Mercando to perform independent research for the CBBG project.

**Member company benefits**

As a fundamental project in its first year, it is difficult to identify specific benefits to member companies at this time. That being said, it is anticipated that once the contributions of microorganisms to the thermos-hydro-chemo-bio-mechanical properties of subsurface environments are better know, numerous applications for resource recovery companies will be identified and developed through bench scale to full deployment.

**If relevant, commercialization impacts or course implementation information**

N/A

### 2.2.5 Thrust 2: Microbial Manipulation of Flows in Subsurface Geomaterials

**ERC Team Members**

*CBBG Faculty*
Sheng Dai, GT

*Graduate Students*
Boyoung Jeong

*Undergraduate Students*
N/A

**Project Goal**

The original goal of this project was to develop a secure and efficient geological carbon sequestration method; enhanced geothermal or hydrocarbon recovery and possible microbial transformation and sequestration of contaminants.

***Based on feedback from the NSF SVT after the Year 1 review, the Thrust that this project was part of "Resource Recovery" was eliminated and then this project, which had only been initiated in early 2017, was subsequently sunset during the review of Year 1 projects. The student is completing the research with partial funding from other sources and will no longer be supported by CBBG after May 2018.***

**The project's role in support of the strategic plan**

This project was initially conceived as part of the Resource Recovery thrust of CBBG. As such, it has important implications in the following topic areas:

- Geological carbon sequestration
- Enhanced geothermal systems
- Enhanced hydrocarbon recovery
- Microbial transformation and sequestration of contaminants.

This thrust has been eliminated following the Year 1 Site Visit.

**Fundamental Research, Education, or Technology Advancement Barriers**

There were a number of fundamental topics outlined in the project as follows:

- To understand phylogenetic, genetic, and functional diversity of microbial communities at 1-2 km subsurface;
- To understand microbial effects on fluid (i.e., viscosity) and interfacial (i.e., contact angle, surface tension) properties at subsurface conditions;
- To understand microbial effects on (multiphase) flow pattern changes;
- To understand fundamental properties of biofilms formed at elevated pressure and temperature conditions;
- Identify bacteria types that suitable to be cultivated at elevated pressure and temperature conditions;
- Evaluate/obtain fundamental hydro-chemo-bio-mechanical properties at subsurface conditions;

**Any research aspect that involves foreign collaborations, especially indicating the length of time US faculty or students spent abroad conducting their work, and vice versa, and the value added of that work to the student's/faculty' work.**
N/A

**Achievements in previous years**
This was a new project that was initiated in January 2017. After 4 months, the project was sunset as noted above. As a result, the achievements to date have been modest. The student is continuing to work on the project with partial support from an external sponsor.

**Achievements in past year**
The project researchers are continuing to develop the apparatus and associated test protocols to perform tests as outlined in the original proposal. Device development costs are being born by others.

**Summary of other relevant work being conducted within and outside of the ERC and how this project is different**
Enhanced understanding on subsurface hydro-chemo-bio-geo-mechanical processes are critical for resource recovery and waste sequestration. Knowledge on microbial effects on fundamental fluid properties, interfacial characteristics, flow patterns, and biofilms behavior are very limited. The proposed work will investigate these fundamental properties and processes at elevated pressure, temperature, and stress conditions in the laboratory by developing unprecedented high pressure devices, sensors, and testing methodologies.

**Plans for the next year**
***Based on feedback from the NSF SVT after the Year 1 review, the Thrust that this project was part of "Resource Recovery" was eliminated and then this project, which had only been initiated in early 2017, was subsequently sunset during the review of Year 1 projects. The student is completing the research with partial funding from other sources and will no longer be supported by CBBG after May 2018.***

**Expected milestones and deliverables for the project**

Expected milestones and deliverables for the project as originally conceived were:
- Identify bacteria communities and suitable types for lab testing under 1-2 km subsurface conditions
- High pressure characterization of microbial effects on fluid properties
- Microbial effects on interfacial (i.e., supercritical $CO_2$ and brine) properties

**Member company benefits**
N/A

**If relevant, commercialization impacts or course implementation information**
N/A

### 2.2.6 Thrust 2: Microbial Metabolic Chain Elongation

**Microbial Metabolic Chain Elongation**

**ERC Team Members**

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César Torres (SEMTE ASU)
Rosa Krajmalnik-Brown, ASU

*Graduate Students*
Sayalee Joshi (SEMTE ASU)

*Undergraduate Students*
Samuel Aguiar (SEMTE ASU)

**Project Goals**
This project aims to establish a novel, sustainable means (a) for improving soil's quality and stability through carbon stabilization and (b) for remediating soils and groundwater contaminated with oxidized contaminants. Both aims explore the process of microbial chain elongation. Microbial chain elongation is the ability of microbes to grow and derive energy from building small molecules into larger, more complex products.

**The project's role in support of the strategic plan**
Carbon stabilization for soil quality improvement and remediation of contaminants in soil and groundwater are primary uses of the Environmental Protection and Restoration thrust. Designing and successfully implementing biomediated, sustainable, and cost effective ways to treat environmental contaminants is a priority in our nation. The presence and persistence of contaminants lowers the quality of soil and groundwater, impedes their use, potentially exposes humans, and negatively affects human health. An effective remediation technology that exploits microbial chain elongation would be commercially valuable.

**Fundamental Research, Education, or Technology Advancement Barriers**
The project will explore several fundamental research questions. These include

- does chain elongation occur in soils?
- what are the products of chain elongation and what microorganisms perform this process?
- is chain elongation effective in all soil types?
- what contaminants can be remediated via chain elongation?
- which substrate, how much substrate, and how much time is required for a desired treatment?

Answering these question is essential into developing microbial chain elongation as a technology for groundwater and soil treatment and quality improvement.

**Achievements in past year**
The project commenced in January 2017. Since project inception, we were able to test microbial chain elongation in four types of soils with various characteristics (Figure 29). We used a combination of the following substrates: acetate + ethanol, acetate +$H_2$, and ethanol + $H_2$. The experiments were performed in soil microcosms containing 25 g soil and 75 mL mineral medium. The microcosms were operated in semi-batch cycles where 1/3 of the slurry volume was removed and replaced with 1/3 mineral medium and substrates. Research performed in the past year demonstrated that microbial chain elongation is a ubiquitous process in soils. Chain

elongation products, including butyrate (C4) and caproate (C6), were produced when acetate (C2) and ethanol were added in all soils tested (one example shown in Figures 30 and 31). Chain elongation products were also formed in the soils fed with acetate (C2) + $H_2$ or ethanol + $H_2$ but in lower concentration than in soils with acetate (C2) and ethanol. An important product also generated during microbial chain elongation is $H_2$ gas (Figure 32). High concentration of $H_2$ were produced in all soils fed with acetate (C2) and ethanol undergoing chain elongation. $H_2$ is an important commodity for bioremediation of many oxidized contaminants. During the next year, an important focus of the project will be to explore the $H_2$ generated from chain elongation to remediate organic and inorganic contaminants.

Also in the past year, we investigated which soil-associated microorganims perform the chain elongation process. Figure 33 highlights the changes in relative abundance of microbial sequences after 5 cycles of chain elongation. As seen in Figure 33, all four soils became enriched in the phylum *Firmicutes* (light green bars). Within this phylum, the predominant families were *Clostridiaceae, Peptococcaceae*, and *Ruminococcaceae*, anaerobic microorganisms known for the ability to ferment organic compounds.

Figure 29. Soil types tested for microbial chain elongation.

| Soil ID | Description and location | Soil type | pH | Conductivity (µS/cm) | Total dissolved solids (ppm) | Salinity (ppm) | Chemical oxygen demand (mg/g soil ) | Total organic carbon (g/kg soil) |
|---|---|---|---|---|---|---|---|---|
| A | Chlorinated solvent-contaminated soil; ~30 m deep; Arizona | Sandy clay | 7.5 | 178 | 126 | 74 | 3.5 | 5.7 |
| B | ~0.2 m deep; Montana | Peat | 7.7 | 183 | 123 | 73 | 0.7 | 133.7 |
| G | Garden soil; ~0.2 m deep; Arizona | Silt + loam | 7.7 | 173 | 121 | 73 | 2.9 | 36.6 |
| L | Hydrocarbon-contaminated soil; ~1.5 m deep; Texas | Clay | 5.0 | 76 | 52 | 36 | 0.9 | 19.9 |

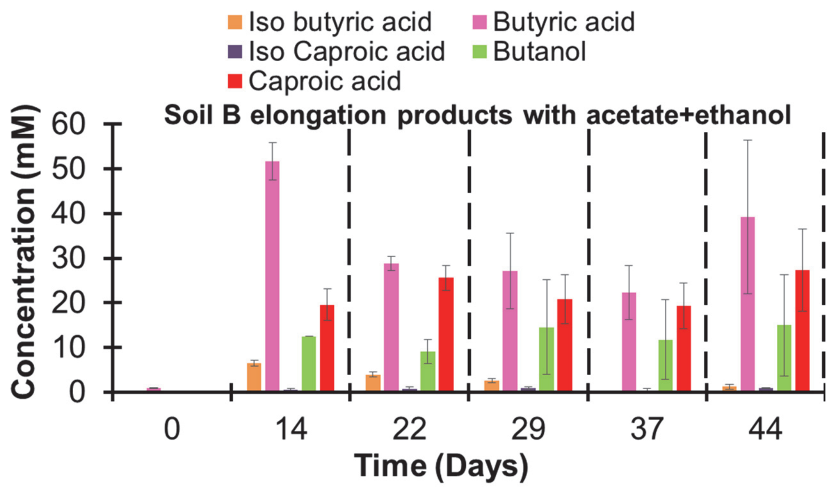



Figure 30. Concentration of chain elongation products in soil B. The data are averages with standard deviation of duplicate soil microcosms. The dashed lines denote the end of a semi-batch cycle.

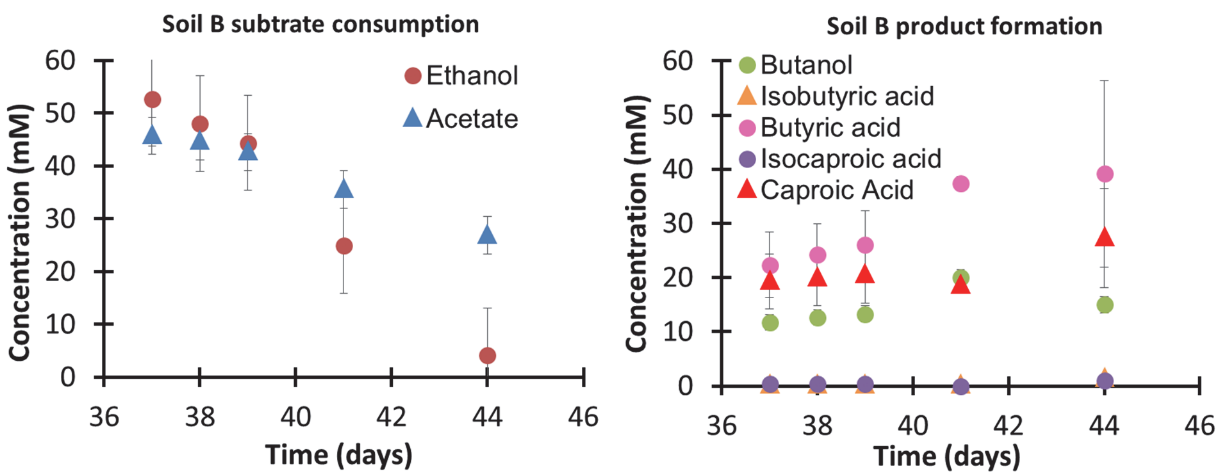



Figure 31. Kinetics of substrate consumption and chain elongation product formation in soil B. The data are averages with standard deviation of duplicate soil microcosms.

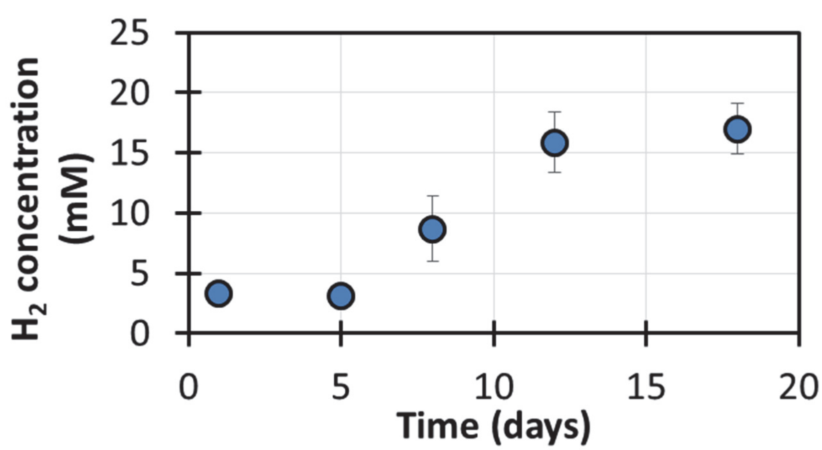



Figure 32. Production of $H_2$ in microcosms with 50 mM acetate and 50 mM ethanol. The data are averages of duplicate microcosms.

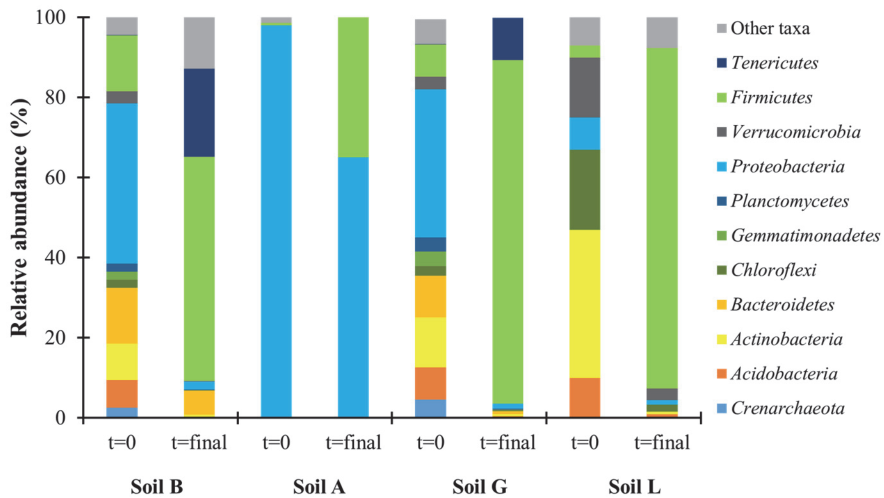



Figure 33. Evolution of microbial communities in soil microcosms performing microbial chain elongation. The substrates for chain elongation were 100 mM acetate and 100 mM ethanol. The data are averages of duplicate soil microcosms.

**Summary of other relevant work being conducted within and outside of the ERC and how this project is different**

Relevant work being conducted within the ERC includes research on groundwater remediation of chlorinated ethenes and perchlorate via biostimulation/bioaugmentation and research of electokinetic transport for ground remediation. Relevant work conducted outside of the ERC includes research on ex situ biological treatment of groundwater contaminated with chlorinated ethenes.

**Plans for the next year**

In the next year, we plan to test the effectiveness of a bioremediation scheme for chlorinated ethenes with the $H_2$ generated from microbial chain elongation. We also plan on testing soil strength, stability, and ability to hold water through carbon sequestration from chain elongation.

**Expected milestones and deliverables for the project**

We expect to dedicate year 3 fundamental science development. We anticipate that, upon successful demonstration of proof of concepts (remediation or soil stabilization), we can proceed to a field site for technology demonstration (years 4-5).

**Member company benefits**

Effective or cheaper techniques for contaminant remediation are of practical value and should be of interest to current CBBG partners, including Chevron, Geosynthec, Freeport McMoRan, and MatrixNewWorld. A strong remediation portfolio within CBBG should be able to attract more remediation/consulting companies as partners.

**If relevant, commercialization impacts or course implementation information**

Soil stabilization and remediation of environmental contaminants topics will be included into the new course EVE 352 Fundamentals of Environmental Engineering. This course will be a core course within the Environmental Engineering Undergraduate Program at ASU. The course will be offered every spring semester. Pending support from laboratory experiments, a discovery disclosure on bioremediation through chain elongation will be submitted fall of 2017.

### 2.2.7 Thrust 2: Microbial Metabolic Exploration from Extreme Environments for Bioremediation and Energy Recovery

**ERC Team Members**

| *CBBG Faculty* | *Graduate Students* |
|---|---|
| Rosa Krajmalnik-Brown, ASU | Sofia Esquivel-Elizondo, ASU |
| Everett Shock, ASU | Alta Howells, ASU |

**Project Goals**

The Microbial Metabolic exploration (MME) project aims to i) explore extreme environments, including high-pH, low-temperature environments, ii) better understand the interaction between microorganisms and geochemistry in these environments, and iii) harvest novel microbial capabilities.

Last 2 years' aims were centered on carbon monoxide (CO)-consuming microorganisms in the environment, including high-pH sites, where carbonate precipitation can occur naturally. The objectives were i) to develop carbon monoxide (CO)-consuming cultures, ii) to discover and isolate novel fermentative microorganisms from extreme environments capable of generating acetate and other chemical and biotechnological feedstock from CO, and iii) to generate protocols that will guide the isolation of a diversity of microbes from extreme environments.

**The project's role in support of the strategic plan**

This is a fundamental knowledge project, which in the future can lead to multiple applications. The applications of the fundamental knowledge generated the last 2 years can be divided into two. First, the established strategic isolation and enrichment techniques of extremophiles (i.e., microorganisms that live under extreme conditions) can be applied to harness microorganisms for other projects. Second, the elucidation of fermentative reactions in environments with extreme-alkaline environments is important to understand the relationship between fermentative microorganisms and carbonate precipitation.

In addition, Remediation of Organic Contaminants in Soil and Groundwater is a primary use of the Environmental Protection and Restoration thrust. Isolates that generate acetate from CO could possibly be used to enhance dechlorination of soils contaminated with chlorinated compounds. *Dehaloccocoides* spp., which are major dechlorinting bacteria, use acetate as their main carbon source and produce toxic amounts of CO as part of their metabolism. Our isolates might benefit the growth of *Dehaloccoides* spps. by lowering CO concentrations in the environment and providing their main carbon and electron sources, acetate and $H_2$.

**Fundamental Research, Education, or Technology Advancement Barriers**

Some major barriers to this project include: toxicity of substrates to microorganisms, establishing extreme conditions in the laboratory, slow microbial growth, good isolation techniques, interpretation on microbial ecology to enhance enrichments and isolations.

In the case of CO, the toxicity of CO to organisms, from humans to microbes, is a critical barrier. Despite its toxicity, a select group of microorganisms are able to grow with CO. Most of these microorganisms are slow growers, and/or are initially inhibited by CO and do not metabolize it until after a period of adaptation which could last up to several weeks. The difficulty of identifying extremophiles that grow at high pH and ferment inorganic substrates (i.e., CO) is another major barrier, since induction of CO-metabolism occurs after several weeks of exposure to CO, and extreme alkaline conditions are detrimental to most organisms.

**Any research aspect that involves foreign collaborations, especially indicating the length of time US faculty or students spent abroad conducting their work, and vice versa, and the value added of that work to the student's/faculty' work.**

We are hoping to get back to Oman (where high-pH samples were collected) and to other international sites with extreme conditions; this will lead to ample international collaboration.

**Achievements in previous years**

Prior to initiation of the CBBG, research work on the isolation of CO-oxidizers demonstrated that serial transfers with CO as sole substrate and at increasing concentrations enriched for these microbes (See Figure 34).

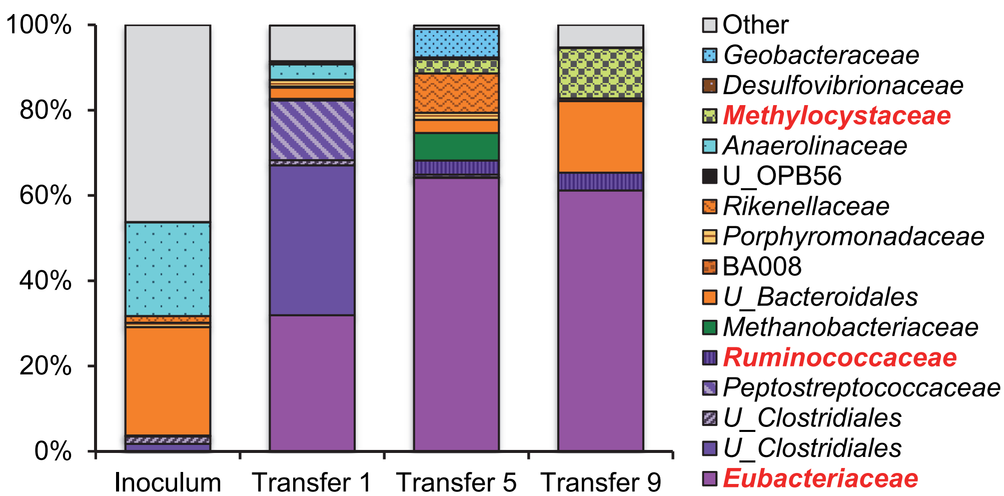



Figure 34. Microbial community structure of selected transfers made during the CO-enrichment process of sludge (inoculum). Samples plotted are an average of triplicates. U_: unidentified. Potential CO-oxidizers include those in the *Eubacteriaceae*, *Ruminococcaceae*, and *Methylocystaceae* families.

Two microbes (98-99% phylogenetically similar to *Acetobacterium wieringae* and *Pleomorphomonas oryzae*) were isolated from the enrichments made from sludge. Both isolates were characterized in terms of CO-converting capabilities (products formed from CO, doubling times, CO-consumption rates, and/or morphology under CO).

**Achievements in past year**

We generated fundamental knowledge to understand microbial metabolic reactions that occur under extreme alkaline conditions. For this, we characterized the geochemistry and microbial community structure of high-pH sites collected at the Oman Semail Ophiolite and other natural environments (i.e., volcanic and lake sediments and the seafloor). We also enriched for and identified fermentative and CO oxidizing microorganisms from these sites, and studied their metabolism. Fermentative microorganisms are archaea and bacteria that produce methane, acetate and other metabolites from organic (i.e., sugars, biomass) and inorganic substrates (i.e. CO). These products of fermentation can be involved in carbonate precipitation and bioremediation.

The high pH (>pH 11) is driven by a subsurface water-rock reaction called serpentinization. The serpentinzation-reacted waters are not only high in pH, they are reduced and $H_2$-rich. As these fluids come up to the surface they come into contact with the atmosphere resulting in $CO_2$ precipitation into carbonate minerals, making the process of serpentinization a potential option for natural carbon sequestration and cementation. Furthermore, upon reaching the surface serpentinization-reacted water can mix with surrounding surface water (~pH 8). The disequilibrium resulting from mixing between these two fluid types has the potential to fuel microbial metabolisms that are involved in the production or consumption of $CO_2$ such CO oxidation, $CH_4$ oxidation and $CH_4$ production (methanogenesis). In these systems, biological CO and $CH_4$ oxidation to $CO_2$, with subsequent precipitation to carbonate, may act not only as a sink for $CO_2$, but also for $CH_4$ and CO. Conversely, with these systems being carbon limited, methanogens could convert inorganic carbon species to $CH_4$, mobilizing carbon back into the atmosphere and enhancing the dissolution of carbonate in these systems. In order to use the process of serpentinization for carbon sequestration and cementation the distribution of microbial populations that may enhance or slow carbonate precipitation must be understood. The microbial community structures of the 4 high-pH sites and the CO-enrichment culture growth at pH 11.5 are presented in Figure 35.

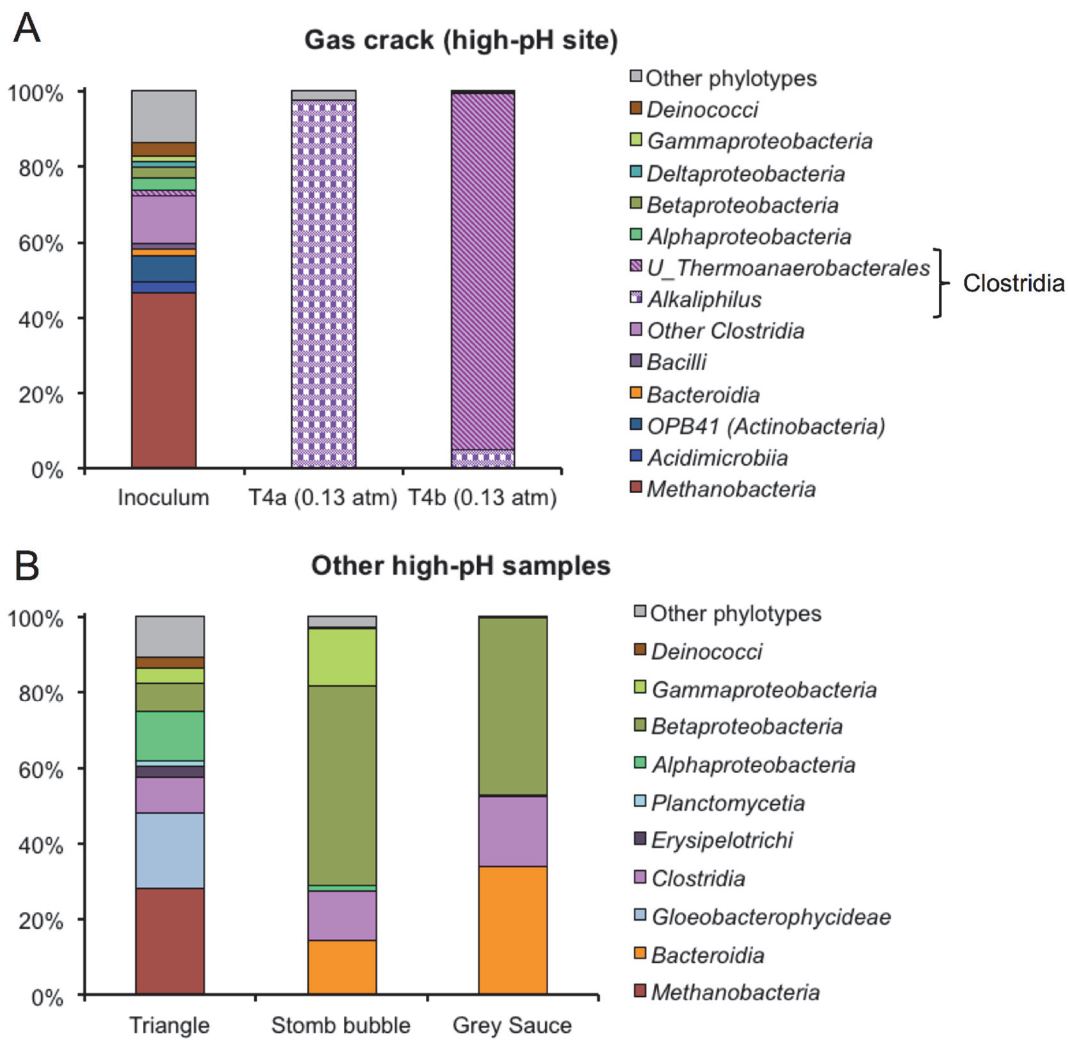



Figure 35. Phylotypes detected in A) "Gas crack", a high-pH sample collected at the Oman Semail Ophiolite, and the CO-enrichments from this sample (cultured at 30 °C and pH 11.5), and B) other high-pH samples from the Ophiolite where carboxidotrophs were not identified.
*Notes*: T: serial transfer, a & b: CO-enrichments in buffered and non-buffered media, respectively. U_: unidentified phylotype within the indicated taxonomic level. The CO partial pressure of the CO-enrichment culture is shown in parentheses.

To evaluate the maximum amount of energy microbial populations can gain from carrying out CO oxidation, $CH_4$ oxidation and methanogenesis in the environment, Alta Howells in collaboration with her colleagues, Kirt Robinson, Tucker Ely and James Leong, have carried out energy calculations. Figure 36 shows the energies at 26 different locations in Oman associated with CO oxidation coupled to the reduction of water (water-gas shift reaction), aerobic methane oxidation, and methanogenesis with bicarbonate as the inorganic carbon source. The energies are plotted against Si concentrations in the environment. Si acts as an indicator for the extent that the two fluid types (at pH >11 and 8) have mixed. Fluids with low concentrations of Si are representative of serpentinization-reacted water and fluids with high concentrations of Si are representative of surrounding surface water. Across the Si gradient, both aerobic methane oxidation and methanogenesis yield far more cal/mL than CO oxidation. While CO oxidation is still energetically favorable, it is unlikely that populations carrying out this reaction are dominant in the environment. Aerobic methane oxidation and methanogenesis have comparable energies in surface waters, however in serpentinization-reacted water aerobic methane oxidation yields up to three orders of magnitude more cal/mL. It would be expected that aerobic methane oxidation is a far more dominant metabolism in hyperalkaline systems than methanogenesis.

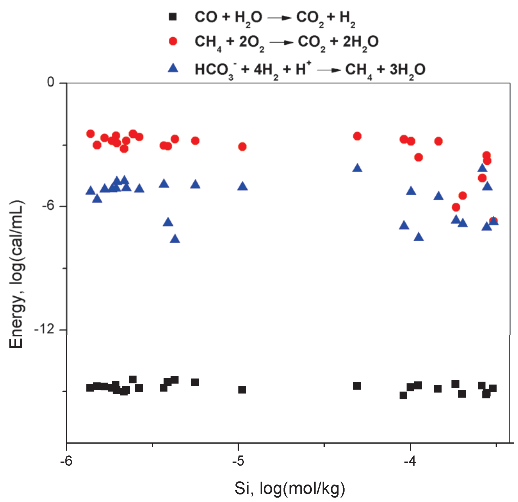
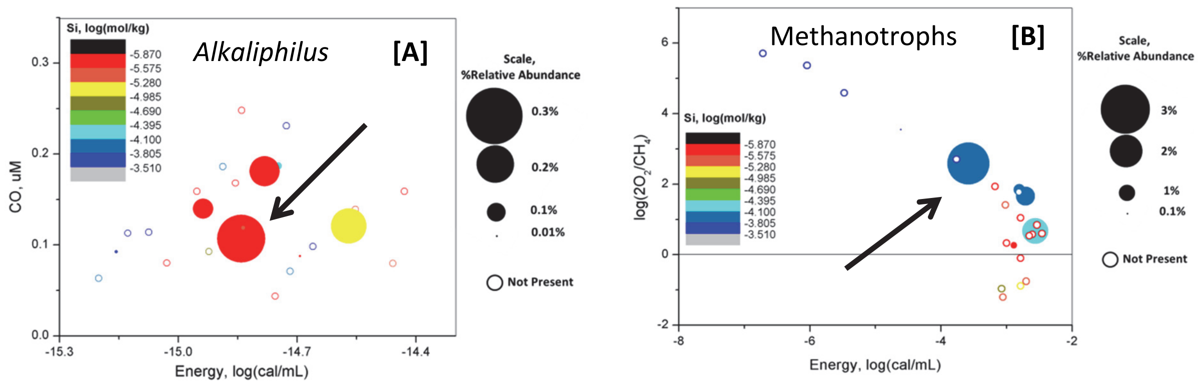



Figure 36. **Energetic calculations for CO oxidation (water-gas shift reaction), aerobic methane oxidations, and methanogenesis using bicarbonate as the inorganic carbon source.** Energy in cal/mL is the maximum amount of energy a microbial population can obtain in a flowing system where the supply of reactants is maintained. Energies are plotted against the log of the Si concentration in the environment. Si is an indicator of mixing between serpentinization-reacted water (> pH 11) and surrounding surface water (~pH 8). Si is high in surrounding surface water and low in serpentinization-reacted water.

In order to evaluate the presence of populations carrying out CO oxidation, aerobic methane oxidation and methanogenesis, 16S rRNA gene sequencing on DNA extracted from sediments from the 26 sites was carried out. For CO oxidation a population closely related to the genus *Alkaliphilus* was isolated from samples collected in Oman by Sofia Esquivel-Elizondo (Figure 35) and were shown to anaerobically oxidize CO. For aerobic methane oxidation, 16S rRNA genes closely related to genera *Methylomicrobium* and *Methylosinus* were found. For methanogenesis, sequences closely related to the genus *Methanobacterium* were found. In order to evaluate the extent the availability of energy influences the presence and abundance of these populations in the environment, presence/absence plots, Figure 37, were made with log energy on the x-axis and the log ratio of the concentration of the reactants in terms of the stoichiometry of the reaction on the y-axis. This helps evaluate the influence of not only the availability of energy, but also the availability of the reactants on the microbial populations. The size of the filled in circle (population present) corresponds to the relative abundance of the populations (*i.e.*, *Alkaliphilus*, methanotrophs and methanogens) and the color scale corresponds to the Si concentration in the environment. If the availability of energy is the only driving factor for the presence of populations in the environment, it is expected that these populations would be present across the Si gradient. However, this is not the case. 16S rRNA genes related to methanotrophs are only present in mixing or surface water systems (high in Si) that are $O_2$-rich and have the most available energy (Figure 37B). 16S rRNA genes related to the methanogens are predominantly found in serpentinization-reacted water systems (low in Si) that are $H_2$-rich and have the most available energy (Figure 37C). The 16S rRNA gene closely related to *Alkiliphilus*, shown to oxidize CO in culture (Figure 35), is present in mostly serpentinization-reacted water systems (Figure 37A). Interestingly, its presence is scattered across the energy gradient. It is possible that, while this population can survive on CO oxidation in culture when it is its only source of energy, in the environment it could survive on and potentially prefer alternative sources of energy.



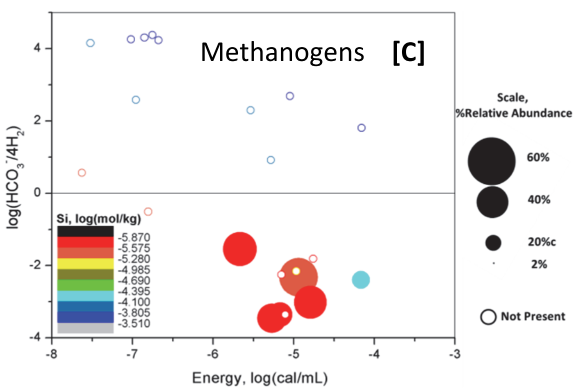




Figure 37. **Presence/Absence plots of populations associated with [A] CO oxidation (water-gas shift reaction) [B] aerobic methane oxidation and [C] methanogenesis.** The energy, log(cal/mL), is plotted against the log ratio of the concentration of the reactants multiplied by the stoichiometric ratio of the reaction. The color gradient is the concentration of Si in the environment and the size of the filled in circle (population present) corresponds to the relative abundance of the 16S rRNA gene. In **[A]** and **[B]** the arrow is pointing to the site that *Alkaliphilus* was isolated from, "Gas crack".

As shown in Figure 38A, microorganisms identified in all the CO-enrichments, including those from high-pH sites, volcanic sediments, frozen lake sediments, or the seafloor, were from the class *Clostridia* (e.g., *Alkaliphilus*) and/or the order *Enterobacteriales*. Likewise, acetate was the main metabolite produced by all enrichments with CO, regardless of the source of the sediment sample. Accordingly, despite the microbial phylogenetic differences in the natural sites where the samples were collected, all CO-enrichment cultures presented a similar phylogenetic diversity, as shown in Figure 38B.

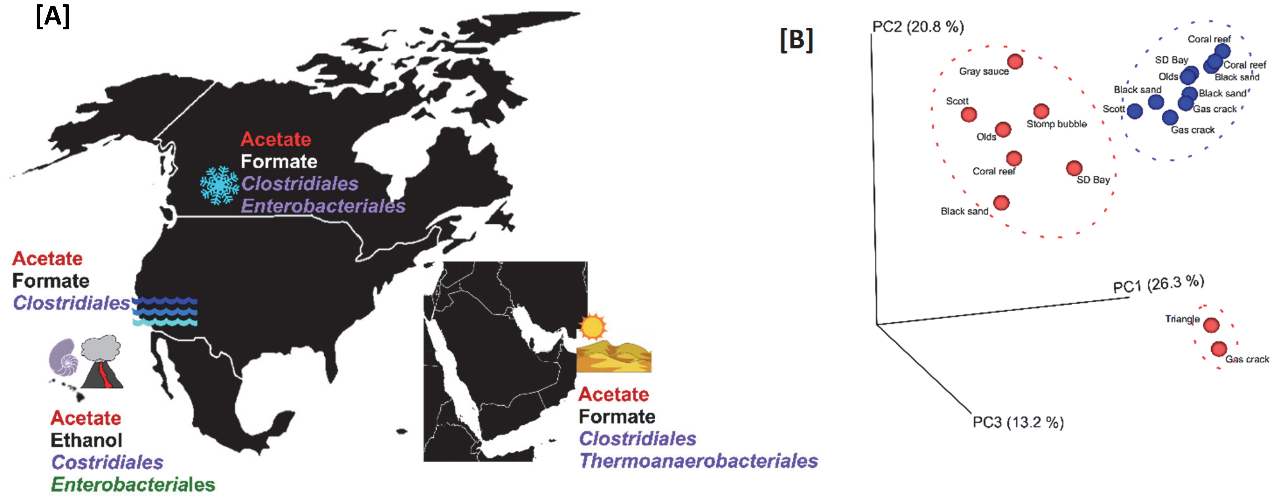



Figure 38. **[A]** Main results from the microbial exploration study. Acetate was the main metabolite produced, and *Clostridia* and *Enterobacteriales* were the main phylotypes detected in all enrichments with carbon monoxide from all sites studied: the seafloor (Hawaii and San Diego), Canada (frozen lakes), or Oman (high-pH sites). **[B]** Principal coordinate analyses of microbial diversity among samples. Ovals with dotted lines highlight that CO-enrichments cultures (in blue) clustered together, separated from the natural sites (in red), based on phylogenetic similarities in major taxa (weighted analysis). *Notes*: The first principal component (PC1) axis explains the maximum amount of phylogenetic variation present in the samples, followed by the second axis (PC2), and the third (PC3). Accordingly, the analysis captured 60.3% of the phylogenetic variability. High-pH sites: "Gray sauce", "Stomp bubble", "Gas crack", and "Triangle". Seafloor samples: "Coral reef" and "SD Bay". Frozen lake sediments: "Olds" and "Scott". Volcanic sediment: "Black sand".

## Summary of other relevant work being conducted within and outside of the ERC and how this project is different

Similar strategies are being implemented at UC-Davis to enrich cultures for ureolytic microbes able to handle higher concentrations of urea and faster ureolytic conversion.

## Plans for the next year

We will continue harnessing existing cultures and data sets but as far as enrichment cultures and microbial isolations, focus will be shifted to metal cycling and metabolic microbial exploration to enhance toxic metal bioremediation.

## Expected milestones and deliverables for the project

1) Protocols for enrichment and isolation of novel microorganisms.
2) Microorganisms from extreme environments isolated.
3) Transfer of knowledge with other projects
4) Further exploration to meet other projects and industrial needs.

## Member company benefits

Protocols established for explorations and isolation can be used to harness a plethora of microbes with various biotechnological properties. Identifying fermenters involved in CO oxidation is of

interest for bioremediation. Additionally findings on CO-metabolism are of ecological interest, specifically, to understand CO microbial role in the carbon cycle at high pH and other environments. CO can be recycled into methane, $CO_2$/bicarbonate, acetate, etc.
Protocols will be applied to harness other microbial activities that can enhance biogeotechnical processes.

**If relevant, commercialization impacts or course implementation information**

The most efficient isolates and/or CO-consuming cultures can be tested as remediation partners.
Fundamental knowledge will be incorporated in graduate classes related to geochemistry, microbiology, and biotransformations at Arizona State University.

### 2.2.8 Thrust 2: Rehabilitation and Restoration of Degraded Soils Using Liquid Organic Fertilizer (LOF)

**ERC Team Members**

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Paola Bandini, NMSU

*Graduate Student*
Saman Mostafazadeh-Fard

*Undergraduate Students*
Jason Alcantar
Victor Lara

**Project Goal**

The goal of this project is to develop a cost-effective and sustainable method that could be used for restoration of soils degraded due to erosion and for prevention of erosion in susceptible soils. This research addresses the problem of soil degradation caused by natural processes or human activities, such as mining, construction and uncontrolled erosion, which has resulted in large-scale loss of valuable top soil in many sites in the United States (U.S.) and around the world. On the other hand, there is an urgent need for developing sustainable techniques to recycle green waste produced from agricultural, horticultural and landscaping activities. The uncontrolled decomposition of organic waste is a major source of environmental contamination and atmospheric greenhouse effects. This research uses liquid organic fertilizer (LOF) produced from organic green waste, such as grass clippings (28 million tons/year generated in the U.S.), for sustainable plant growth and soil rehabilitation and restoration.

**The Project's Role in Support of the Strategic Plan**

This research addresses primarily the use case "Restoration of Denuded Landscapes," which is one of the priorities of the Environmental Protection thrust, by working directly on three of the factors that cause soil erosion, namely soil erodibility factors, cover crop, and rainfall erosivity. Human activities such as mining and construction have led to loss of native vegetation cover in soils of the affected areas. Loss of vegetation cover causes eventually to displacement of soil particles, and loss of nutrients and organic matter due to water and wind erosion, leading to degradation of the affected soil. Re-establishment of native vegetation cover or establishment of erosion control vegetation cover has been proven to be the most effective restorative and erosion prevention technique used so far. Effective establishment of any vegetation cover in these cases requires an easy to access, sustainable and cost-effective fertilization technique. This project is focused on this major problem through evaluation of use of liquid organic fertilizer produced through anaerobic digestion of organic (green-leaf) waste for establishment of erosion control vegetation cover (*Lolium perenne*, also called ryegrass) in modeled degraded soils.

**Fundamental Research, Education, or Technology Advancement Barriers**

Fundamental research and technology advancement questions that must be answered to develop and commercialize this technique include: 1) what is the optimum production of the LOF; 2) what is the advantages of using LOF compared to other fertilizers; 3) what is the impact of LOF on growth and quality of erosion-control plants compared to other fertilizers; 4) what is the impact of LOF on soil erosion-related parameters compared to other fertilizers; 5) do traces of herbicides or pesticides from the original grass (substrate) remain in LOF after the digestion in concentrations that can affect the plants.

**Any research aspect that involves foreign collaborations, especially indicating the length of time US faculty or students spent abroad conducting their work, and vice versa, and the value added of that work to the student's/faculty' work**

N.A.

**Achievements in previous years (Year 1)**

**Study on optimization of LOF production**

A technology consisting of adding the desired proportions of organic waste (fresh grass clippings), molasses and water into a sealed tank (bio-reactor, see Figure 39) was proposed to biologically break down (digest in anaerobic conditions) the organic compounds in the grass into simpler organic compounds. The process includes recirculation of leachate inside the bio-reactor to progressively recover nutrients from the organic input (grass clippings and molasses) by leaching the simpler organic compounds into the leachate, enriching it with macro- and micro-nutrients and organic matter, which are essential components of a bio-fertilizer. Three bio-reactor tests were performed (Year 1) to determine the close-to-optimum combination of organic input (grass clipping waste, liquid molasses) and water required for efficient nutrient recovery. Figure 40 shows the potential of each of the three proposed combinations of organic input and water on nutrient recovery (TKN: total Kjeldahl nitrogen; TP: total phosphorus; K: total potassium) after three successive cycles (C1, C2, C3). Each cycle consisted of full extraction of the leachate (LOF production) after two weeks of digestion and reintroduction of fresh water into the bio-reactors.

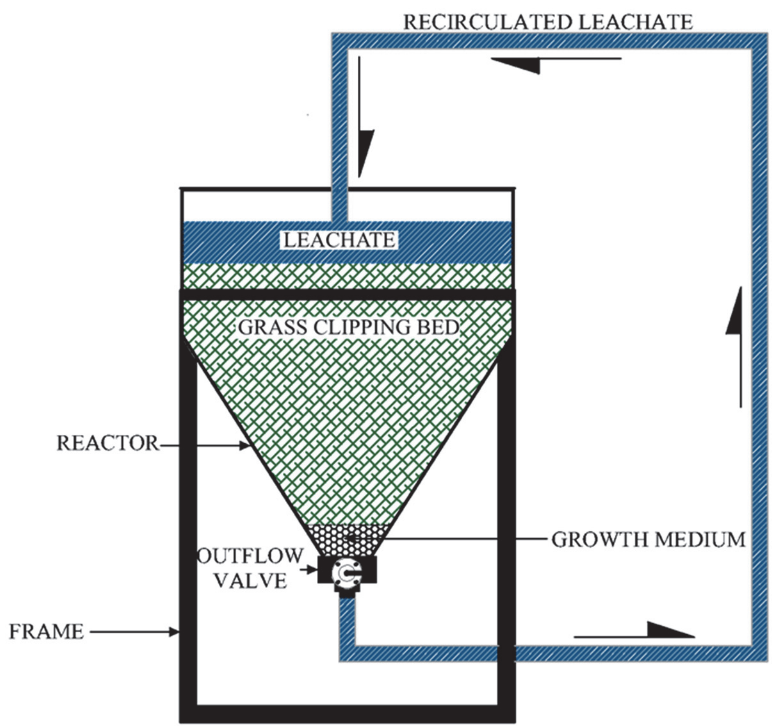



Figure 39. Bio-reactor for LOF production.

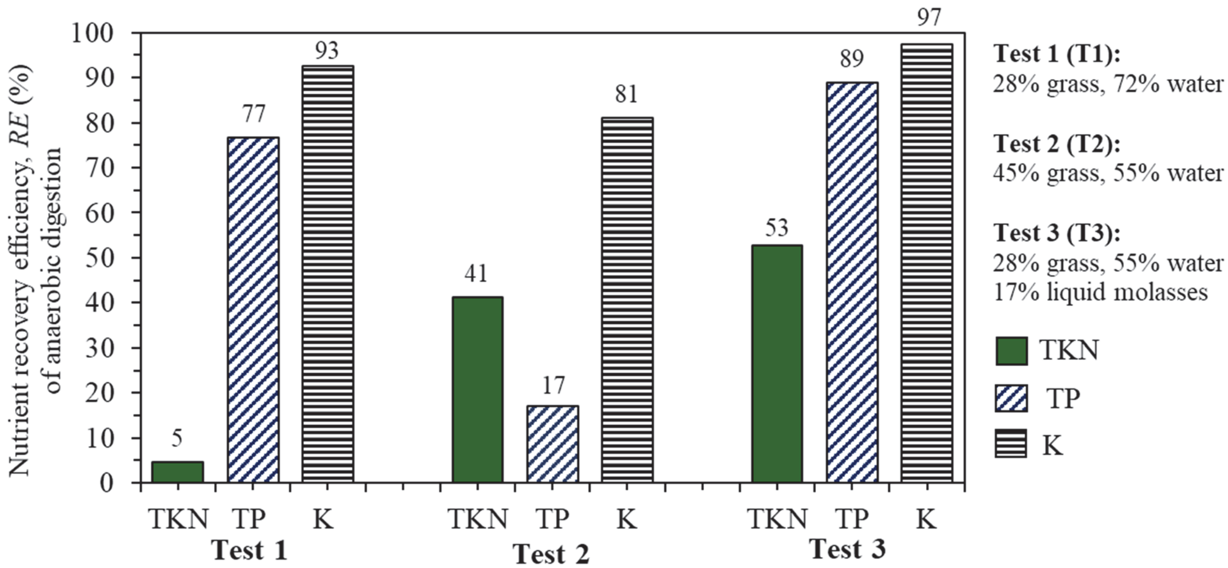


Figure 40. Nutrient recovery from grass clippings for three organic input and water combinations.

**Use of LOF for establishment of ryegrass in modeled degraded soil**

A complete randomized block experiment (greenhouse) was designed and conducted (Year 1) to determine the effect of LOF compared to a commercially available synthetic fertilizer on plant (ryegrass) growth and quality (Figure 41), as well as on soil erosion-control parameters. The growth medium was sandy soil with negligible organic content to represent a degraded soil condition. This sand was sampled from fill material used locally for embankment construction of bridge abutments. Three treatments were applied: LOF in sand as growth medium; LOF in sand mixed with zeolite as growth medium (LOFZ); and synthetic fertilizer in sand as growth medium (CF). The soil water content was maintained close to field capacity throughout the experiment. The fertilizer treatments (LOF and CF) were applied monthly in four equal doses based on nitrogen content. Greenhouse environmental conditions were monitored during the experiment. The interpretation and dissemination of these results were carried out in Year 2.

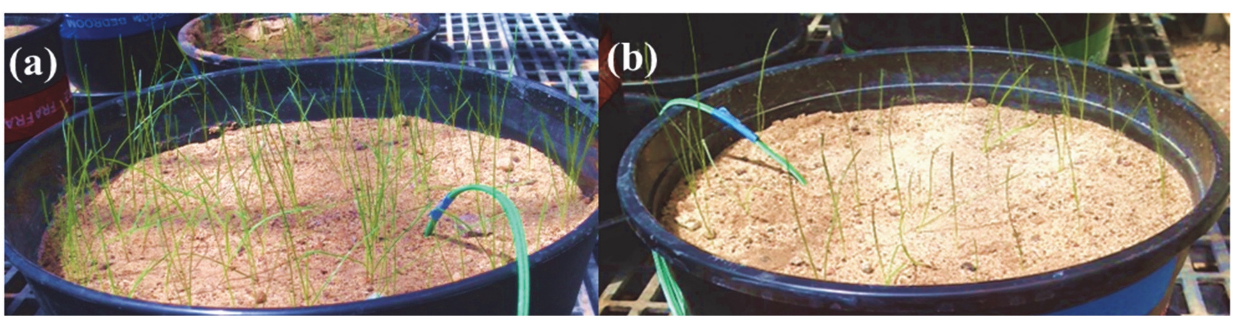


Figure 41. Effect of LOF compared to conventional synthetic fertilizer (CF) on visual quality of ryegrass, 24 hour after application: (a) LOF treatment, and (b) CF treatment.

**Achievements in past year (Year 2)**

**Analysis of results from the study on optimization of LOF production**

The results obtained from the LOF production optimization experiment (three bio-reactors) were analyzed and compared in terms of nutrient recovery efficiency, nutrient accumulation (TN: total nitrogen, TP, K) in the leachate per week and per cycle, and nutrient amount normalized by organic load (i.e., input mass of grass and molasses) per cycle. The most efficient of the three combinations considered was determined (See Figure 42 for Cycle 1). A journal paper on this topic was submitted and accepted for publication (2017) in Waste and Biomass Valorization journal (Impact factor: 1.337).

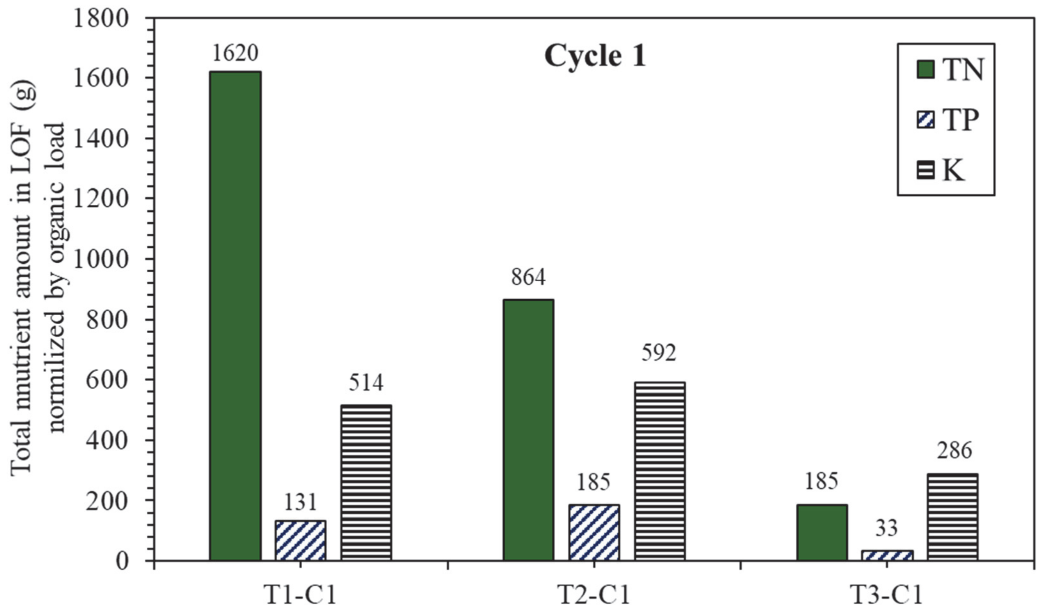
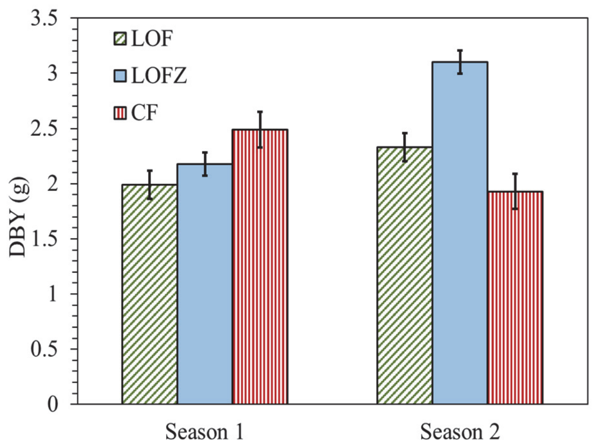


Figure 42. Normalized total nutrient amounts (TN, TP and K) in the leachate in Cycle 1.

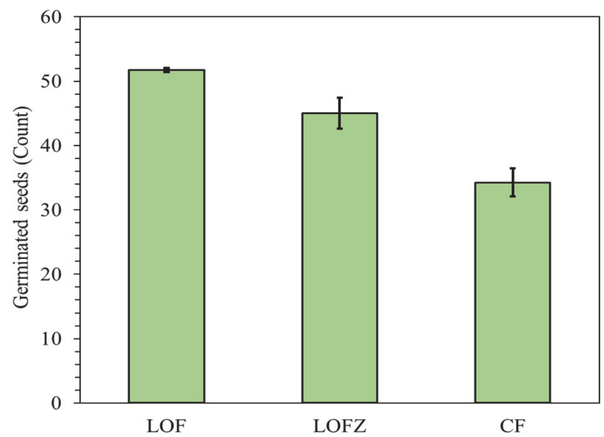
**Evaluation of the effect of LOF on establishment of ryegrass in modeled degraded soil**

The results of the complete randomized block experiment with ryegrass initiated in Year 1 (two seasons) were analyzed in Year 2. It was found that the LOF treatment leads to comparable above-ground biomass yield (DBY) in ryegrass (Figure 43a). In addition, the combined use of LOF and zeolite (LOFZ treatment) improved (statistically significant) the yield of ryegrass in the long term during the experiment compared to CF treatment (Figure 43). It also improved the soil's nutrient content (TN, TP, K), organic matter content, and bulk density as well as germination rate (Figure 43b) compared to CF treatment. The results of the experiment also demonstrated that by incorporation of zeolite into the growth medium treated with LOF, the improvement of nutrient content of the growth medium could be significantly improved (Figure 44). From this work, a Master's thesis was completed in summer 2017 and a paper on this topic was prepared and is in process of being submitted to a journal publication that focuses on soil restoration and land management (See Publications).

Select physical and chemical properties of the growth medium for the three treatments are provided in Figure 44 for comparison. The organic matter and, consequently, the organic carbon content in all soil samples increased during the two seasons regardless of the treatment (See Figure 44). This increase could be linked to physical, chemical and/or biological transformation of root exudates and dead and living microorganisms in the soil organic matter and the adhesion of this organic matter to soil minerals (Lehmann and Kleber 2015). This increase in soil organic matter and soil organic carbon (SOC) could ameliorate the erosivity of soil because SOC contains a substance called glomalin that helps bind the soil aggregates making the soil structure more resistant to erosion (e.g., USDA NRCS 2009, Lal 2015, Peng et al. 2016). It was expected that LOF treatment would be related to greater organic matter; however, it appears that the organic matter levels in both LOF and CF treatments at the end of the experiment are the same (Figure 44).




(a)




(b)

Figure 43. Results of the greenhouse experiment: (a) dry biomass yield (DBY) for the three treatments; (b) number of germinated seeds per treatment.

Figure 44. Effect of treatments on some physical and chemical properties of the experimental soils

| Property | Treatment | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | LOF | | | LOFZ | | | CF | | |
| | Initial | Final | Difference (%)[a] | Initial | Final | Difference (%)[a] | Initial | Final | Difference (%)[a] |
| Organic carbon (%) | 0.20 | 0.23 | 15 | 0.24 | 0.26 | 8.3 | 0.20 | 0.23 | 15.0 |
| Organic matter (%) | 0.30 | 0.40 | 33.3 | 0.4 | 0.5 | 25 | 0.30 | 0.40 | 33.3 |
| N (%) | 0.01 | 0.014 | 40 | 0.01 | 0.022 | 120 | 0.01 | 0.015 | 50 |
| P (Bray) (ppm) | 7.1 | 10.9 | 53.5 | 4.3 | 7.9 | 83.7 | 7.1 | 8.8 | 23.9 |
| K (ppm) | 67 | 82 | 22.4 | 273 | 313 | 14.7 | 67 | 67 | 0 |
| Ca (ppm) | 2482 | 2708 | 9.1 | 2709 | 2553 | -5.8 | 2482 | 2629 | 5.9 |
| Mg (ppm) | 117 | 140 | 19.7 | 126 | 137 | 8.7 | 117 | 140 | 19.7 |
| Salinity copper (ppm) | 0.02 | 0.05 | 150 | 0.02 | 0.05 | 150 | 0.02 | 0.05 | 150 |
| Salinity manganese (ppm) | 0.11 | 0.14 | 27.3 | 0.14 | 0.13 | -7.1 | 0.11 | 0.11 | 0 |
| CEC (meq/100 g) | 14 | 16 | 14.3 | 15.5 | 15.2 | -1.9 | 14 | 14.3 | 2.1 |
| Salinity SAR | 3.18 | 5.37 | 68.9 | 1.89 | 2.58 | 36 | 3.18 | 5.14 | 61.6 |
| Salinity sulfate (ppm) | 295.9 | 473.6 | 60.1 | 164.6 | 243.5 | 47 | 295.9 | 415.5 | 40.4 |
| Bulk density (g/cm$^3$) | 1.71 | 1.62 | -5.3 | 1.67 | 1.66 | -0.6 | 1.71 | 1.68 | -1.8 |
| pH | 8.6 | 8.4 | -2.3 | 8.5 | 8.3 | -2.4 | 8.6 | 8.5 | -1.2 |

[a] Difference calculated as [(final value – initial value)/(initial value)]x100%

For LOF treatment, the levels of N, P, K, $SO_4$, Ca, Mg, Cu, $HCO_3$, Cl, Fe, Zn and Mn increased in the experimental soil. Except for Ca, Fe, Mn and Si in LOFZ treatment, and K, $BO_3$, Fe, Si and Zn in CF treatment, the levels of all nutrients increased in these treatments (Select data is available in Figure 44). Total nitrogen and K increased more in LOFZ treatment than in LOF treatment (Figure 44). The increase in N and P contents as well as other nutrients in the soil in LOFZ treatment may be linked to ammonium oxidizing microbes, that oxidize the ammonium in LOF and other organic sources captured by the zeolite and transform it into nitrite and eventually to nitrate [Leggo 2014] for easier plant uptake.

**Determination of trace of herbicide present in grass tissue in the body of LOF**
One of the research questions is whether the application of herbicides or pesticides to the grass used as source of the grass clippings could lead to traces of these chemicals in the produced LOF at levels that may affect crops fertilized with LOF, including erosion-control grasses. (This can also have implications when applying for organic certification of the product.) An individual test was designed and conducted to address this question. A commercial herbicide (single isomer form of Mecoprop-p) that is typically used in treatment of northern and southern lawns was used. To control the amount of herbicide present in the substrate in this experiment, the fresh grass clippings were sprayed with the herbicide solution (at the concentration recommended by the manufacturer) prior to placing them into the reactor. Then, the LOF produced using these herbicide-treated grass clippings was applied as fertilizer (in the appropriate concentration based on nitrogen content) to multiple herbicide-sensitive crops including tomato, watermelon and chili pepper plants, with three replicates. In some plants, the LOF treatment was sprayed on the leaves even though this is not the normal fertilizing method but it represented a worst-case scenario. No sign of burning or drying of the plants or any other herbicide-damage symptom was observed. This indicated that the anaerobic digestion leading to LOF production breaks down the herbicide compounds found on the input grass clippings. Additional chemical analysis is in progress to investigate any potential chemical trace in the LOF produced from herbicide-sprayed substrate.

**Production of liquid organic anti-icer as a derivative product from liquid organic fertilizer**
Throughout this experimental program, we discovered a combination of organic input (grass clippings and liquid molasses) and water to produce a liquid that can be used as organic anti-icer. For this purpose, multiple laboratory tests were conducted to measure freezing and melting points and other properties of the organic solution under different conditions and determine its potential for application as liquid organic anti-icer on paved surfaces. The results of the experiments demonstrated the feasibility of this anti-icer application.

An invention disclosure was filed at NMSU (by Dr. Samani, Dr. Bandini, and graduate student Mostafazadeh-Fard) in August 22, 2016 (NMSU Arrowhead Center Case Number INV-00044). A provisional patent application is in progress through NMSU (See commercialization impacts or course implementation information).

**Publications and presentations**

**<u>Publications</u>:**

Mostafazadeh-Fard, S., Samani, Z., and Bandini, P. (2017). Production of liquid organic fertilizer through anaerobic digestion of grass clippings. *Waste and Biomass Valorization* (Technical paper. Accepted, August 2017).

Mostafazadeh-Fard, S. (2017). *Restoration of Degraded Soils using Organic Fertilizer and Zeolite*. Master's Thesis, Department of Civil Engineering, New Mexico State University, Las Cruces, New Mexico.

Mostafazadeh-Fard, S., Samani, Z., Bandini, P., and Shukla, M. Rehabilitation of degraded soils using liquid organic fertilizer and zeolite (Technical paper. Draft).

Mostafazadeh-Fard, S., Bandini, P., and Samani, Z. Effect of liquid organic fertilizer and zeolite on the soil-water characteristic curve (Technical note. Draft).

**<u>Presentations</u>:**

Valorization of agricultural residue through biophysical transformation into an organic soil enhancer. Samani, Z. and Bandini, P., 251st ACS National Conference, San Diego, California. March 13-17, 2016.

Production of liquid organic fertilizer using anaerobic digestion of grass clippings. Presented by: S. Mostafazadeh-Fard. New Mexico Society of Professional Engineers (NMSPE) Annual Issues Conference, Albuquerque, New Mexico, November 2016.

Production of liquid organic fertilizer using anaerobic digestion of grass clippings. Presented by: S. Mostafazadeh-Fard. Pumps and Wells Workshop, New Mexico State University, Las Cruces, New Mexico, March 2017.

**Preliminary design of field scale test (test bed)**

This section briefly describes the concept and preliminary design of a field test bed to demonstrate the erosion prevention using LOF in a denuded soil such a bridge or road embankment. Field test plots (in sloping ground) will be constructed with three treatments and two replicates as shown in Figure 6. The treatments will include "LOF + ryegrass," "commercial fertilizer (CF) + ryegrass," and a control. The control test bed will be used to measure soil erosion where no conservation measure is taken. The treatment test beds will be seeded with ryegrass and watered to establish the vegetation prior to the on-set of rainy season. The plots will be next to each other to maintain all other variables constant. The soil erosion will be monitored and measured at the bottom of each test plot. The experiment will evaluate the impact of erosion control vegetation on soil treated with LOF through the initial establishment, dormant season and the spring and summer re-growth. Candidate sites for this project are located near NMSU campus. Funding for this test bed will <u>not</u> be available from CBBG. Therefore, funding for this testbed will be sought from industry or the New Mexico Department of Transportation.

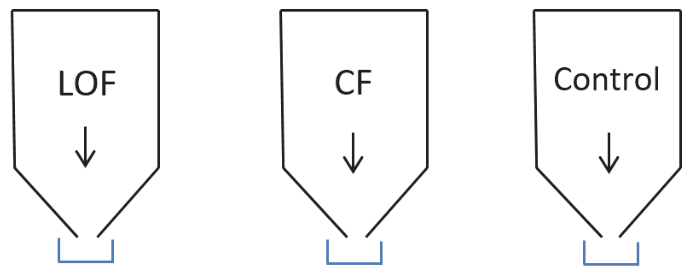



Figure 45. Schematic of field testbeds (plan view, not to scale) and sediment collection areas. Downward slope direction is indicated by arrows.

**Other activities – Education and outreach impact**
The team has mentored and trained 4 undergraduate research students:

- CBBG REU student Jose Martinez in summer 2016.
- Community College REU student Andres Osorio, participant in SCCORE (Summer Community College Research Experience) program at NMSU in summer 2016.
- Undergraduate research student at NMSU: Jason Alcantar (summer and fall 2016). Graduated in December 2016 and currently in the Master's program (Geotech).
- Undergraduate research student at NMSU: Victor Lara (spring, summer and fall 2016), participated through the New Mexico Alliance for Minority Participation (NM AMP) Program. Graduated in December 2016 and currently in an industry position.

**Plans for the next year (Year 3)**
This project is scheduled to end in May of 2018 (with reduced funding in Year 3). The plans for next year will be mainly focused on a field-scale test on LOF, the LCSA analysis, and dissemination of results. The aim is to conduct a field-scale study on LOF with one or more industry collaborators and/or investors, which will be identified through entrepreneurship and commercialization programs in which the team is participating (NSF I-Corps, Aggie I-Corps, SBRI, and Arrowhead Center's LAUNCH).

**Expected milestones and deliverables for the project (Year 3)**
The results of the experiments have shown that LOF has the potential to be used as a bio-based and sustainable alternative for commercially available fertilizers for cultivation of erosion-control cover plants (grass) in soils affected or susceptible to erosion. In Year 3, the team will:

- Submit two additional papers currently in draft form (fall 2017). See Publications.
- Conclude the chemical analyses for herbicide trace in LOF (fall 2017).
- Finalize submission of provisional patent application for organic anti-icer, a spin-off of this research (fall 2017).
- Identify industry collaborator for field-scale test (fall 2017-spring 2018), and carry out the test.
- Revise information provided to the LCSA team based on feedback received, to improve analysis on sustainability rating of LOF (fall 2017).

**Member company benefits**

The costumer interviews conducted through the participation in the commercialization programs (Aggie I-Corps and LAUNCH) have shown that the proposed technology for LOF production is of significant interest to various industries such as Organic Technology International (OTI), HMI, Chevron, and Sustane, hydroseeding and erosion control companies such as Apex, Challenger Construction Corp., Environmental Restoration LLC, and other environmental and construction firms who are actively practicing land reclamation practices. More of the domestic and international companies who may benefit from this technology will be also identified through the participation in commercialization programs (NSF I-Corps and LAUNCH).

**If relevant, commercialization impacts or course implementation information**

Received $50,000 NSF grant in support to participate in **NSF Innovation Corps** (I-Corps) costumer discovery program and evaluate the market and commercialization potential of LOF. In the NSF I-Corps, the team will receive mentorship and conduct extensive domestic and international costumer interviews. The NSF I-Corps application was submitted in spring 2017, but program participation starts in fall 2017. https://www.nsf.gov/news/special_reports/i-corps/teams.jsp

Received $2,000 stipend to participate in NMSU Arrowhead's Aggie I-Corps costumer discovery program to evaluate the market and commercialization potential of LOF through receiving mentorship and conducting extensive domestic costumer interviews (summer 2017). http://arrowheadcenter.nmsu.edu/icorps/why/

Participated in NMSU Arrowhead Center's LAUNCH entrepreneurship training program (semester-long program). The team was a **2017 LAUNCH finalist** this spring.
http://arrowheadcenter.nmsu.edu/launch/

Filed an **invention disclosure** (by Z. Samani, P. Bandini, and S. Mostafazadeh-Fard) in August 22, 2016 (NMSU Arrowhead Center Case Number INV-00044) for the production technology and application of a liquid organic anti-icer (a spin-off of this project). The team presented the invention to the NMSU Arrowhead's Intellectual Property Advisory Committee (IPAC) in summer 2017, which recommended to proceed with filing the patent. A provisional patent application is in progress through NMSU Arrowhead Center.

Accepted into the competitive "Ag Assembly" event, a showcase of Agtech Startups organized by the NMSU Arrowhead Center (http://arrowheadcenter.nmsu.edu/agassembly/). The presentation to national and international investors is scheduled for August 10, 2017.

Preparation of proposals are in progress for Phase 1 Small Business Innovation Research Request for Proposals (RFP) to be submitted to the USDA and DOT:
https://nifa.usda.gov/funding-opportunity/small-business-innovation-research-program-phase-i

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### 2.2.9 Thrust 2: Microbially Enhanced Iron-Modified Zeolite Permeable Reactive Barrier

**ERC Team Members**

*CBBG Faculty*
Charalambos Papelis, NMSU
Paola Bandini, NMSU

*Graduate Students*
Neda Halalsheh
Audrey Smith

*Undergraduate Student*
Amadeo Trujillo

**Project Goals**
The goal of this project is to develop a permeable reactive barrier that is enhanced by the presence of microbiological communities and iron-coated zeolites to enhance the remediation of sites contaminated with oxyanions, such as arsenic and selenium.

**The project's role in support of the strategic plan**
This project is part of the Environmental Protection thrust. Migration of trace metals and metalloids, such as arsenic and selenium, from contaminated sites, including mining sites, is a major environmental concern. This research has the potential to enhance the remediation of contaminated sites, as well as to prevent spreading of contamination to adjacent aquifers. Therefore, the proposed research has also the potential to safeguard drinking water sources.

**Fundamental Research, Education, or Technology Advancement Barriers**
Fundamental research and technology advancement questions that must be answered to develop and commercialize this technique include: 1) what is the dependence of arsenic and selenium removal from water as a function of zeolite characteristics? 2) What is the effect of Na-exchange of the zeolites on metalloid removal efficiency? 3) What is the effect of iron coating characteristics on metalloid removal efficiency? 4) How easy would be to establish a viable biofilm on the zeolites and to control their ability to change the oxidation state of metalloids? 5) How easily reversible would these microbially controlled redox processes be? 6) Would the presence of a microbial biofilm have detrimental effects on groundwater flow characteristics? 7) What would be the rate of the microbially mediated redox reaction and would it be fast enough to be practical? 8) How easy would be to scale up these processes for a commercialized application?

**Any research aspect that involves foreign collaborations, especially indicating the length of time US faculty or students spent abroad conducting their work, and vice versa, and the value added of that work to the student's/faculty' work.**
N.A.

**Achievements in previous years**
Prior to initiation of the CBBG, preliminary batch experiments, including arsenic sorption on iron-coated zeolites, were conducted along with studies exploring the reversibility of the sorption process. However, no exploration of the effect of zeolite pretreatment was conducted and no experiments with selenium were conducted either. Finally, the effects of microbial activity on the sorption of metalloids on zeolites have not been explored.

**Achievements in past year**

During the past year, the iron modification process of the zeolites was further investigated and optimized. Sorption experiments were conducted with four different types of zeolites: unmodified "natural" zeolite (NZ), sodium pretreated zeolite (SPZ), iron modified zeolite (IMZ), and sodium pretreated iron modified zeolite (SPIMZ). The unmodified zeolite, NZ, was used as received. The SPZ was zeolite exchanged with sodium, whereas the IMZ resulted from coating the zeolite, as received, with iron. Finally, SPIMZ resulted from coating with iron, zeolites that were first exchanged with sodium. Given that zeolites have naturally a very low anion exchange capacity, it was not expected that non-iron-coated zeolites, either NZ or SPZ, would show significant affinity for either of the two oxyanions.

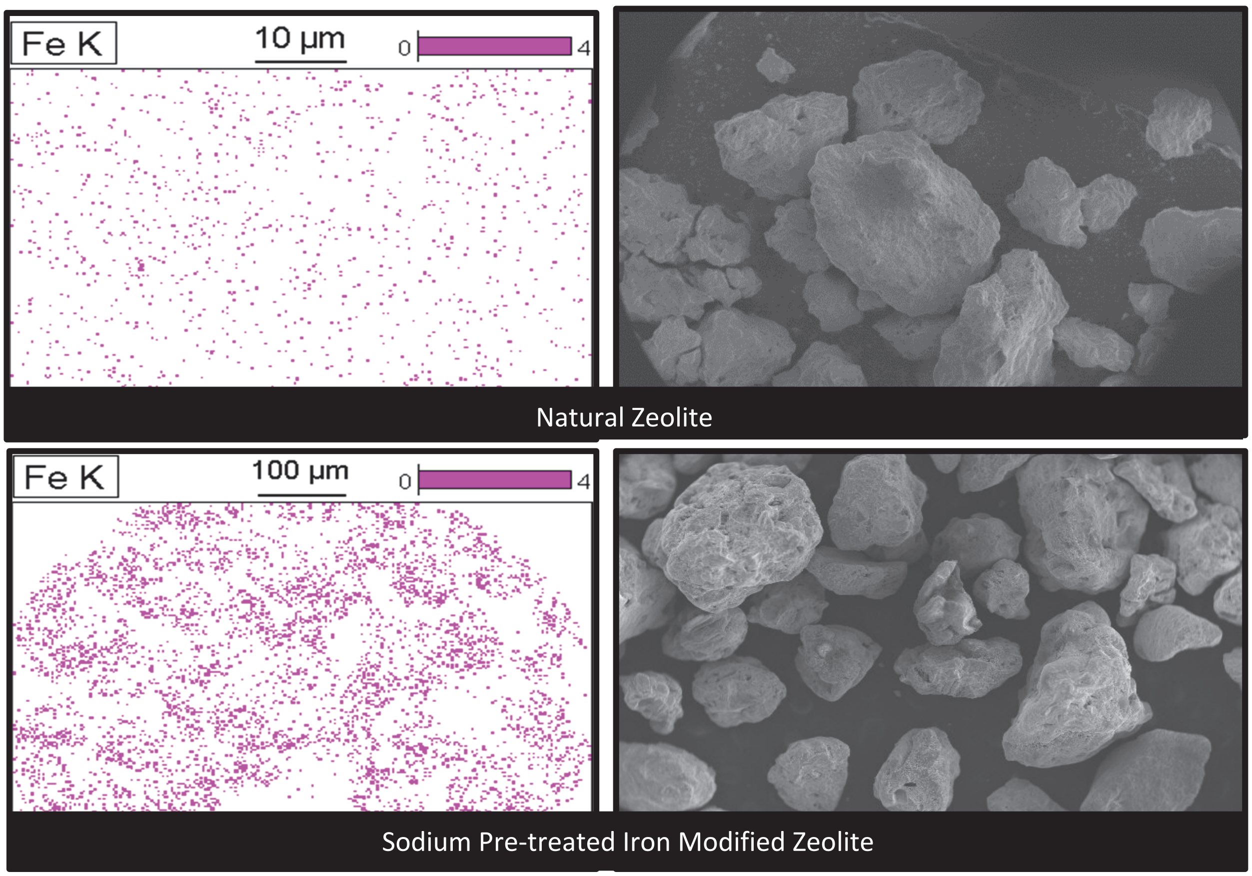


Figure 46. Morphology and iron coating uniformity for unmodified zeolite (NZ) and sodium pre-treated iron modified zeolite (SPIMZ).

The chemical composition of the SPIMZ was analyzed using scanning electron microscopy–energy dispersive x-ray spectroscopy (SEM-EDX). The results suggest greater iron content for the SPIMZ compared to IMZ, suggesting that sodium-pretreatment of the zeolites may affect the coating process, hence increasing the iron content. Clearly, the larger the iron percentage, the greater the capacity of the zeolites for oxyanion sorption would be. The particle morphology, as well as the iron content of the two types of zeolite are shown in Figure 46.

Sorption of selenium oxyanions on NZ is shown in Figure 47. As can be seen from Figure 47, there was very limited sorption of selenium on NZ, on the average around 10% or less, regardless of selenium oxidation state, concentration, solution pH, or ionic strength. These results were expected, given the very low anion exchange capacity of natural zeolites. Even for selenite, the stronger binding oxyanion of the two, sorption was very limited and essentially pH independent, suggesting the absence of amphoteric sorption sites on the NZ.

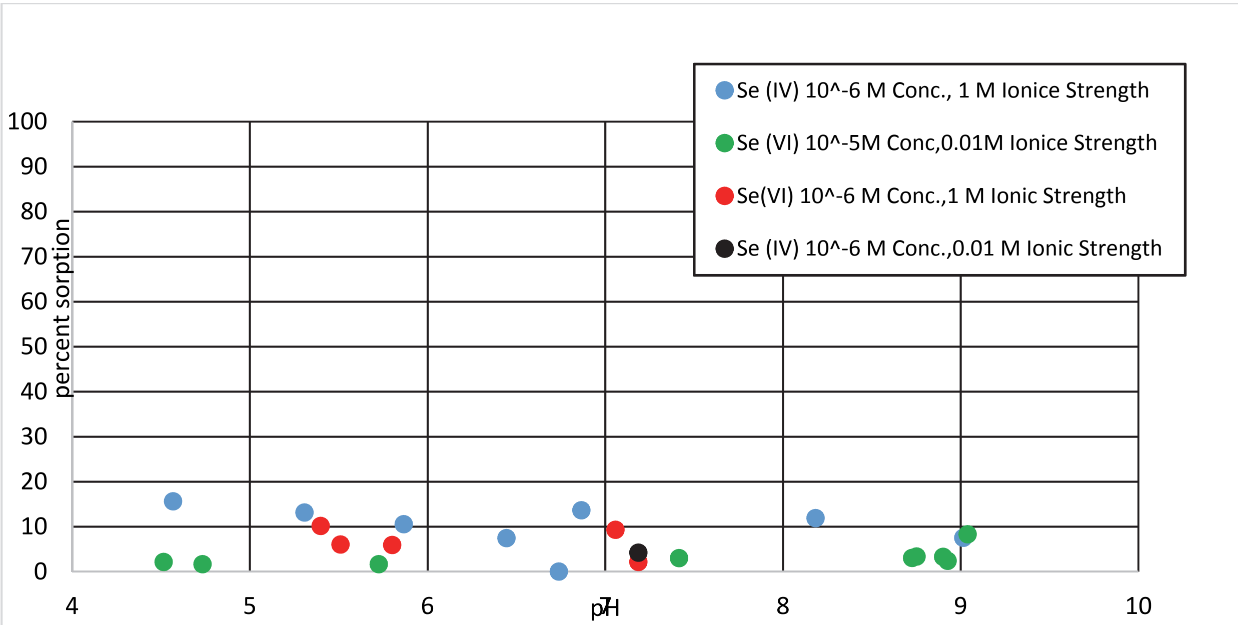


Figure 47. Selenium sorption on natural zeolite as a function of selenium concentration, selenium oxidation state, and ionic strength.

Sorption of selenium on either of the non-iron-modified zeolites, NZ or SPZ, as a function of oxidation state and pH is shown in Figure 48. Similarly to the results shown in Figure 47 for sorption on NZ, the sodium exchange process did not have an effect on the sorption of selenium on zeolites that were not modified with iron. These results are not surprising, given that sodium exchange might affect the sorption of cations on the zeolites, but not the sorption of anions. The observed fractional uptake was around 10%, regardless of pH and oxidation state. This fractional uptake is essentially negligible, given the experimental uncertainty in these experiments.

The sorption of $10^{-6}$ M selenite in a 0.01 M sodium nitrate solution, on all four different zeolite types, is shown in Figure 49. The effect of iron-modification of the zeolite surface on selenite sorption is apparent by inspection of the results in Figure 49. Whereas there was essentially no selenite sorption on either NZ or SPZ, sorption of selenite on both IMZ and SPIMZ was substantial. In addition, selenite sorption on IMZ and SPIMZ was pH dependent, as expected for anion sorption on amphoteric sites, increasing with decreasing pH. By reducing the pH to about 6, one can maximize sorption. It is also worth noting that maximum fractional uptake on SPIMZ, approximately 80-90%, was greater than the fractional uptake on IMZ, approximately 60-70%. This difference can be explained by the fact that the iron content of SPIMZ was greater than the iron content of IMZ.

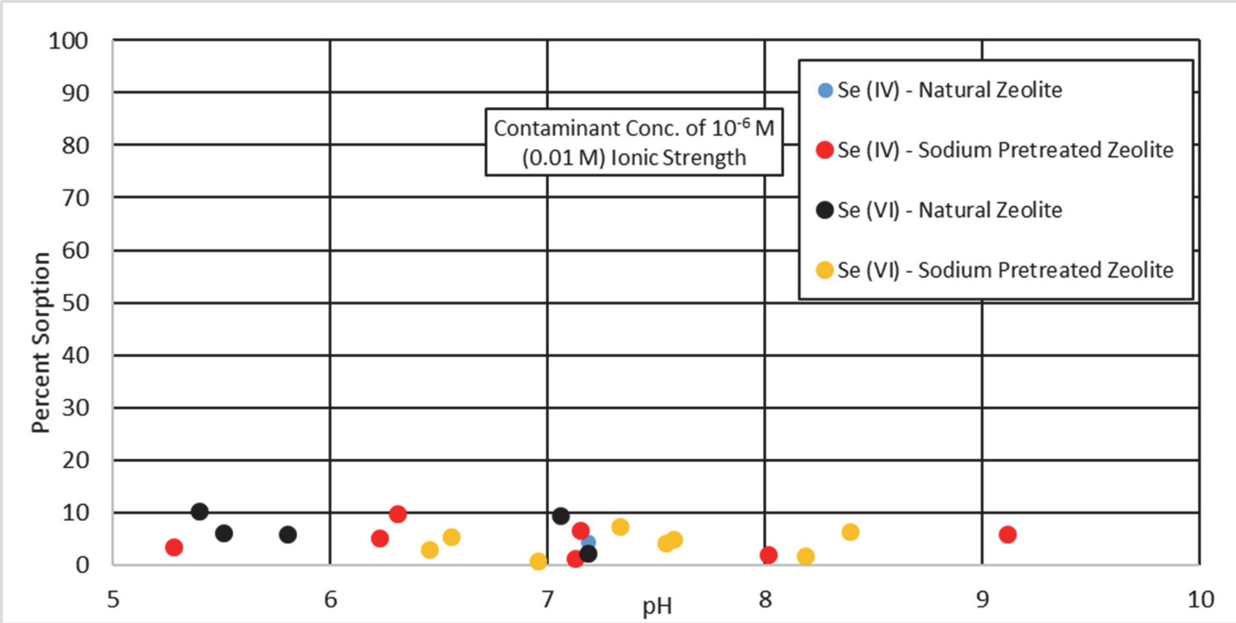


Figure 48. Selenium sorption as a function of non-iron-modified zeolite type and oxidation state.

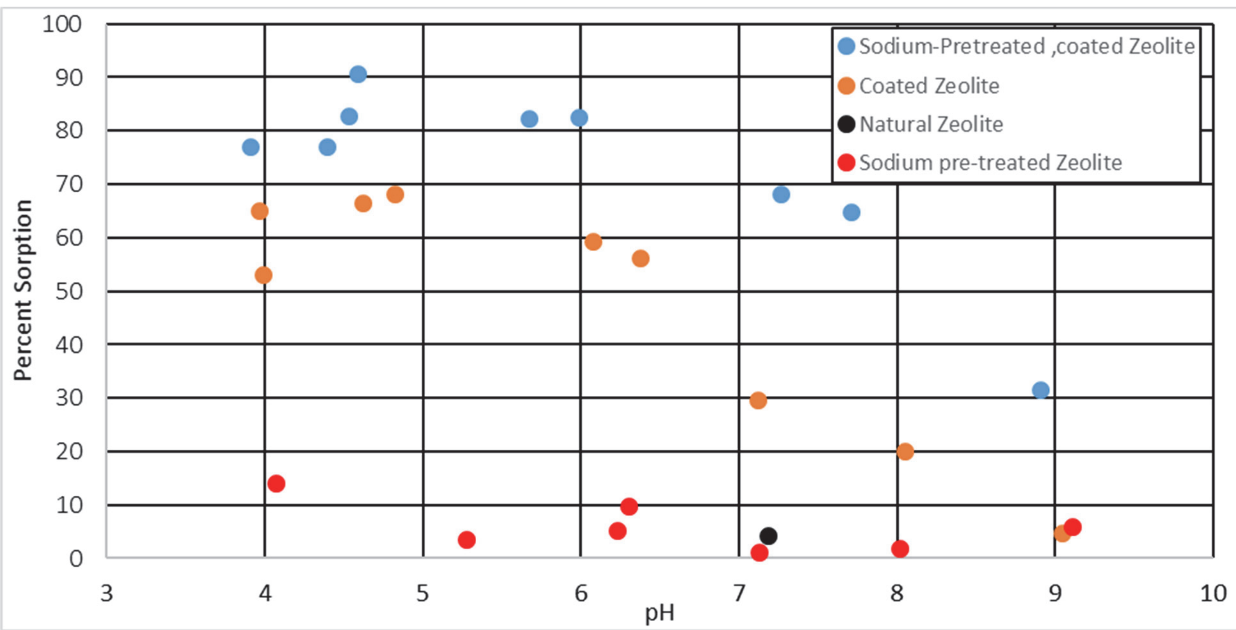


Figure 49. Selenite sorption as a function of zeolite type (total selenite $10^{-6}$ M; ionic strength 0.01 M sodium nitrate).

Given that SPIMZ had the greatest iron content, subsequent experiments were conducted using this sorbent primarily. The sorption of selenium on SPIMZ as a function of pH, oxidation state, and ionic strength is summarized in Figure 50. Several observations can be made by inspection of Figure 50. First, it is clear that selenite sorbs much stronger on SPIMZ compared to selenate. While maximum fractional uptake for selenite reaches approximately 80-90% at pH values 6 or below, fractional uptake of selenate barely reaches 30%, even at the lower ionic strength of 0.01 M. This finding is consistent with previous observations of others. The weak sorption of selenate compared to selenite is a major reason for the greater concern regarding selenate migration in groundwater, compared to selenite. This project is trying to address this challenge by exploring processes that would convert selenate to selenite, thereby helping to immobilize selenium.

Second, the sorption of selenite appears to be much more pH dependent compared to the sorption of selenate. Sorption that is pH dependent is consistent with sorption on amphoteric sites, such as those present on iron oxides. The sorption of selenate does not appear to be as pH dependent, possibly only because the maximum fractional uptake is much lower in the case of selenate.

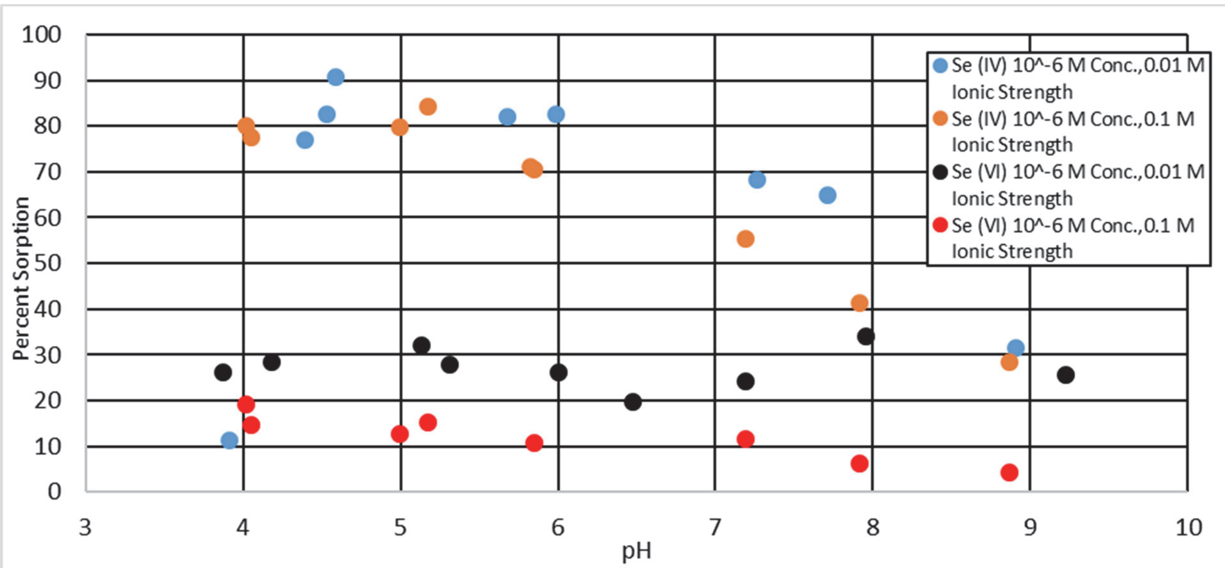


Figure 50. Selenium sorption on sodium-pretreated iron coated zeolite as a function of oxidation state and ionic strength (total selenium $10^{-6}$ M).

Finally, the sorption of selenate on SPIMZ appears to be significantly more ionic strength dependent compared to selenite. While there is hardly any difference in fractional uptake of selenite between 0.01 and 0.1 M ionic strength, especially at the lower pH and greatest fractional uptake conditions, the uptake of selenate by SPIMZ at 0.1 M ionic strength is approximately one half to one third of the uptake at 0.01 M ionic strength. This finding is also consistent with previous research and the hypothesis that selenate forms weaker, ion-pair, outer-sphere complexes on amphoteric oxide surfaces, whereas selenite forms stronger, coordination, inner-sphere complexes. In fact, ionic-strength-dependent sorption is often considered a strong indication for the formation of outer-sphere surface complexes and conversely ionic-strength-independent sorption is assumed to suggest formation of inner-sphere surface complexes. Another summary of selenium sorption on SPIMZ is presented in Figure 6, showing selenium sorption as a function of selenium oxidation state, selenium concentration, and ionic strength. As expected, increasing selenium concentration results in decreasing selenium fractional uptake, although the total amount of selenium sorbed probably increases.

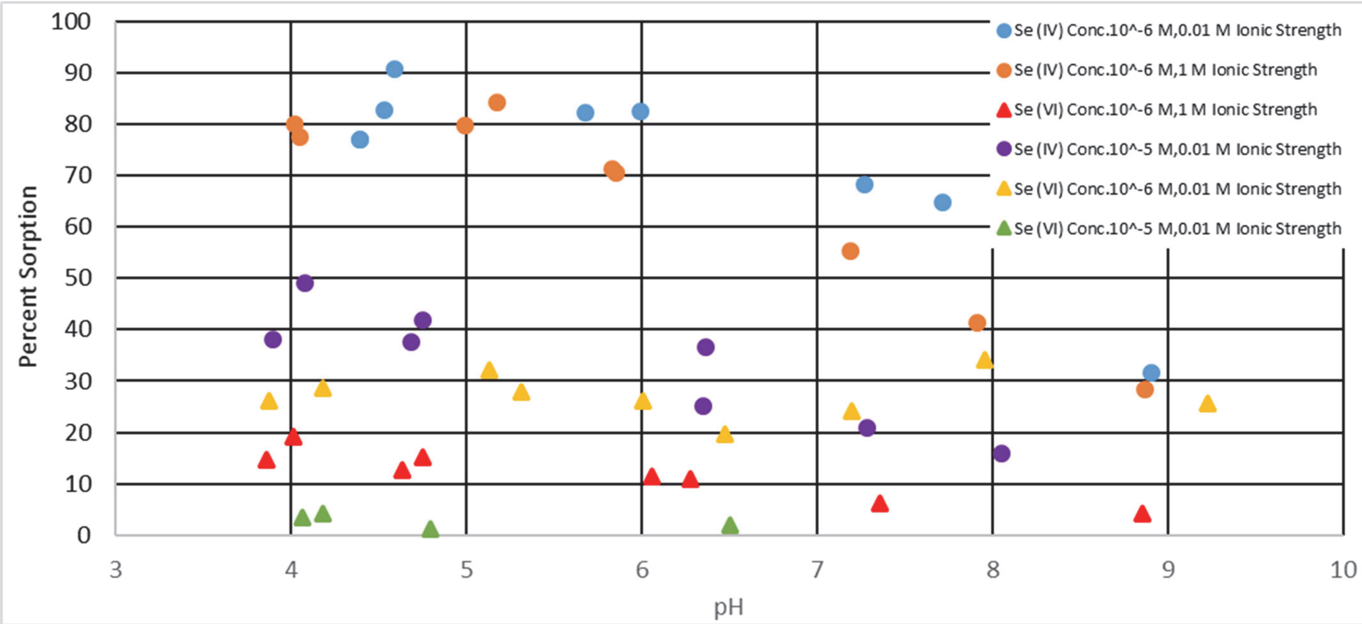


Figure 51. Selenium sorption on sodium-pretreated, iron-coated zeolite as a function of selenium concentration, oxidation state, and ionic strength.

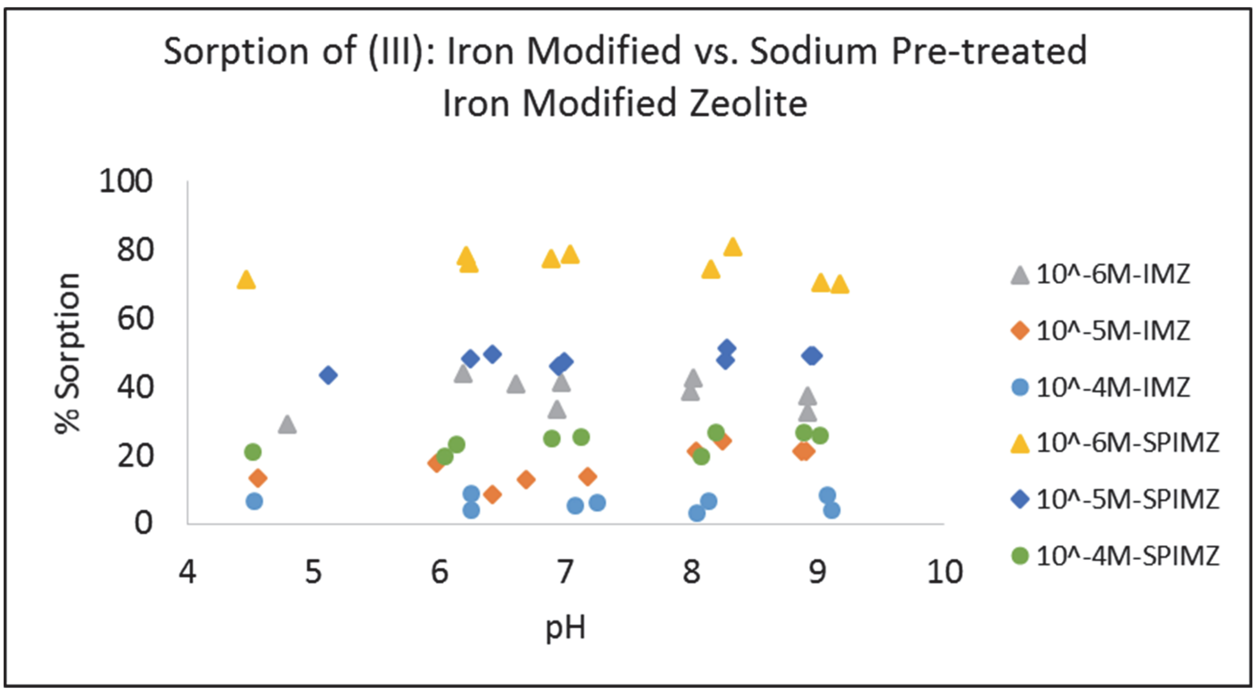


Figure 52. Sorption of As(III) onto iron modified zeolite and sodium pre-treated iron modified zeolite as a function of pH and metal concentration (Ionic strength = 0.01 M sodium nitrate).

Sorption of arsenic on iron modified zeolites is shown in Figures 52 and 53. Given that sorption of arsenic on non-iron-coated zeolites was negligible, only sorption of arsenic on IMZ and SPIMZ is shown here. The sorption of arsenite, As(III), as a function of sorbent, IMZ or SPIMZ, arsenite concentration, and pH, in 0.01 M sodium nitrate is shown in Figure 52. In all cases, arsenite fractional uptake on SPIMZ is greater than on IMZ, consistent with the results reported for selenium sorption and the greater iron content of SPIMZ compared to IMZ. In addition, the fractional arsenite uptake decreases with increasing arsenite concentration, although the total amount of arsenite sorbed increases. Finally, and more importantly, arsenite sorption appears to be largely independent of pH. The latter observation is commonly attributed to the fact that within the pH range of interest the arsenite species is not charged and therefore sorption is less dependent on the effect of pH on the surface charge of the sorbent.

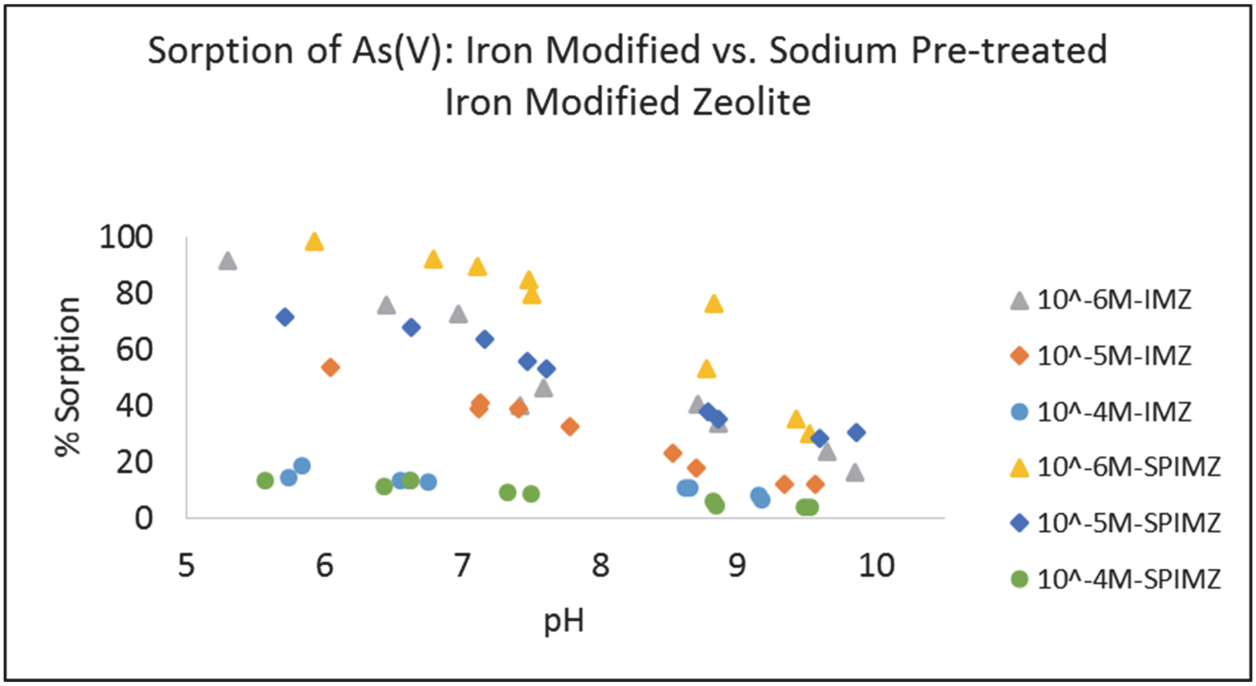


Figure 53. Sorption of As(V) onto iron modified zeolite and sodium pre-treated iron modified zeolite as a function of pH and metal concentration (Ionic strength = 0.01 M sodium nitrate).

The sorption of arsenate, As(V), on IMZ and SPIMZ as a function of pH and arsenate concentration in 0.01 M sodium nitrate is shown in Figure 53. As expected, in all cases, arsenate sorption was greater on SPIMZ compared to IMZ, for the reason previously noted. Again, fractional uptake decreased with increasing arsenate concentration. Unlike arsenite, however, arsenate uptake is a much stronger function of pH. Unlike arsenite, both arsenate species predominant in the pH range of interest are charged and therefore the interactions of these species with a charged surface are expected to be pH dependent given that the surface charge is also pH dependent.

Following the completion of the batch sorption experiments, column experiments have been initiated to assess the sorption capacity of the iron modified zeolites for arsenic and selenium as a function of geochemical and flow conditions in order to obtain a more realistic assessment of the performance of a permeable reactive barrier in the field. These column experiments will be used subsequently in combination with microbial cultures to tailor arsenic and selenium speciation as needed.

**Summary of other relevant work being conducted within and outside of the ERC and how this project is different**

This project is different compared to other similar work conducted outside CBBG in that it is focusing on two metalloids of concern, arsenic and selenium, through a thorough parametric study involving a complete set of parameters, including zeolite treatment and pretreatment, metalloid concentration, ionic strength, and oxidation state. In addition, the effect of microbial activity on metalloid sorption is being investigated. Finally, incorporating the ability of microorganisms to modify metalloid oxidation state, thereby maximizing metalloid retention on sorption media without the use of harsh oxidants or reductants, is an obvious environmental benefit.

**Plans for the next year**

Plans on this project for next year include completion of column experiments with arsenic and selenium using iron-coated zeolites, as well as modeling of arsenic and selenium transport through the column under different conditions. In addition, column experiments using microorganisms will be initiated. Of particular interest is the ability of microorganisms to alter the oxidation state of metalloids, thereby altering the affinity of the metalloids of concern for the iron-modified zeolite surface.

**Expected milestones and deliverables for the project**

It is anticipated that demonstration of the effectiveness of this technology at a field site will take place by the end of Year 4, and by the end of Year 5 the technology will be available for deployment at appropriate sites, such as mining or metalloid-contaminated sites.

**Member company benefits**

A microbially enhanced permeable reactive barrier based on iron-modified zeolites would be of importance and interest for many companies that must deal with potential pollution of ecosystems from metalloids such as arsenic and selenium. Enhanced techniques for the remediation of contaminated sites or prevention of spreading of groundwater pollution are likely to be of interest to both environmental consulting companies, as well as companies concerned with the impact of their activities on the environment. Mining operations, in particular, would benefit directly from such improved remediation and pollution prevention technologies. It is anticipated that the proposed technology will become a cost-effective and environmentally friendly method for the treatment of aquifers contaminated with challenging contaminants, such as selenate.

**If relevant, commercialization impacts or course implementation information**

Information on these processes and their potential benefits on environmental remediation and restoration will be incorporated in graduate classes on environmental remediation at New Mexico State University or any other of the sister institutions.

## 2.3 Thrust 3: Infrastructure Construction

### 2.3.1 Thrust 3: Biofilm Enabled Permeability Reduction in Sands

**ERC Team Members**

*CBBG Faculty*
Rebecca Parales, UC Davis
Douglas Nelson, UC Davis
Jason DeJong, UC Davis

*Graduate Students*
Jordan Greer, UC Davis
Charles Graddy, UC Davis

*Collaborators*
Mary Roth, Faculty, Lafayette College
Laurie Caslake, Faculty, Lafayette College
Ziqi Chen, Undergraduate Student, Lafayette College
Vivian Chen, Undergraduate Student, Lafayette College
Rebecca Kandel, Undergraduate Student, UC Davis
Ruixing Wang, Visiting Professor, Southeast University (China)

**Project Goals**

The Year 2 project goals were to improve bio-film formation uniformity and demonstrate treatment potential in a bench scale 2-D model. Also, to learn the fundamentals behind biofilm formation and how it can be a reliable and repeatable form of seepage control.

**The Project's Role in Support of the Strategic Plan**

The project is involved in infrastructure construction with use cases as temporary low permeability barriers for reduced groundwater pumping in dewatering efforts during short term excavation work and localized seepage reduction of high flow zones through dams/levees/walls through localized upstream treatment. It also pertains to Environmental Remediation and Protection as temporary low permeability barriers for mediation of flow regimes during environmental remediation.

Biofilm formation is a natural biologically-mediated process that is sometimes considered problematic. Here we are using it in a positive way to decrease the permeability of soils. This project utilizes bio-stimulation, to stimulate the growth of bacteria already present in the soil, although bio-augmentation will also be considered. This technology has the potential to contribute to resilience and sustainability as it would replace the use of carbon footprint intensive materials. In addition, this technology would allow the subsurface environment to return to its natural condition instead of being permanently altered.

**Fundamental Research, Education, or Technology Advancement Barriers**

The primary fundamental research barrier is in understanding, and then controlling, the spatial distribution of biofilm formation as well as the repeatability and resilience of biofilm formation. The spatial distribution of bacteria, oxygen, and nutrients during bacterial stimulation and during biofilm formation must be better understood for upscaling of the technology to be possible. These studies will provide a fundamental base of knowledge against which the potential use and effectiveness of quorum sensing inhibitors can be evaluated.  Collectively, this will result in the knowledge and ability to control the first order factors that dictate the spatial distribution of biofilm formation, and hence permeability reduction.  Many other factors have been identified, explained in the section ‘Achievements in the past year’.

**Any research aspect that involves foreign collaborations, especially indicating the length of time US faculty or students spent abroad conducting their work, and vice versa, and the value added of that work to the student’s/faculty’ work.**

Dr. Ruixing Wang, a professor in Materials Science and Engineering at Southeast University in Nanjing, China visited UC Davis from September 1st 2016 to September 1st 2017. During his stay, he participated in lab work and meetings for the biofilm project.  He offered an interesting perspective during the planning of the experiment as he drew connections from the research he performs at Southeast University.  Dr. Wang works on a project that involves recycling steel slag into bricks, giving him a unique view on sustainability efforts in both the short term and long term stages of the biofilm project.

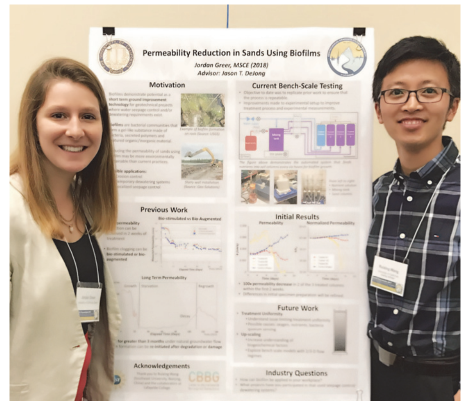

Figure 54. UC Davis graduate student Jordan Greer (left) and visiting professor Ruixing Wang at UC Davis Round Table Poster Presentation.

**Achievements in previous years**

The current biofilm project started in year 2 of the ERC (official start date of January 1, 2017).  Previous research was performed at UC Davis and Lafayette College.  Exploratory bench-scale work was performed and biofilm growth was shown to reduce the permeability of sand by 100-fold based on studies carried out by former graduate student Clayton Proto  at UCD.  Also, bio-stimulation was shown to work as well as bio-augmentation.  However, the previous research left unanswered many questions concerning the spatial variability and reproducibility of biofilm formation.

**Achievements in past year**

In the past year there have been many discoveries made through the three sets of column tests performed at UC Davis.  There have also been developments in the analysis of biofilm formation and the role of quorum sensing inhibitors. More details are included below.

*Column Test 1 & 2: Capability Development*

In the first two column tests, the goals were to replicate the results of prior biofilm work. An experimental set-up was created in the lab that was automated and programmable to allow the maximum number of test treatments (Figure 55).  The columns were bottom fed and the graduated cylinders were set-up to be used as falling head permeameters.  A concentrated stock of nutrients was connected to the system, and diluted with water before being pumped into the columns.

The results of the first two column tests are shown in Figures 56 and 57.  Figure 56 shows the reduction in permeability of four columns compared to a control column that was fed only water.

The columns were treated four times a day with a solution containing 0.1 g/L yeast extract, 0.05 g/L casein peptone and 0.5 g/L glucose as opposed to twelve times with one-fifth the amount of glucose (in Proto's work) and the reduction in permeability took about three times longer to occur. The permeability decreased to approximately the same value as in the study by Proto, but the initial permeability was lower, primarily due to differences in the porosity of the sand used. In test 1, tap water was used in the system, which was found to contain chlorine that could have been toxic to the bacteria. In the second test do-ionized water was used instead of tap water and the permeability decreased as seen in Figure 57.

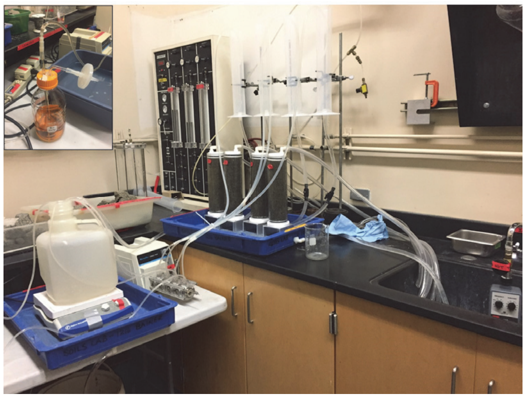

Figure 55. Biofilm Column Test Set-up with automated feeding

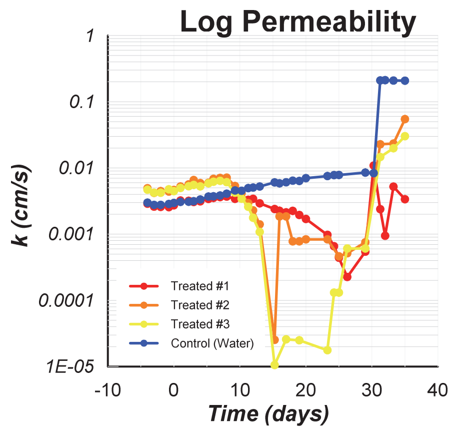


Figure 56. Column Test 1 Results

An issue that arose was the apparent clogging in the permeameter system. After treatment began, bacteria started forming biofilm in the tubing that delivers the nutrients to the columns. This was problematic as it was unknown how much biofilm formation occurred in the tubing versus the columns and whether movement of preformed biofilm from the tubing could have affected the permeability results. When dissecting the columns, a bacterial seal at the air-water interface at the top of the column was found that had burst through; this could have contributed to the sudden jump in permeability in test 1 at Day 16 (Figure 56). In the second column test, the tubing was changed on Day 14, and as seen in Figure 57, this resulted in a small increase in permeability. However, the permeability remained lower than at the start of the study, leading to the conclusion that there indeed was clogging occurring in the soil. The overarching question of the spatial variability of the biofilm formation throughout the columns was highlighted by the observation of a large buildup of biofilm on the inlet porous stone at the inlet after dissecting the columns.

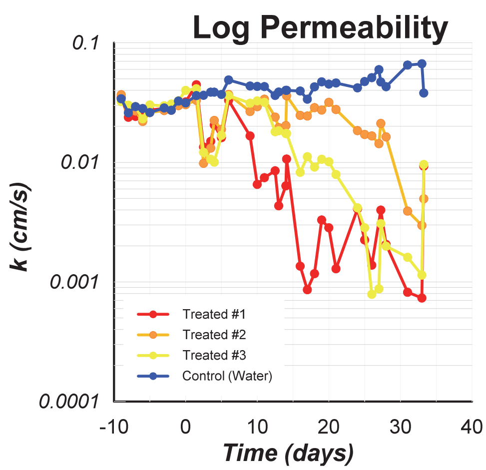


Figure 57. Column Test 2 Results

*Column Test 3: Quorum Sensing Iteration*

In certain bacteria, biofilm formation is under quorum sensing control. Quorum sensing is a process by which bacteria communicate with each other and work as a group, typically by coordinating gene expression. The process involves production and accumulation of small signaling chemicals called autoinducers. When these acylhomoserine lactone (AHSL) signals build up to a critical concentration, large sets of genes, including genes for biofilm formation, are turned on. It was hypothesized that by initially adding quorum sensing inhibitor to the columns, the bacteria will be unable to communicate with each other and will grow more evenly throughout the column. Once the quorum sensing inhibitor feeding is stopped, the bacteria will form a spatially uniform biofilm throughout the column. Column test three was therefore set up to examine permeability reduction when quorum-sensing inhibitors were added. The quorum sensing inhibitor that was chosen was Furanone 56. This chemical is known to target certain bacteria, including *Pseudomonas aeruginosa*; an additional type of quorum sensing inhibitor was investigated by the microbiology lab (see more details below).

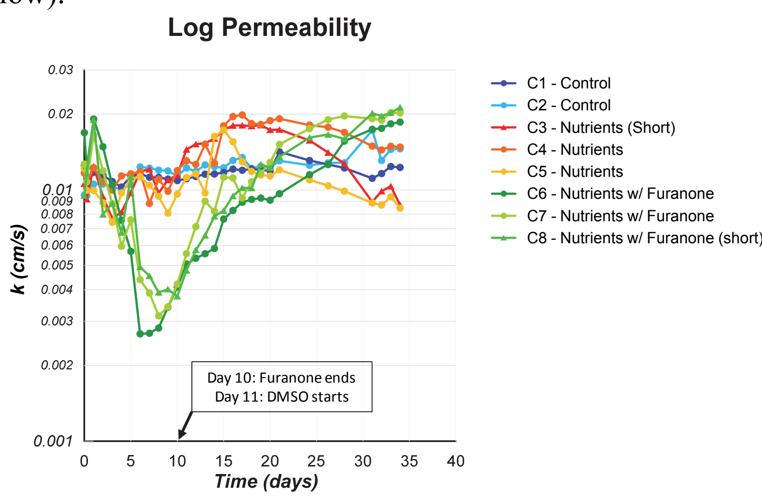


Figure 58. Column Test 3 Results

Figure 58 shows the results of the third column test, which consisted of 8 columns total, with two replicates of each treatment. The sand used for column test 3 was collected more recently than that used in tests 1 & 2. In addition, in an attempt to shorten the lag time before permeability reduction began, the sand was seeded with soil from column 1 (5% of total mass) in the second column test. The legend to Figure 58 describes the treatments for each column. In contrast to column tests 1 and 2, in which columns were completely filled with sand and fed from the bottom, these columns were fed from the top and the porous stone was replaced with a layer of gravel and liquid at the top. This was done in an effort to prevent clogging at the inlet. Surprisingly, the columns that received the quorum sensing inhibitor showed decreased permeability almost immediately, in contrast to the other columns. In addition, when the furanone was stopped on day 10, the columns returned to their initial permeability values. The furanone was dissolved in DMSO, so to eliminate the possibility that DMSO was causing the permeability reduction, possibly by acting as an alternative electron acceptor for anaerobic respiration, we began adding an equivalent amount of DMSO to columns C4 and C7 on Day 11. The results of this test are still being analyzed, but it appears that DMSO did not have any effect on permeability reduction. The columns are currently continuing to run and we plan to carry out additional controls (ie., re-feed furanone-56) to try to understand these results.

Two of the columns in test 3, C3 and C8, are shorter columns with piezometers built in to measure head loss throughout the column (Figure 59). Knowing the head loss in certain areas throughout the column gives insight to the spatial variability of the biofilm formation. The initial piezometer readings showed that most of the head loss occurred in the bottom section of the columns rather than evenly throughout the columns, even in the first feedings. Figure 59 shows a graph of the different permeabilities occurring in C3, computed from head loss, throughout the column. It is hypothesized that the fines migrating in the column are effecting the head loss distribution. This will be further studied, as it is currently unknown how fines effect where biofilm formation occurs.

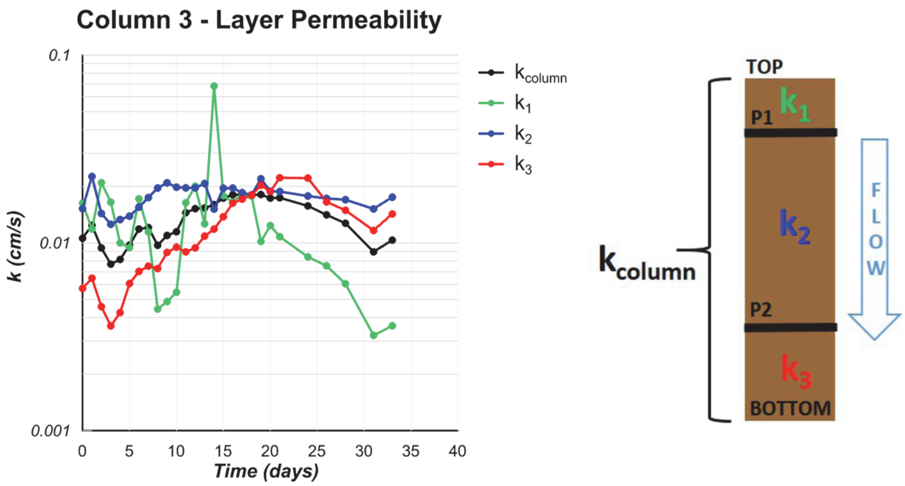


Figure 59. Sketch of and data collected from a column fitted with piezometers (P1, P2) for monitoring head loss throughout the column in column test 3.

*Analysis of biofilm formation and the role of quorum sensing inhibitors*

In order to understand the function of biofilm inhibitors in our column studies, we wanted to be able to quantify biofilm formation in the presence and absence of different quorum sensing inhibitors. We chose furanone 56 (CAS-Number: 199744-38-2; $C_5H_3BrO_2$ from Adipogen), which is known to inhibit biofilm formation by *Pseudomonas aeruginosa* PAO1, and was proposed to be used by the Lafayette group in column studies. Furanones are thought to target the LuxR receptor proteins, most likely by preventing binding of the autoinducer molecules (acylhomoserine lactones; AHSLs) that build up in high-density bacterial cultures. We also obtained from Amy Schaefer at the University of Washington an *E. coli* expression clone that can be used to purify the *B. thuriengensis* AHSL lactonase enzyme AiiA, which cleaves lactone rings of a wide variety of AHSLs and thus is capable of inhibiting quorum sensing and biofilm formation by a different mechanism. Lafayette undergraduate Vivian Chen and UCD graduate student Charles Graddy grew up several liters of *E. coli* carrying the cloned lactonse gene and purified three batches of lactonase. After testing activity of the lactonase, it was determined that the amount of purified protein needed to run bench-scale column studies was prohibitive in the short amount of time available to the summer students, so the lactonase was used in small scale microtiter plate tests.

A microtiter plate test was developed to monitor biofilm formation and examine the ability of furanone 56 and AiiA to inhibit biofilm formation by the model organism *Pseudomonas aeruginosa* PAO1 using the method of O'Toole (2011). Under the conditions used, with the same medium that was being used to feed the columns, a clear reduction in PAO1 biofilm formation was observed with furanone-56, but not with lactonase for reasons that are not yet understood. Ultimately, we plan to use this assay to monitor the presence of biofilm forming organisms in the columns by taking samples over time from different locations in the columns to monitor the distribution of biofilm forming cells and determine whether early treatment of the columns with quorum sensing inhibitor results in more uniform biofilm distribution.

**Summary of other relevant work being conducted within and outside of the ERC and how this project is different**

Inside the ERC there is formal linkage but no overlap with the following projects:

- Electrokinetic Sub-surface Transport for Soil Remediation and Mineral Precipitation – Torres/ASU
- Microbially Enhanced Iron-modified Zeolite Permeable Reactive Barrier – Papelis/NMSU
- Microbial Ecology of Stimulated Ureolytic Biocementation – Nelson/UCD

Outside of the ERC we have been actively collaborating with researchers Mary Roth (Professor of Civil and Environmental Engineering), and Laurie Caslake (Professor of Biology) at Lafayette College, an Undergraduate Research College. Professors Roth and Caslake have been awarded a NSF grant ("RUI: Reducing Permeability in Sands Using Biofilm-Forming Bacteria and Quorum Sensing Inhibitors to Create Uniform Growth") to engage undergraduate students in geotechnical research. Our groups have participated in joint monthly webinars since January 2017 and have exchanged many emails back and forth. The experiments at both colleges are complementary, and the discoveries made at each site have benefitted both groups. In Summer 2017 two undergraduates from Lafayette college spent 7 weeks carrying out research at UC Davis. Ziqi Chen (pictured in Figure 60) is a rising senior in Civil Engineering who worked with Jordan Greer on the design, performance and data analysis of bench-scale column experiments. Vivian Chen is a rising senior studying microbiology, who has been working with Professor Caslake since January 2017. This summer she worked with graduate student Charles Graddy in the microbiology laboratory. Both undergraduate students are currently in the process of applying to graduate school.

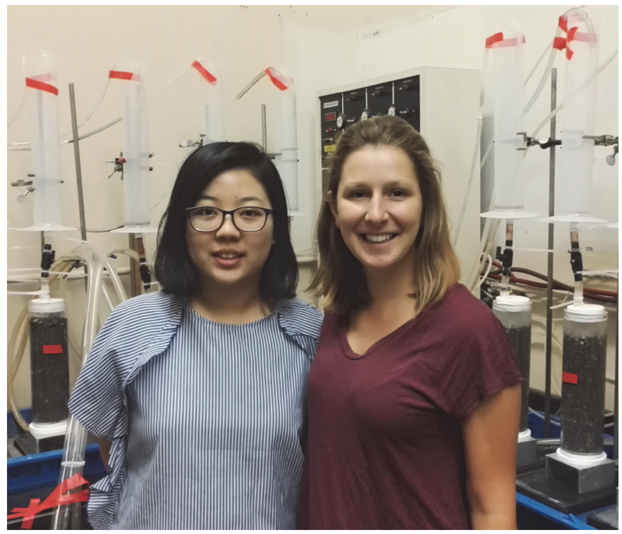

Figure 60. Lafayette REU student Ziqi Chen (left) and UC Davis graduate student Jordan Greer (right) in UC Davis lab

**Plans for the next year**

There have been many unanticipated challenges in creating an effective biofilm to influence permeability reduction due to the amount of pore volume that requires the amount of EPS produced to be substantial. The plans for next year are based on discoveries at UC Davis and Lafayette in the past year. Using information from the first three column tests performed at Davis, the team is considering the many variables that influence biofilm formation for permeability reduction. One important aspect we are going to look into is how the type of soil influences biofilm formation.

The type of soil affects biofilm formation due to the size and gradation of particles (which collectively affect the pore space structure) as well as existing bacteria present. Additional column tests will be carried out to establish the effects of bottom vs. top feeding, as well as different tubing configurations to reduce unwanted clogging.

Small scale growth tests (both aerobic and anaerobic) will be carried out to optimize the nutrient solution. One hypothesis is that with the current nutrient mixture, phosphate may be limiting in the columns, and addition of phosphate will stimulate growth and biofilm formation. We assume that aerobic respiration is occurring near the inlet of the columns and fermentation deeper into the column where oxygen is depleted. We plan to examine the inclusion of alternative electron acceptors, such as nitrate, in the nutrient solution, as anaerobic respiration is much more efficient than fermentation and should result in faster growth of bacteria. The use of quorum sensing inhibitors will be further investigated to determine their effectiveness in developing uniform biofilm throughout the column.

There will also be continued collaboration with Lafayette, including biweekly meetings and continuous email exchange. Two undergraduate students from Lafayette will again spend the summer carrying out research at UC Davis.

**Expected milestones and deliverables for the project**

- Advancements in biofilm quantification and small scale assays in biology lab through use of quorum sensing inhibitors and fluorescence microscopy.
- Develop a protocol for biofilm quantification, including sampling and analysis process.
- Develop a protocol for measuring the uniformity of biofilm formation using piezometers and sampling techniques
- Demonstrate effectiveness of permeability reduction using biofilms across a range of soil types
- Expand research to include physical seepage model (e.g. sheet pile model) to explore additional complexities in treatment method and effectiveness in 2-D space
- Identify and bring in industry partner to review and comment as technology moves towards 2-D model testing

**Member company benefits**

The biofilm project currently has no official industry partners as it is in the first year and working primarily in the fundamental technology plane. However, in the coming year it will be beneficial to bring in industry partners as we try to begin upscaling of the technology. For industry member companies participation would provide an opportunity to become engaged in a new, sustainable technology for groundwater flow reduction and/or modification that could be useful for dewatering, seepage control, and groundwater remediation technologies.

**If relevant, commercialization impacts or course implementation information**

Biofilm enabled permeability reduction has the potential to be a more cost-effective, sustainable, and possibly reversible technology compared to the chemical or cement based technologies currently in use today.

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Shrout, J. D., Chopp, D. L., Just, C. L., Hentzer, M., Givskov, M., & Parsek, M. R. (2006). The impact of quorum sensing and swarming motility on *Pseudomonas aeruginosa* biofilm formation is nutritionally conditional. Molecular Microbiology, 62: 1264-1277.

### 2.3.2 Thrust 3: Bio-inspiration for Resilient Earthen Construction

**ERC Team Members**

*CBBG Faculty*
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Brad D. Weldon, NMSU

*Graduate Students*
Tsegaye Gebremariam (MSCE, May 2017)
Eduardo Davila (GA from January 2017)
Diego I. Garcia-Vera
Peter Zelkowski

*Undergraduate Students*
Lorenzo Martinez (BSCE, May 2016)
Eduardo Davila (BSCE, December 2016)
Oscar Gallegos (former SCCORE/REU)
Judit Garcia
Cori Cromwell

**Project Goals**

The main goal of this project is to develop and propose enhancements to the traditional adobe construction, inspired in biological processes and materials, to increase its resilience against weather and natural hazards while preserving its inherent sustainable, economic, and accessible aspects.

This research seeks inspiration and materials in nature to create sustainable, low-cost and easy-to-do methods of making adobe bricks and masonry that perform better than those made with the traditional adobe techniques when subject to moisture and/or lateral loading. A key aspect of this project is using solely natural materials. The research targets new construction as well as rehabilitation or retrofitting of existing mud-brick masonry (regionally called adobe).

**The Project's Role in Support of the Strategic Plan**

This research on resilient, sustainable earthen construction addresses primarily the Use Cases "Alternatives to Portland Cement" and "Infrastructure Construction Methods and Materials," which are two of the priorities of the Infrastructure Construction thrust. For over two thousand years, humans have used soil to create their shelters and other utilitarian structures. Today, about one third of the world population lives in some form of earthen dwelling, made of rammed earth or mud-brick masonry, and many are in regions affected by earthquakes.

Mud-brick masonry is made of sun-dried mud blocks (or adobe bricks) and mud mortar. Many traditional adobe buildings and historic landmarks as well as modern adobe structures are found in the southwestern United States, where the drier or semiarid climate lends well to this type of natural, economical, and sustainable construction method. Unfortunately, adobe is very susceptible to moisture penetration and weakening from groundwater, runoff water, and rain. Unreinforced adobe structures have also been severely damaged or collapsed during earthquakes (1994 Northridge earthquake, USA; 2003 Bam earthquake, Iran; 2007 Peru earthquake; 2011 Van earthquake, Turkey; 2011 Christchurch earthquake, New Zealand) with significant loss of life, even in regions of medium seismicity risk.

Because regions with widespread earthen construction are in underdeveloped and developing countries, this building method and material are often perceived as substandard. Nevertheless, in the last decade there has been an increasing interest in using earth as an engineered material for construction; new research on design and performance of earthen construction is underway by multidisciplinary teams in Europe, Asia, the U.S., and South America. Some of the attractive aspects of earthen construction is its sustainability (i.e., relatively low energy and water use in manufacturing, local materials, local labor, very small or no waste at the end of the structure's life cycle) and the indoor thermal stability of earthen buildings. Mud bricks and mortar are made of soil and remain soil (i.e., behave as soil) during service.

**Fundamental Research, Education, or Technology Advancement Barriers**

- Most research on earthen building materials has assumed a dry condition; however, adobe exists in unsaturated conditions and is affected by seasonal cycles of moisture variation. Modeling long-term effects of water and weathering in adobe is a complex problem.
- The construction of field-scale structural adobe systems to test the new methods and materials is time-consuming and labor intensive.
- Adobe construction is mostly based on experience. Adobe brick sizes and masonry construction practices also have regional variability. The strength and other requirements set in building codes for this type of construction are mostly based on local practices.
- Solutions and methods developed by this project should preserve the accessible, low-cost features and the simplicity of the traditional adobe masonry.

**Any research aspect that involves foreign collaborations, especially indicating the length of time US faculty or students spent abroad conducting their work, and vice versa, and the value added of that work to the student's/faculty' work.**

Dr. Umaima Al Aqtash (Assistant Professor, Department of Architectural Engineering, Hashemite University, Jordan) has joined this CBBG research team as an international collaborator and leads the numerical modeling component. She brings to the team her expertise on numerical modeling of adobe materials. Drs. Bandini and Weldon have collaborated and published with Dr. Al Aqtash since 2013. Meetings (via videoconference) with Dr. Al Aqtash are held regularly. Dr. Al Aqtash will travel to NMSU to work with the CBBG faculty and students in summer 2018.

**Achievements in previous year (Year 1)**

During Year 1, baseline material data were collected and analyzed on the strength characteristics of adobe bricks (two sizes), prism, and beams. The specimens were composed of soil and cut straw as in the traditional adobe. The parameters investigated in Year 1 were water content at mixing ($w_m$) and water content at breaking ($w_b$). The results confirmed the important influence of the water content of the soil used to compact and mold the mud bricks because it determines the soil fabric and density of the bricks (Figure 61a). The water content at breaking (i.e., at testing) was also found to be very important for both compressive and tensile strengths (Figure 61b). These findings can be useful to practitioners as well as those who develop building codes for earthen construction.

In addition, the results of six quarter-scale walls were analyzed. Two walls had an adobe footing; two walls had a concrete footing; and two walls had a concrete footing with dowels. For each foundation type, one wall was tested air-dry and another was tested with a wet region along the base (height: 20 cm = 8 inches) with water content of about 6-7% (by mass). Results from this work were included in a 2017 conference paper and a Master's thesis.

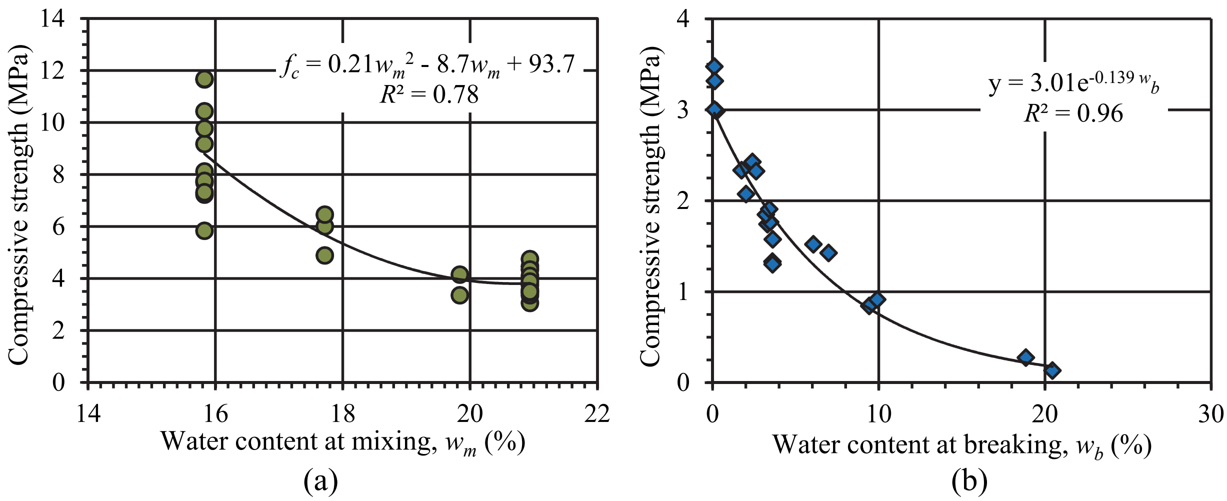



Figure 61. Compressive strength of (a) quarter-scale bricks, (b) half-scale prisms with $w_m$ = 26%.

**Achievements in past year (Year 2)**

**Fiber-reinforced soil – Material behavior**

The emphasis of the fiber-reinforced soil experiments was on improving the mechanical properties, particularly the compressive and tensile strengths, and evaluating the effects of $w_m$ and $w_b$. The testing of adobe beams containing 0.38% straw was completed (Figures 62 and 63a). It is evident the importance of water content on the material (soil) behavior. Preliminary testing with other natural fibers (palm leaf, sisal fibers) was done to select the most promising fibers. DIC technique was applied to select specimens (Figure 63b) with and without reinforcement.

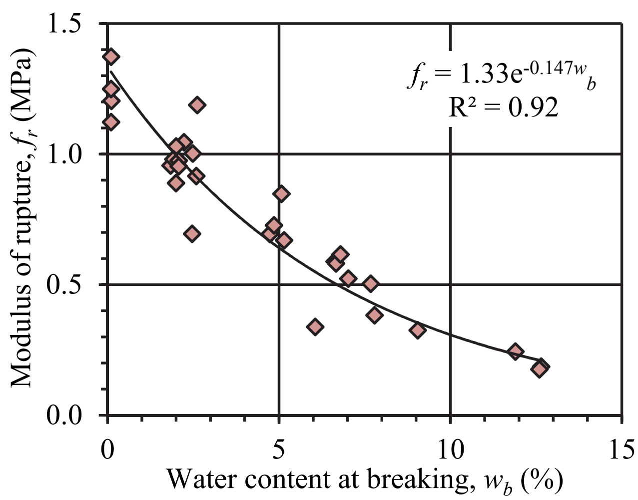
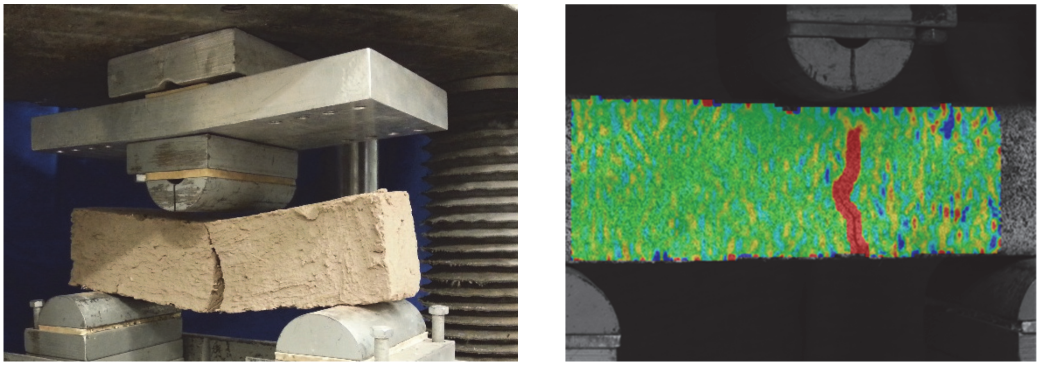



Figure 62. Modulus of rupture on adobe beams (with straw) with $w_m$ = 28%.

**Bench-scale and quarter-scale adobe walls – Soil behavior in a system**

To complement the fiber-reinforced soil study, the project included lateral load tests on model walls to evaluate the material (soil) behavior when it is part of a system (i.e., a mud-brick wall). Traditional adobe masonry is composed of sun-dried mud bricks, laid in courses with mud mortar. Therefore, ***adobe is soil and behaves like soil during its service life***.



(a) (b)

Figure 63. Modulus of rupture test on adobe beams: (a) failed specimen, and (b) DIC data at the onset of tensile failure.

Two series of adobe wall tests were carried out in the laboratory. The first series consisted of six bench-scale adobe walls (fall 2016 and early spring 2017). Two were tested air-dry without reinforcement; two were tested in wet condition (approximately 6-8% water content, by mass) without reinforcement; and two had natural fiber reinforcement throughout the adobe footing and wall (one dry and one wet). The bench-scale walls were seismically loaded in a shake table (in-plane loading). Seismic records of major earthquakes and a sinusoidal sweep were applied to failure, and the behavior was recorded. DIC data was recorded in all these tests to assist in identifying behavior patterns during loading and visualize the failure mechanisms for the cases with and without reinforcement, in dry and wet conditions (Figure 64). Note that there are scale effects in the bench-scale models, but useful information for better design was provided for the next series of larger test specimens.

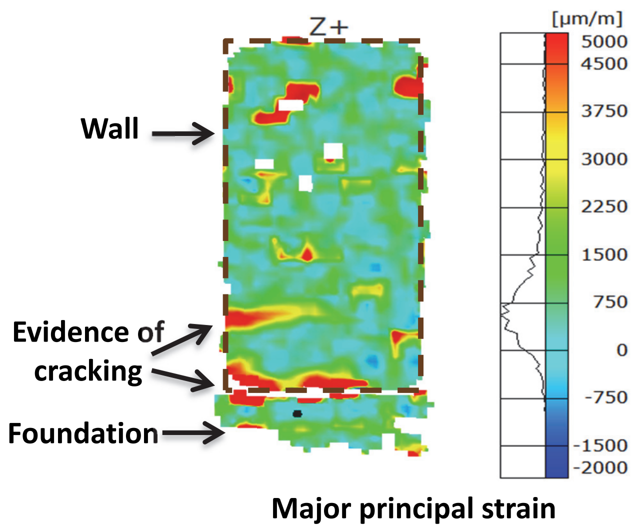
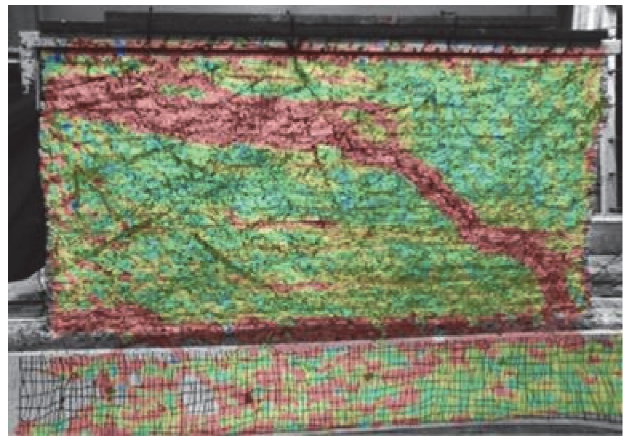



Figure 64. Principal-strain distribution in a bench-scale adobe wall model at the onset of collapse from DIC data.

The second series of tests consisted of six quarter-scale adobe walls (spring and summer 2017) instrumented with five string potentiometers (cable-extension transducers) and five linear variable displacement transducers (LVDT) to determine in-plane and out-of-plane wall deformations (Figure 65a) during loading. These models had a different (more realistic) aspect ratio (height: 0.76 m = 2.5 ft; length: 1.52 m = 5 ft) than the prior quarter-scale walls of Year 1. Three were tested air-dry and two were tested with a wet region along the base. For each of these conditions, two walls had fiber reinforcement and one did not. All models had an adobe brick footing. Five walls were studied with DIC during lateral (in-plane) loading to failure (Figure 65b). The goal of these tests was to study the effects of reinforcement and the wet region on the wall behavior, load capacity, and failure mechanism. The data interpretation from these tests and the paper preparation will be completed in Year 3.

(a)



(b)

Figure 65. Lateral loading test of quarter-scale wall: (a) side view of the model, and (b) strain distribution from DIC (highest strains in red) superimposed on the wall photograph. In-plane loading was applied on the top left corner, from left to right.

**Historic building instrumentation**

The project includes moisture and temperature monitoring in walls of a historic adobe building located near NMSU campus (Subject to formalizing memorandum of understanding with the City of Las Cruces to allow the installation and long-term monitoring of sensors). The building is a two-story adobe structure currently being rehabilitated and restored to its original condition (Figure 66a). The sensors will be installed and used to collect data of the structure during its life-cycle to examine the effect of moisture ingress and temperature fluctuations. This information will provide a better understanding of the detrimental conditions that are encountered in-situ so that researchers can recommend better techniques to mitigate their effects. Furthermore, the data collected will be used to develop realistic conditions for modeling and laboratory testing.

In preparation for the site instrumentation, four moisture sensors were installed in two prisms composed of four full-size mud bricks, each over a soil foundation (this simulates the foundation of the historic building). One prism has mud plaster and the other has lime plaster (Figure 66b). They are located outdoors and exposed to rain and direct sunlight. Two sensors are 12 cm long and the other two are 30 cm long. This exercise served to practice and troubleshoot the sensor installation, calibrate the sensors, and assist the students in becoming familiar with the datalogger, software, and data format before instrumenting the historic building.

**Products, collaborations, and personnel exchanges**

During the past year, the team initiated three research collaborations, one industry engagement, graduated one Masters student (with thesis), and prepared two papers:

(a) (b)

Figure 66. (a) Main hall of the historic Amador Hotel (circa 1866) to be instrumented with moisture sensors, and (b) moisture sensors installed in prisms for preparatory work.

- International collaboration with Dr. Umaima Al Aqtash (Hashemite University, Jordan) on numerical modeling (Please refer to earlier section on international collaboration for more details).
- Personnel exchange and collaboration with Dr. Michael McGinnis, Associate Professor in the Civil Engineering Department at University of Texas at Tyler, on material and structural nondestructive testing. Dr. McGinnis visited NMSU three times in 2016-2017 and worked on DIC testing of adobe specimens and small-scale models for this project.
- Potential industry partner: We reached out to Jake Barrow, Director of Cornerstones Community Partnerships (Santa Fe, New Mexico), about the opportunity to collaborate with our CBBG project. Cornerstones Community Partnerships is a well-established non-profit organization that supports communities to preserve their historic buildings. http://cstones.org/about/. Cornerstones has expressed interest in joining CBBG as an industry partner and provide access to expertise and field sites.
- Collaboration with Prof. Sonya Cooper, NMSU Regents' Professor and Associate Dean. Dr. Cooper is a nationally recognized expert in adobe materials and construction as well as in preservation and restoration methods. She has expertise in the geotechnical and structural aspects of earthen construction. She is advising this project in several technical aspects and serves as the connection with Cornerstones Community Partnerships and the Amador Foundation, which manages the restoration efforts of the historic Amador Hotel (http://amadorfoundation.org/).
- Thesis completed: Gebremariam, T. (2017). *Experimental Evaluation of the Effect of Moisture on Adobe Material Strength and Wall Behavior under Lateral Loads*. Master's Thesis, Department of Civil Engineering, New Mexico State University. Las Cruces, New Mexico.
- International Conference paper: Gebremariam, T., Weldon, B., and Bandini, P. "Experimental evaluation of two small-scale walls under lateral loading." *Proc. Earth USA 2017, Ninth International Conference on Architecture and Construction with Earthen Materials*, Santa Fe, New Mexico, September 30-October 1, 2017.
- Journal paper: Gebremariam, T., Bandini, P., and Weldon, B. Compressive and flexural strengths of adobe bricks and beams. Submitted August 2017.

**Other activities – Education and outreach impact**

a. The team has mentored and trained 5 undergraduate research students (2 females, 1 Native American, 3 Hispanic):

- Undergraduate research student at NMSU: Lorenzo Martinez (fall 2015 and spring 2016), participated in the New Mexico Alliance for Minority Participation (NM AMP) Program. Graduated in May 2016 and currently in an industry position.
- SCCORE REU Community College student Oscar Gallegos in summer 2017.
- Three undergraduate research students at NMSU: Judit Garcia and Cori Cromwell (spring and summer 2017), Eduardo Davila (fall 2016, currently graduate student).

b. In summers 2016 and 2017, the team delivered a two-day outreach activity with the theme of CBBG and this project for high school students interested in engineering careers. This outreach module is new for CBBG and is offered as part of the NM PREP High School Academy. Please refer to the last section of this report for more details.

**Plans for the next year (Year 3)**

Plans for next year include three research components, a partnership, and an external proposal. Each research component is led by a graduate student, but all students have multiple opportunities (and the responsibility) to contribute to all aspects of the project.

a. <u>Material study</u>: In Year 3, the research emphasis will be on studying material properties of fiber-reinforced adobe as an engineered material. The testing program will consider:

- Natural fiber reinforcement: straw, sisal, palm leaf, and jute fibers.
- Fiber content: 0, 0.34%, 0.68% (by dry mass).
- Compressive strength (bricks and prisms) and tensile strength (modulus of rupture test).
- DIC testing of adobe specimens during loading tests to assist in the evaluation of the effects of natural fibers (This is a collaboration with UT Tyler).
- Effects of water content at mixing and water content at breaking on fiber-soil strength.
- Size effects: quarter-, half- and full-scale bricks.
- Fabric of fiber-soil composite (density, microscope imaging) for different fibers.
- Spatial distribution of fibers in the soil mixtures.
- Properties of the natural fibers: tensile and shear strength tests, thickness and length measurements, water absorption and desorption tests, etc.
- Explore other potential geotechnical applications of fiber-soil mixtures and the results obtained in this testing program.

With the results of this testing program, a Master's thesis and several papers will be prepared.

b. <u>Completion of quarter-scale adobe wall testing</u>: two more model walls (height: 0.76 m = 2.5 ft; length: 1.52 m = 5 ft) will be constructed and tested to assess the effect of loading and boundary conditions in this experimental setup. This part includes numerical modeling (using finite element method) of the physical wall model tests (Collaboration with Hashemite University). In addition, the results of the lab-scale walls will be analyzed, and a Master's thesis and a paper will be prepared.

c. <u>Instrumentation of historic building</u>: Moisture and temperature sensors will be installed (fall 2017) inside the walls of the historic Amador Hotel building to obtain field data on moisture values and fluctuations (daily, seasonal) with respect to sensor location, ambient temperature, and humidity. These data will provide important information for design of experiments and numerical modeling. Note: We have initiated the discussions to formalize an agreement with the City of Las Cruces to ensure long-term access for monitoring. In addition, the results of the instrumentation program will be collected and analyzed, and one Master's thesis and a paper will be prepared.

d. Partnership: We will formalize the collaboration with Cornerstones Community Partnerships as a CBBG industry partner.
e. Proposal: The preparation of a proposal to an external agency is in progress. The purpose is to leverage funding and expand the research to other aspects not addressed in this CBBG project.

**Expected milestones and deliverables for the project (2015-2018)**

We anticipate reaching these project milestones at the end of Year 3:

- Testing program on lab-scale walls completed and data analyzed.
- Material testing on fiber-reinforced adobe and data analysis partially completed.
- Sensors installed in a historic building and data collection under way.
- Characterization of natural fibers completed.
- 2 journal papers submitted and 1 in preparation, 3 conference papers, 3 international conference presentations.
- Four Master's theses (in Civil Engineering) completed or in progress.
- An external proposal submitted.

**Member company benefits**

The team is working on recruiting industry members in the area of restoration and preservation of adobe structures as well as private/non-profit and government agencies that own and are responsible for the maintenance and preservation of historic adobe structures in the U.S. There is interest from Cornerstones Community Partnerships (non-profit) in joining as industry partner in Year 3. The team is interested in collaboration with these agencies and non-profits including instrumenting and monitoring adobe buildings with historic significance to obtain data (input data for analysis, model calibration), and eventually test the products resulting from the research.

**If relevant, commercialization impacts or course implementation information**

Curriculum "Bio-inspiration for Resilient Earthen Construction": In Years 1 and 2, Drs. Weldon and Bandini developed and delivered a 2-day STEM module to introduce high school students interested in engineering careers to the CBBG core principles of bio-inspired design, sustainability and infrastructure resiliency, as well as seismic loads and their effects on structures, and the importance of foundation engineering. This is a new activity and material developed for CBBG. In summers 2016 and 2017, this outreach module was part of the NM PREP High School Academy, which is a 2-week Pre-Freshman Engineering (PREP) summer residency program organized and hosted yearly by NMSU.

In this activity, students used their creativity and STEM knowledge to design and construct bench-scale adobe walls incorporating bio-inspired reinforcing elements using only natural materials and fibers, and test their wall models under dynamic loading in a shake table. At the end, each team presented and explained their design, results and recommendations to the faculty, student mentors and peers. The participants were high school students (44 in 2016 and 46 in 2017), mostly minority students from southern New Mexico schools.

### 2.3.3 Thrust 3: Bio-inspired Unsaturated Soil Improvement and Reinforcement: Mechanisms and Strategies

**ERC Team Members**

*CBBG Faculty*
Paola Bandini, NMSU
Craig M. Newtson, NMSU

*Graduate Students*
Seyed Ali Aleali
Jose N. Pasillas (MSCE, July 2017)
Jason Alcantar (GA from January 2017)

*Undergraduate Students*
Jason Alcantar (BSCE, December 2016)
Adam Sanchez (BSCE, May 2017)

**Project Goals**

The goal of this project is to develop cost-effective, sustainable bio-inspired soil improvement and foundation methods, particularly for unsaturated soils. The team is addressing this goal using the root analog through various approaches: i) soil improvement or strengthening below and/or around the pile foundation; ii) modification of the soil-pile interface; and iii) modification of the shape of the foundation itself. In years 1-2, the team has focused on the idea of integrating a root-inspired "vascular system" into a precast pile foundation for improving the soil around/below the pile to achieve greater pile capacity. In Year 3, the project will continue developing this concept and will study root-inspired mechanisms for modifying the soil-pile interface in unsaturated soil.

**The Project's Role in Support of the Strategic Plan**

Development of adaptive foundations inspired in root physiology is one of the goals of the Infrastructure Construction thrust and part of the bio-inspired portfolio of the Center. The primary Use Case addressed is "Infrastructure Construction Methods and Materials" and the secondary Use Case is "Ground Improvement for Infrastructure Construction."

This project exploits the concepts of improving the mechanical properties of the soil directly below and around piles, modifying the pile shape/size, and modifying the soil-pile interface after installation to increase the load bearing capacity. These approaches could be also applicable to anchor or tieback systems. It is expected that increasing pile capacity with these approaches could lead to more cost-effective pile foundations, and potentially the use of shorter piles and/or fewer piles.

**Fundamental Research, Education, or Technology Advancement Barriers**

Adapting functions or mechanisms of the root-system analog to deep foundations to increase load capacity is a complex problem. Several key components of a root-inspired pile with a "vascular system" need to be determined and refined in this research, including:

- the internal conduit system (the tubular tissue in the root analog, called xylem and phloem),
- the grout (mucigel secreted by the roots, or other substance exchange in the biological analog),
- the fluid transport, exchange and/or injection system (pressure flow, the mechanism by which sugars are transported through the phloem from sources to areas in need of nutrients, called sinks), and

- the soil-pile interface properties or mechanism (water uptake and substance secretion, resulting in flow and pore water pressure in the root analog).

Major barriers of this research are constructability, reproducibility, and quality control in the laboratory (prototypes) and in the field. Some of the questions that must be answered are: 1) is it feasible to achieve ground improvement through ground percolation/injection with a vascular system in the pile; 2) what type of grout or soil improvement solution works best at great depths (30+ feet); 3) what level of soil improvement or modification can be achieved; 4) what chemical and physical properties should the improving agent have depending on the soil conditions; 5) what timeframe is needed to achieve the desired soil improvement; 6) what is the performance of the improved soil or modified soil-pile interface under loading conditions, in the short and long terms; and 7) what are the associated costs of implementing the vascular system pile foundation versus the potential savings of increasing pile capacity.

**Any research aspect that involves foreign collaborations, especially indicating the length of time US faculty or students spent abroad conducting their work, and vice versa, and the value added of that work to the student's/faculty' work.**
N.A.

**Achievements in first year (Year 1)**
The team conducted a literature review on plant (root) physiology, root anchoring mechanisms and tensile or pullout resistance, and bio-inspired design principles. Draft summary papers were prepared. Analogies from the vascular system of plants and its functions were identified to inspire this research. Specifically, the root, the vascular system, and the exchange of substances between the soil, root, and stem systems were used as analogies. Preliminary modeling of the problem using finite element method was performed to evaluate the benefits of attaining ground improvement around the tip of a driven precast pile (after installation in relatively unsaturated loose sandy soil) through the adaption of a root-inspired vascular system.

The bio-inspiration led to permeation grouting being considered as a mechanism for soil improvement under or around the tip of a precast pile driven in loose unsaturated sand. The team started exploratory testing of materials (grouts) in a bench-scale experiment to assess the feasibility of various soil improvement materials and techniques for this application. The bench-scale experiment consisted of a clear acrylic box (46 x 30 x 15 cm) with removable sides, partially filled with dry sand; a PVC pipe inserted into the sand simulated the vascular system of the pile.

**Achievements in past year (Year 2)**
In Year 2, the emphasis was on assessing feasibility of permeation grouting as a technique for soil improvement to develop a root-inspired prototype pile (proof-of-concept experiment). Specifically, the experiments consisted of evaluating different grouts and their ability to permeate two local sands and two standard sands. Two methods to introduce the grouts into the soil were employed. The first method consisted of adding the grouting material directly to the sand and allowing it to percolate by gravity. The second delivery method consisted of injecting the grouts at different pressures using a manual sprayer (with a pressure gauge). When possible, the strength increase of the sands after grouting was determined with the unconfined compression test.

The factors involved in the exchange of substances (e.g., permeation grouting) between the pile and the soil were considered, namely the sand type, gradation, void ratio, and hydraulic conductivity. Additionally, the effects of grout rheology, viscosity, and injection pressure were also investigated for the prototype problem. The sands used in this testing and their coefficients of uniformity ($C_u$) and curvature ($C_c$), mean diameter ($D_{50}$), and maximum and minimum void ratios ($e_{max}$ and $e_{min}$) are provided in Figure 67. The following is a summary of the experiments and main conclusions.

Figure 67. Sands used in the experiments and some properties.

| Sand description | Label | Fines content (%) | Hydraulic conductivity* (cm/s) | $D_{50}$ (mm) | $C_u$ | $C_c$ | $e_{max}$ | $e_{min}$ |
|---|---|---|---|---|---|---|---|---|
| Fine, poorly graded sand, light brown, medium to low permeability | SS | 0.29 | $1.74 \times 10^{-2}$ (0.48) | 0.38 | 2.63 | 1.17 | 0.67 | 0.44 |
| Medium, poorly graded sand, medium to low permeability | CS | 0.95 | $1.35 \times 10^{-2}$ (0.56) | 0.50 | 3.16 | 1.01 | 0.66 | 0.41 |
| Ottawa 20/30 Graded sand, medium, poorly graded, white to light gray, medium permeability | OS1, OS2 | 0 | $4.47 \times 10^{-2}$ (0.57) | 0.70 | 1.16 | 1.04 | 0.73 | 0.48 |
| F-85 sand, fine, poorly graded, white, low permeability | F85S | 0.92 | $3.23 \times 10^{-3}$ (0.56) | 0.17 | 1.58 | 0.86 | 0.68 | 0.44 |

*Sand void ratio within parenthesis.

**Permeation by gravity (percolation)**

The purpose of the first permeation by gravity tests was to determine the ability of the different grouts to penetration the sands. This was evaluated by considering the depth of penetration, size and shape of a grouted element, and curing time. The adhesive or cementitious materials used are listed in Figure 68. The volume of material used in each specimen was adjusted based on the sand pore space and specimen size. The following tests were performed:

Series 1.1: Permeation by gravity in SS and CS in a short test box.

Series 1.2: Columns of OS1, SS, and CS sands (three specimens each sand, approx. 10 cm x 5 cm) were treated with ER to observe the penetration of highly viscous material into differently graded sands.

Series 1.3: OS2 sand was treated with EICP in the clear acrylic test box and allowed to percolate by gravity. A PVC pipe (diameter = 35 mm = 1-3/8 in) was installed as the sand was placed at a depth of 165 mm (6.5 in) from the top surface (Figure 1). After curing for four days, the treated EICP element was extracted and thoroughly rinsed with deionized water.

Conclusions: It was confirmed that the composition and viscosity of the grouting agent are of great importance for successful permeation grouting. The composition and viscosity of the grouting agent affected the ability of a grout to penetrate the sand. If the solids contained in a grouting agent are slightly larger than the pore sizes in the soil, then the particles are retained by the soil at the injection point. Permeation with pressure of relatively high viscosity grout (PC and SiGel mixtures) had similar effect. Additionally, if the grouting mixture was delivered by pressure, it caused soil particle displacement and became compaction grouting. It is expected that the grout rheology will also affect large-scale testing, as noted in the literature.

Figure 68. Materials used in the testing.

| Adhesive/cementitious material | Grouting mixture label | Mix design | Spread (mm) | Viscosity (Pa-s) |
|---|---|---|---|---|
| Type I portland cement | PC | w/c=0.5 | 122 | NA |
| | | w/c=0.75 | 333 | NA |
| | | w/c=1 | 423 | NA |
| Liquid polymer concrete adhesive | LPCA | w/LPCA= 2 | NA | 0.07 |
| Acrylic polymer emulsion additive | APEA | w/APEA=0 | NA | 0.2 |
| SoilSement (R) | SSe | w/Sse=0 | NA | 0.4 |
| Enzyme-induced carbonate precipitation | EICP | A/B=1 | NA | 0.3 |
| Two-part marine epoxy resin | ER | A/B=1 | NA | 5* |
| Silica gel | SiGel | 8% $Na_2SiO_3$, 4%$NaAlO_2$, 88%$H_2O$ | NA | 3* |

NA: not applicable
*Estimated by direct observation and comparing with common fluids

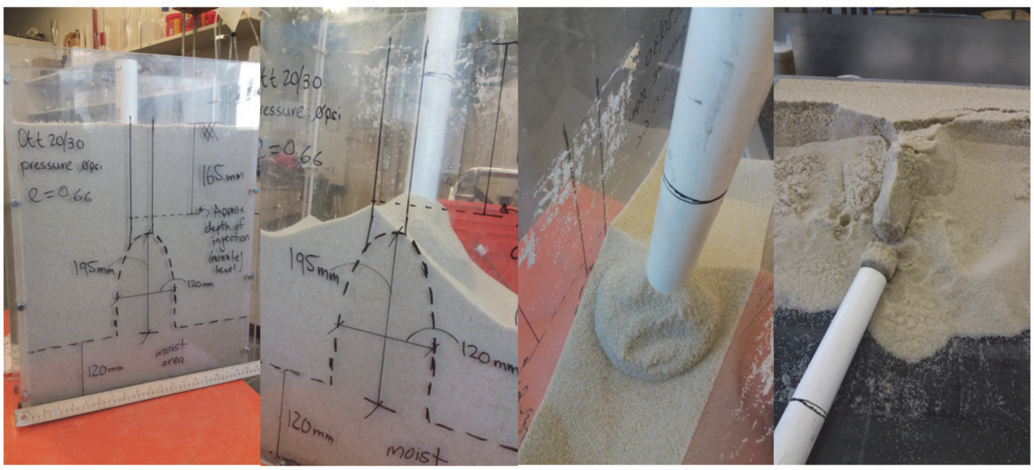


Figure 69. Excavation sequence of EICP-treated element.

**Permeation by injection**

In a second set of tests, the same grouting mixtures were injected into SS, CS and OS2 sand inside the acrylic test box. A PVC pipe (diameter = 32 mm = 1.25 in) was installed during sand placement and was used as injection pipe representing a conduit of the vascular system (Figure 70). The injection pressures, volume of injected grout, and depth of injection are summarized in Figure 71. The purpose of the injection tests was to determine penetration ability of the selected grouts in the three types of sand, at a given pressure. The depth of penetration, size and shape of a grouted specimen, and curing time were recorded.

Results and Conclusions: Evaporative solutions, such as the polymeric materials (LPCA, APEA, SSe), are not suitable for deep soil improvement because they do not cure or harden in the absence of air circulation. In bench-scale testing, low viscosity grouts (polymeric solutions and EICP solution) were more effective with permeation grouting by gravity (percolation) and permeation grouting by injection in fine sands.

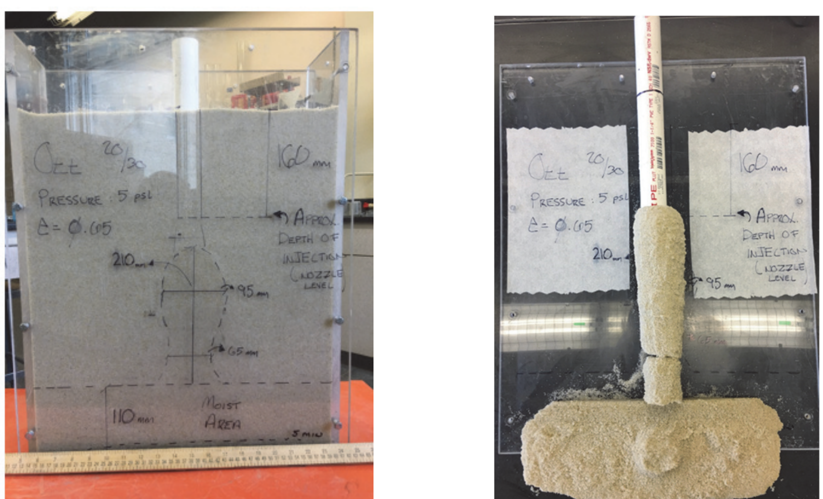
Figure 70. Grout injection in test box.

Figure 71. Injection program.

| Grouting Mixture | Sand Type | Injection Pressure (kPa) | Volume (mL) | Depth of Injection (mm) |
|---|---|---|---|---|
| PC w/c = 0.5 | SS & CS | 172 | 150 | 228 |
| PC w/c = 0.75 | | 172 | 150 | 228 |
| PC w/c = 1.0 | | 172 | 150 | 228 |
| LPCA | SS & CS | 172 | 150 | 228 |
| APEA | SS & CS | 172 | 150 | 228 |
| SSe | SS & CS | 172 | 150 | 228 |
| SiGel | SS | 172 | 485 | 228 |
| EICP | OS2 | 103 | 500 | 180 |
| | OS2 | 35 | 500 | 180 |
| | SS | 35 | 500 | 180 |

Bench-scale testing served only to understand the mechanics of permeation grouting. At this scale, the operation of permeation grouting was very sensitive to the combined effects of soil gradation, grout properties, and injection pressure. Soil gradation and grain size are impossible to downscale for a small-scale test. However, small-scale testing assisted in understanding the main mechanisms involved in the process of permeation grouting. Additionally, because no realistic confinement (overburden) was provided in the test box, it was easy to displace sand grains at low pressures. In large-scale testing, the effects of pressure could be regulated more easily.

The observations from the percolation of EICP at low pressure show promising outcomes for further development of a prototype (Figure 72). However, EICP treatment can be very sensitive to sand chemistry, and particle roughness and shape among several factors (e.g., lack of cementation in CS sand). Further research on the chemical properties of CS sand, the optimum chemistry of EICP treatment, and the ranges of grain size in which EICP can be effective are needed.




(A) (B)

Figure 72. Permeation by injection with EICP solution: (A) moistened area in test box showing permeation of EICP solution in OS2 sand; and (B) grouted OS2 element treated with EICP solution (pressure = 34.5 kPa [5psi]).

**Sand columns (EICP treatment)**

Four experiments were performed on sand columns treated with EICP solution. The goals of these experiments were to test:

a. Effectiveness of EICP in local sands (1 batch, 3 columns of SS, CS, and OS1 sands, two EICP applications of 50 mL and 30 mL each column).
b. Unconfined compressive strength and effects of time after preparation of EICP solution (6 batches, 18 columns of SS, CS, and OS1 sands, single EICP application of 80 mL each column. Each batch had a different treatment order).
c. Unconfined compressive strength of OS1 columns treated with EICP solution (2 batches, 6 columns of OS1, single EICP application of 80 mL each column).
d. Effects of viscosity-modified EICP treatment in OS1 and F85S, and corresponding unconfined compressive strength of columns (6 batches, 6 sets, 12 columns, one with open bottom and one with capped bottom in each set). The viscosity of EICP solution was modified with glycerol and xanthan gum (Tests performed in collaboration with ASU).

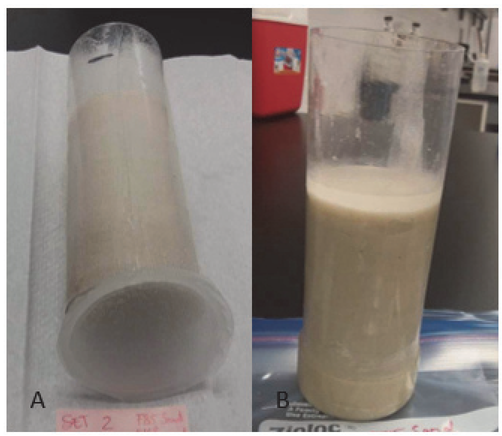



Figure 73. Open-bottom column (A), and closed-bottom column (B) of OS2 sand treated with viscosity-modified EICP solution. Columns are shown inside plastic molds. Open-bottom columns had a No. 200 sieve at the base to hold the sand.

Results and Conclusions: The EICP solution is effective in this application because it penetrates fine sands due to its low viscosity. However, the fast initiation of the chemical reactions shortly after application is a shortcoming in fine sands such as SS and F85S because the carbonate precipitation occurs in the upper part of the column (Figure 74B). This effect was not observed in coarser sands (OS1, OS2) (Figure74A).

The EICP solution with low viscosity was effective penetrating OS1 and OS2. However, greater viscosity may be desirable to prevent rapid drainage of the EICP solution in coarser sands. Further research into the optimum viscosity for a given type of sand can be helpful in the advancement of this program. Significant unconfined compressive strength was achieved (See Figure 75 and Figure 76). On average, EICP-treated OS1 specimens had unconfined compressive strength of 638 kPa (92.5 psi), and standard deviation of 149 kPa (21.6 psi), after aspect ratio correction.

Viscosity-enhanced EICP treatment increased the percolation time of the EICP solution. However, the addition of glycerol or xanthan gum reduced the unconfined compressive strength of EICP-treated columns by approximately 50% compared with specimens treated with EICP solution without viscosity modification (Pasillas et al. 2018).

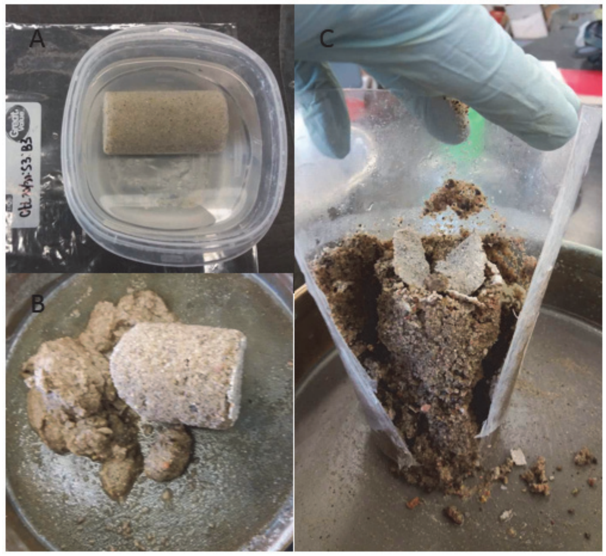



Figure 74. Cementation of sand columns: (A) OS1 column successfully cemented, (B) SS column partially cemented, and (C) CS column showing no cementation.

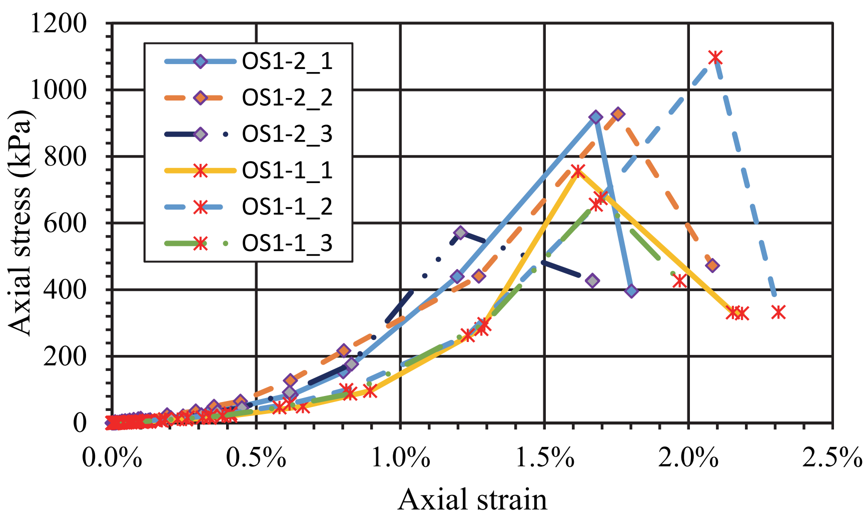



Figure 75. Unconfined compression of EICP-treated OS1 columns (no viscosity modification).

Figure 76. Unconfined compressive strength of EICP-treated OS1 columns (shown in Figure 75).

| Sample ID | Height (mm) | H:D | Void Ratio, e | Relative Density (%) | Peak Stress (kPa) | Strain at peak stress (%) | *Corrected Peak Stress (kPa) to H:D=2 |
|---|---|---|---|---|---|---|---|
| OS1-1_1 | 98.6 | 1.89 | 0.53 | 80 | 755 | 1.62 | 585 |
| OS1-1_2 | 98.1 | 1.88 | 0.51 | 88 | 1097 | 2.09 | 851 |
| OS1-1_3 | 95.9 | 1.83 | 0.53 | 80 | 675 | 1.70 | 523 |
| OS1-2_1 | 87.6 | 1.67 | 0.53 | 80 | 919 | 1.68 | 712 |
| OS1-2_2 | 97.1 | 1.86 | 0.52 | 84 | 928 | 1.76 | 719 |
| OS1-2_3 | 94.4 | 1.81 | 0.52 | 84 | 571 | 1.21 | 443 |

*Correction Coefficient = 0.78

**Products and collaboration**

During the past year, one personnel exchanged took place with the ASU EICP team, one Masters student graduated (with thesis), and a conference paper was submitted:

- Personnel exchange and collaboration: NMSU graduate student Jose Pasillas-Rodriguez spent 5 weeks in training at the CBBG ASU geotechnical laboratory in spring 2017. He worked under the primary guidance and mentorship of CBBG Post-doctoral Research Associate Hamed Khodadadi Tirkolaei. The NMSU student was trained on EICP techniques and specimen preparation procedures. They performed experiments to study viscosity-enhanced EICP. Jose Pasillas brought to NMSU the knowledge and experience obtained at ASU and trained on EICP two other NMSU graduate students to continue this project and another project new in Year 3.
- Paper submitted: Pasillas, J. N., Khodadadi T., H., Martin, K., Bandini, P., Newtson, C., and Kavazanjian, E. "Viscosity-enhanced EICP treatment of soil." Submitted to IFCEE 2018, Orlando, Florida, 2018.
- Thesis completed: Pasillas Rodriguez, J. N. (2017). *Bio-inspired Soil Improvement for End-bearing Capacity Enhancement of Precast Piles Driven in Unsaturated Granular Soils*. Master's Thesis, Department of Civil Engineering, New Mexico State University. Las Cruces, New Mexico.

**Plans for the next year**

Plans for next year include:

Continuing percolation testing and development of proof-of-concept experiment. Emphasis will be on EICP for ground improvement because this method showed promising results for the application of the precast pile with a vascular system. This will be in collaboration with the ASU EICP team and the new EICP project at NMSU that will focus on subgrade improvement and slope stabilization.

Filing an invention disclosure form (September 2017) for the precast pile with a vascular system, and preparing to file a provisional patent application if the idea is accepted by the NMSU Arrowhead Center's IPAC (Intellectual Property Advisory Committee).

The team will also work on another related bio-inspired concept identified in Year 1. We are interested in studying the soil-root substance exchange and the resulting pore water pressure condition in the soil to understand how or if this affects the soil properties around the root system and its load capacity (in compression or tension). Using this root analog, the team will create and model a mechanism to enhance the soil-pile interface. In Year 3, NMSU faculty with expertise in plant (root) physiology will join the team for this study (NMSU Plant Physiology Laboratory).

**Expected milestones and deliverables for the project**

The project is evaluating feasibility and applications of the precast pile with a vascular system. At the end of year 3, we expect to have obtained a working prototype as a proof of concept. If feasibility is shown, then pilot tests will be planned for years 4 and 5.

Using the root analog, the team will define a model of enhanced soil-pile interface or region by modifying the pore water pressure and, consequently, the soil and/or interface properties.

**Member company benefits**

The concept of precast piles with a vascular system may be of interest to current or future member companies engaged in pile driving or installation and the soil improvement aspect of this research may be of interest to industry members specializing in ground improvement.

**If relevant, commercialization impacts or course implementation information**

Preparation of an invention disclosure document is in progress, to be filed in September 2017.

### 2.3.4 Thrust 3: Bio-Inspired Design of Interwoven Flow Networks under Topological Constraints for Optimizing Utilities Systems

**ERC Team Members**

*CBBG Faculty*
Chloé Arson, Georgia Tech

*Other Research Staff*
Scott Retterer, Oak Ridge National Laboratory

*Graduate Students*
Wencheng Jin
Fernando Patino-Ramirez

*Undergraduate Students*
Nicholas Djohan
Aditya Gupta

**Project Goals**

This project aims to optimize flow networks that connects a set of sources and sinks in the presence of obstacles, under environmental fluctuations including sudden disruptions. In particular, we will investigate the decision-making mechanisms that drive:

- Network deployment – Growth in steady state conditions with various space distributions of sources and sinks
- Network accommodation – Topological changes due to geometric constraints such as flow resistant obstacles and cut connections
- Network adaptation – Topological changes due to environmental fluctuations such as steady/transient/cyclic flow, and uncoupled/coupled processes

The basic idea is to express the purposes of the engineering network in terms of objective functions (e.g. difference of pressure head), and to find biological analogs of these functions (e.g. difference of nutrient concentration). Once the biological objective functions and boundary conditions are defined, network dynamic simulations are performed to compare several biological designs, e.g. plant root architectures, plant leaf venations and *physarum polycephalum* (slime mold) networks. Optimization criteria are defined based on engineering constraints, e.g. minimum volume of porous media and minimum network redundancy. Network topological descriptors are defined to determine the bio-inspired solution that is best suited to the engineering design requirements.

The ultimate deliverable of this project will be a numerical platform that will integrate several biological network dynamics models, including root system architecture, leaf venation and slime mold models. The principle of the Bio-Inspired Geotechnical Network Design program (BIGND) is explained in the flowchart below. Dedicated subroutines will be written to connect the bio-inspired solver to pre- and post- processing tools commonly used in geotechnical engineering (e.g. GiD). Practical applications include:

- *Engineered barriers*: This project aims to provide simulation tools that will aid the design of resilient porous networks, i.e. networks that can serve their drainage or confinement purposes under a variety of environmental fluctuations and in the presence of microstructure heterogeneities. We have used slime mold algorithms to design the topology of a fracture network in a porous rock of given initial Pore Size Distribution for optimal drainage. The simulation tool will allow designing the best fracturing strategy in a rock mass of heterogeneous stratigraphy or with non-uniform distributions of inclusions.

- *Subsurface utility systems*: The bio-design numerical tool developed in this project is currently being used to test the optimality of Georgia Tech water lines. The ultimate goal is to provide a decision-making tool for the adaptation of subsurface utility networks and for the design of emergency recovery plans in case the supply network gets disrupted.
- *Transportation infrastructure*: Bridges can be seen as nodes on a road map. The bio-inspired design tool proposed in this project will bring innovative solutions for the incremental replacement or improvement of portions of road infrastructure networks. A variety of scenarios can be explored, based on expected flow, accidents and population dynamics.

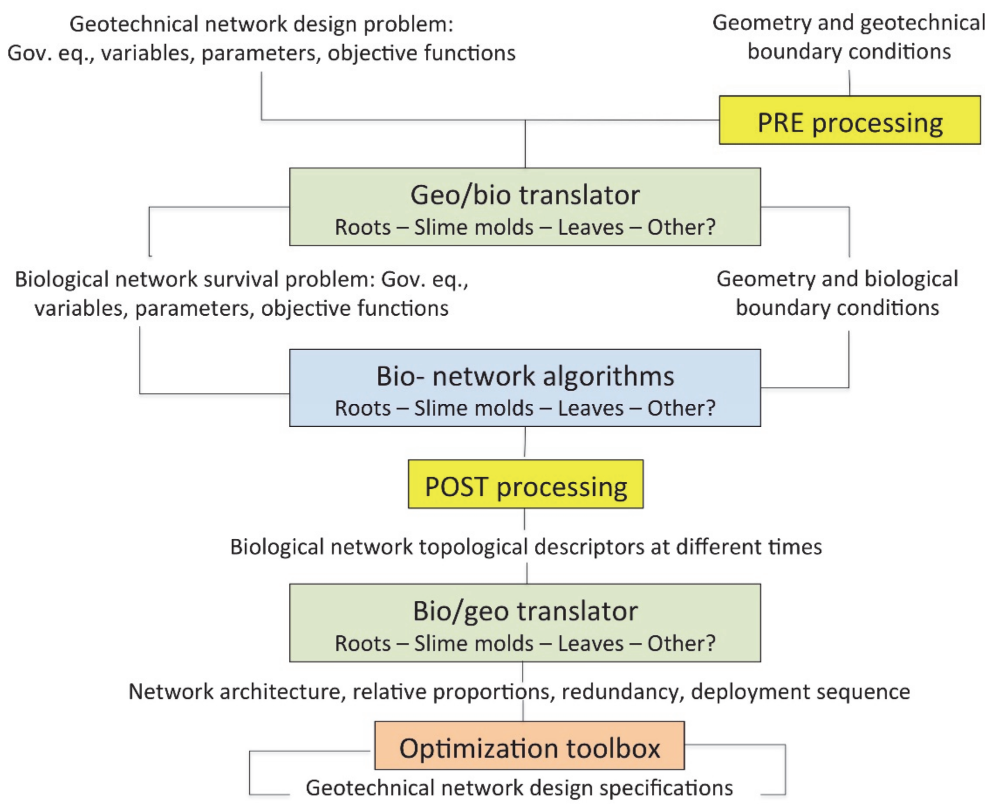



Figure 77. Principle of the Bio-Inspired Geotechnical Network Design (BIGND) program

**The project's role in support of the strategic plan**

*How is the project is bio-mediated and/or bio-inspired.* The project is bio-inspired: we model how natural networks grow and adapt to topological and environmental constraints to infer geotechnical solutions for the deployment, maintenance and adaptation of engineering barriers, utility systems and infrastructure networks. By contrast with classical engineering models that optimize flow under deterministic boundary conditions, we are exploring the dynamic topological changes of networks that are needed to accommodate changing demands and to overcome disruptions. As part of the development of the BIGND program, we are implementing, benchmarking and calibrating biological network models that will be integrated in the solver. For model calibration and validation, we are conducting physical experiments on plants roots in collaboration with Oak Ridge National Laboratory (ORNL) and we are designing slime mold growth experiments at Georgia Tech and abroad (see the section about international collaborations below). We have contacted a number of biologists in and outside the CBBG to obtain datasets on plant roots, slime molds and leaf venation systems. The pre- and post- processing interfaces, the Bio/Geo translator and the optimization toolbox will then shift the project from fundamental knowledge to enabling technology in the three-plane diagram.

*Potential contribution to resilience and sustainability.* Engineering design codes are based on tabulated loading scenarios and standardized factors of safety. Over-dimensioning is the most common response to uncertainty. The BIGND program will provide alternative solutions based on a fundamental understanding of intelligent biological network dynamics. For instance, closed-loops leaf venation systems have more mechanical resistance and higher flow resiliency than open-loop venation systems. However, closed loop leaf venation systems present a degree of redundancy, and are thus less cost-efficient than open loop venation systems. Leaf-inspired fracture patterns could be used to design multi-functional geomaterials - for optimal drainage and optimal resistance to mechanical stresses. Slime molds are foraging mono-cellular organisms that grow into networks that form the shortest paths between food spots. They conserve a memory of the areas that are poor in nutrients. Slime mold dynamics could therefore inspire the deployment and adaptation of subsurface utility networks in urban areas, where part of the underground space is already exploited. Root systems adapt their topological structure to connection disruptions and rigid obstacles, which provides a good model to repair transportation infrastructure. As a result, the BIGND program is expected to reduce environmental hazards associated to geological storage, save construction materials, optimize underground space and provide fast network deployment strategies in case of catastrophic network disruption or exceptional demand. The BIGND program will optimize design and deployment methods based on the comparison of survival strategies used by several biological systems that adapt to constraints and environmental fluctuations. By contrast with state-of-the-art geotechnical design tools, the BIGND program will provide guidelines to not only optimize the network design in response to current constraints but also, to optimize the degree of redundancy that will allow fast adaptation to future constraints. In addition the BIGND will provide a roadmap for the construction of networks that can be in service while being deployed – similar to living organisms that grow.

*Geosystem(s) that that project could directly impact.* We envision three main applications for the BIGND platform: (1) Optimization of the porous structure of multi-functional engineering barriers; (2) Design of adaptable subsurface utility systems; (3) Emergency deployment or reconstruction of transportation infrastructure after catastrophic collapse. Although the last application listed affects roads and bridges, the need to optimize natural construction materials and construction methods for embankments will also impact geosystems.

*List formal linkage(s) with other CBBG projects.* Although we do not collaborate formally with any CBBG scholar, we have initiated conversations with several CBBG members and linkages can be established with the following CBBG projects: (1) Root-System Evaluation for Multi-Function Foundation Bio-Inspiration (Dr. Frost, Georgia Tech); (2) Root-Inspired Foundation and Retaining Systems (Dr. Wilson, UCD); (3) Utilitarian Subterranean Annelid-Inspired Geo-probe (Dr. Cortes, ASU); (4) Microbially-Enhanced Iron-Modified Zeolite Permeable Reactive Barrier (Dr. Papelis, NMSU). In addition, we maintain several collaborations outside of CBBG (see below), and we will continue to seek collaborators within the CBBG partner institutions.

**Fundamental research, educational, or technology advancement barriers and methodologies used to address them**

The processes driving flow network growth and transformation are still poorly understood, especially under dynamic injection and withdrawal cycles. That being said, astonishing similarities were noted between the geometry of networks formed by living organisms (e.g. roots, slime mold) and that of infrastructure facilities (e.g. railway systems, see Tero et al., 2010). Based on these observations, we hypothesize that natural systems can be emulated to optimize pore network formation and infrastructure network deployment. To validate or invalidate this assumption, we focus on the optimization of networks that connect a given set of sources (stems, flow sources or influx points) with a set of sinks (food spots, drains or outflux points), as efficiently as possible. Note that efficiency can be defined in many different ways. Engineering network design approaches are based on scenarios in which the offer, demand and environmental conditions are assumed to be deterministic or somewhat predictable along the life cycle of the system. On the contrary, biological systems are known for exhibiting dynamic and adaptive networks, which are strongly influenced by the environmental conditions and fluctuations. Natural networks are the best possible *morphing* systems at any time, given the actual constraints, resources and requirements.

Currently, our project is concerned with the study of three natural systems, which follow different decision-making mechanisms: root system architecture, leaf venation and slime mold networks. We focus on the optimization of networks that connect a given set of sources (stems, flow sources or influx points) with a set of sinks (food spots, drains or outflux points), given boundary conditions and optimization criteria. The programming work will be done in three main steps:

- Biological network algorithms: implementation of biological network models, selected upon benchmarking, in MATLAB, Fortran or C++ (starting with RSA, slime mold and leaf venation systems);
- Pre- and post- processing interfaces: development of dedicated subroutines to call specific biological network algorithms, input biological model parameters, import CAD files for geometrical constraints, generate a mesh (or a grid), apply boundary conditions and print out the results;
- Bio/Geo translator and optimization toolbox: development of plug ins to translate engineering problem equations into biological analogs, match geomechanics variables and

parameters to biological ones, translate the biological network characteristics into geotechnical network design specifications, and assess the cost, adaptability, resiliency and sustainability of the bio-inspired network design based on a given set of objective functions and constraints.

Bio-inspired network design is expected to improve the utilization of underground space in growing urban areas, reduce the environmental impact of energy geotechnologies and provide guidelines to design resilient, adaptable and multi-functional infrastructure networks. The numerical platform proposed in this project (BIGND program) will compare survival strategies used by several biological systems in order to adapt network design to engineering constraints and environmental fluctuations. By contrast with state-of-the-art geotechnical design tools, the BIGND program will provide guidelines to not only optimize the network design in response to current constraints but also, to optimize the degree of redundancy that will allow fast adaptation to future constraints. In addition the BIGND will provide a roadmap for the construction of networks that can be in service while being deployed.

**Any research aspect that involves foreign collaborations, especially indicating the length of time US faculty or students spent abroad conducting their work, and vice versa, and the value added of that work to the student's/faculty' work.**

Dr. Emmanuelle Javaux, Université Libre de Liège (Belgium) shared the subroutines of a Root System Architecture (RSA) code and advised Wencheng Jin on how to use, improve and expand this code.

In February 2017, Drs. C. Arson and J.D. Frost visited the Soils, Solids, Structures and Risks Laboratory in Grenoble, France (L3SR). Based on a proposal written in collaboration with L3SR researchers, funding from IDEX Université Grenoble Alpes and CBBG was obtained to support 3 GRA students for three years, to work on micro-mechanical soil/root interactions and root-inspired design of multi-functional geotechnical networks. Each student will be co-advised by a CBBG researcher at Georgia Tech and a researcher at L3SR and will spend time doing research at both institutions. Dr. Arson went to L3SR in June 2017 and in July 2017 to kick off the project with the researchers and the Ph.D. student appointed there. The student will spend six months at Georgia Tech between Fall 2018 and Spring 2019. Fernando Patino will spend about a month at L3SR in Summer 2018 and in Summer 2019. Biweekly Skype meetings will be organized between Georgia Tech and L3SR, starting in Fall 2017.

In June 2017, Dr. Arson visited Dr. Audrey Dussutour at Sabatier University in Toulouse, France. Dr. Dussutour is an expert in slime mold cultures, particularly interested in how slime mold species interact in the presence of several types of nutrients and obstacles, and how slime molds "learn" to choose where to expand their networks efficiently, based on a "memory" of previous foraging efforts. Dr. Dussutour meets Fernando Patino and Dr. Arson every 3 weeks on Skype to advise on the slime mold experiment being set up at Georgia Tech. In the upcoming academic year, Dr. Dussutour will conduct experiments in her own lab to understand the influence of spatial distributions of strong and weak food attractors and strong and weak repulsive salts on the topology of slime mold networks. Time-lapse images taken in her lab will be analyzed at Georgia Tech for slime mold model calibration and validation. If funds are available, Fernando Patino will spend a few weeks in Toulouse in Summer 2018 to learn about slime mold culture techniques and to improve the Georgia Tech experimental set up. Dr. Dussutour is also planning to come to Georgia Tech for a few days in Spring 2018. Drs. Arson and Dussutour are pursuing funding opportunities within the joint NSF-ANR program (French National Agency for Research) and in collaboration with the CEA (Atomic Energy Center).

**Achievements in previous years**

<u>Slime mold inspired flow networks (e.g., engineered barriers)</u>

According to the constructal theory, a flow network of finite volume, embedded in a finite porous matrix of constant flow rate, is optimal for fluid withdrawal from a sink point when its topology is fractal. We tested the constructal optimum for slime mold propagation by building an analogy between slime mold propagation and steady fluid flow. We grew slime mold on several fractal-shaped nutrient pathways. Time lapse photographs were taken to observe the growth of the slime mold on these nutrient networks over several days. Preliminary results showed that slime mold propagates faster on fractal nutrient pathways, which tends to indicate that slime mold propagation can be modeled by transport equations similar to those of steady state fluid flow.

<u>Plant root inspired pipeline systems</u>

Top notch bean plants were grown between two paper towels for two weeks, and root branching was observed by time lapse. A tap root grows first, followed by secondary and tertiary branches. The growth of the root can then be quantified by the length of the tap root and number of branches at each level. The number of secondary branches is observed to increase over time before tertiary branches begin to form.

**Achievements in the past year**

<u>Slime mold inspired flow networks (e.g., engineered barriers)</u>

- Design of slime mold growth experiments in a sterile, moisture and light controlled environment on an adaptable, translucent lego base
- Programming of a computer to control the lighting system
- Programming and benchmarking of slime mold growth algorithms
- Preliminary simulations of slime mold inspired design of a fracture network for fluid withdrawal in porous rock

<u>Plant root inspired pipeline systems</u>

- Design and execution of root growth experiments on agar substrate, time-lapse photographs, image processing, root network image analysis: We are working on an ImageJ analysis that will automatically measure the number of branches and lengths of roots at different stages of the plant growth, which will be used on experiments in which the plant root grows around obstacles. We are also collaborating with Oak Ridge National Laboratory (ORNL) to study the adaptation of *Arabidopsis Thaliana* roots and root hairs to obstacles. The setup at ORNL allows roots to be grown in gel, making it easy to record and observe their growth.
- Calibration of a Root System Architecture (RSA) program for wheat roots
- RSA validation: We are comparing both the growth of the bean and *Arabidopsis* roots to model predictions, and combine the models and experiments to investigate the problems of adaptation, accommodation, and competition of man-made networks.
- Improvement of the RSA code to simulate plant root growth around obstacles

- Application of the RSA to the optimization of Georgia Tech water line system: root growth experiments on a 3D printed reduced scale model of Georgia Tech campus, time lapse photographs
- Programming and testing of open leaf venation models and Steiner Tree algorithms
- RSA sensitivity analyses and benchmark against leaf venation models

Publications:

- F. Patino-Ramirez, C. Arson. Bio-inspired fluid extraction model for reservoir rocks. *51st US Rock Mechanics/Geomechanics Symposium of the American Rock Mechanics Association*, San Francisco, CA, June 25-28 2017, Paper 17-0515

Presentations:

- C. Arson, L.F. Patino-Ramirez, W. Jin, "Bio-inspired design of subsurface flow networks", Seminar at the CNMS at Oak Ridge National Laboratory, March 9th, 2017
- C. Arson, L.F. Patino-Ramirez, W. Jin, "Bio-inspired design of subsurface flow networks", Workshop L3SR-Georgia Tech, Université Grenoble Alpes, L3SR Lab, Grenoble, France, February 9th, 2017
- C. Arson, L.F. Patino-Ramirez, W. Jin, "Bio-inspired models for infrastructure and flow network optimization, deployment and adaptability", seminar of the Engineering Research Center on Bio-inspired and Bio-mediated Geotechnics, January 18th, 2017
- C. Arson, "Bio-inspired Subsurface Networks", *Army Research Office Workshop on Geo-surface materials dynamics*, Chicago, August 17th, 2016
- C. Arson, D. Hu, W. Jin, O. Shishkov, "Bio-inspired design of interwoven flow networks under topological constraints for optimizing utilities systems", *presentation of a project of the Center for Bio-Inspired and Bio-mediated Geotechnics to the city of Atlanta*, December 8th, 2015

**Summary of other relevant work being conducted within and outside of the ERC and how this project is different**

Bio-inspired design of flow networks is a research field tightly related to the research projects related to root-inspired design, in particular: (1) Root-System Evaluation for Multi-Function Foundation Bio-Inspiration (Dr. Frost, Georgia Tech); (2) Root-Inspired Foundation and Retaining Systems (Dr. Wilson, UCD); (3) Utilitarian Subterranean Annelid-Inspired Geo-probe (Dr. Cortes, ASU); (4) Microbially-Enhanced Iron-Modified Zeolite Permeable Reactive Barrier (Dr. Papelis, NMSU). Our project treats the modeling of the formation of networks that convey a flow of mass or heat or information or electricity, for instance slime molds, plant roots, plant branches, ant pathways. By contrast with the projects led by other PIs within the ERC, our project does not aim to model of composites that contain root inclusions. We focus on network optimization for transport processes instead of mechanical soil reinforcement, even though we are planning to model the mechanical interactions between growing roots and the surrounding geomaterial.

**Plans for the next year**

The project is not funded by the CBBG next year. However, if we find financial support from other resources, below are our upcoming 1-year objectives:

3. Calibrate and validate the RSA and slime mold algorithms against network growth experiments on agar substrate, without or with obstacles, and without or with sinks (food spots acting as attractors).
    - Design and set up network growth experiments that include sinks and not only obstacles. Vertical syringes will be placed at dedicated locations on the substrate for applying nutritive fluids at constant pressure head. We will calibrate the viscosity of the nutritive fluid to ensure low diffusion in the agar.
    - Execute and monitor slime mold growth experiments and plant root experiments with a variety of sets of sources, sinks and obstacles (periodic distribution, random distribution, etc). Calibrate the RSA and slime mold models accordingly.
    - Execute, monitor and simulate the network growth experiment on Georgia Tech campus for both wheat roots and slime molds; compare the biological network topologies with the topology of the actual water line systems; assess the RSA and slime mold models for bio-inspired design of water lines.

4. Implement selected network algorithms of RSA, slime mold growth and leaf venation systems into subroutines that can be integrated into a unified solver platform, and develop plug-ins to connect to a pre- and post- processing interfaces.
    - Improve RSA models to simulate competitive growth (i.e. growth of several plants in the same finite volume environment).
    - Implement and test the algorithm for the closed leaf venation system.
    - Integrate the solver subroutines in a user-friendly platform with prompts to choose a biological model (RSA, slime mold or leaf venation) and provide relevant input data to set up the model.
    - Develop plug-ins to connect to pre- and post- processing interfaces to input model parameters, import geometry files, apply the boundary conditions and call the appropriate solver.
    - Test the interface: repeat the calibration tests described in point (1) above and check that results are the same without and with the BIGND program interface.

5. Analyze the topology of biological networks over time and assess their optimality for cost, adaptability and resiliency.
    - Extract quantitative design information from the optimal bio-inspired networks: sequence of the deployment, relative dimensions of the network components, degree of redundancy, etc.
    - Express functions of cost, adaptability and resiliency in terms of the topological descriptors defined in 3.a.
    - Assess bio-inspired network designs.

**Expected milestones and deliverables for the project**

Expected outcomes in bio-inspiration knowledgebase match the expected capabilities of the enabling technology that the project aims to produce: (1) After understanding the biological processes that control the growth, adaptation and survival of networks, we have implemented, benchmarked and started calibrating root system architecture, leaf venation and slime mold growth network algorithms; (2) We will design pre- and post- processing interfaces that will allow the translation of geotechnical problems into biological problems, and biological solutions into geotechnical solutions; (3) We are examining several sets of design criteria to design an optimization toolbox attached to the bio-inspired solver: the idea is to guide the user towards the biological analog that is the best suited for the geotechnical problem of interest. The ultimate goal is to develop a Bio-Inspired Geotechnical Network Design (BIGND) numerical tool to assess the relevance of the biomimicry approach for improving geomaterials and geotechnical infrastructure, and for providing alternative designs based on survival requirements. Not only the BIGND program will inspire sustainable design options, but it will also provide a set of quantitative tools to transform optimal biological analogs into geotechnical structures. If funding is available, we expect to be able to provide useful computing tools and network construction methods within 4 years. To fully investigate the topics of accommodation, adaptation and selection, we anticipate that we will need 10+ years.

**Member company benefits**

Dr. Scott Retterer and his students Jayde Aufrecht and Peter Shankles, from Oak Ridge National Laboratory, collaborated on this project by providing 3D printed textured support for testing root growth and slime mold network development in the presence of obstacles, conducting plant root experiments and image acquisition, designing slime mold growth experiments. In April 2017, Dr. C. Arson submitted an ORNL facilities user proposal to continue the experiments currently undertaken at ORNL. If funded, the project will allow us to use ORNL internal funding to dispose of the equivalent of 5 working days of laboratory work, and to get access to facilities such as the 3D printer and the environmental chambers where the biological network growth experiments are conducted.

Dr. Arson and her group had phone conversations and physical meetings with engineers working for the watershed department at the city of Atlanta. Engineers agreed to share maps and technical details of projects related to: (1) The optimization of water pipe networks in residential areas which include dead end streets; (2) The renovation of water pipe networks due to modernization needs or due to the change of regulation on the pipes needed to mitigate fires (case of Whittier Mills); (3) The adaptation of pipe systems in neighborhoods where population grows. We made a presentation to a team of representatives of the information infrastructure department at the city of Atlanta. We agreed to collaborate, when our models are more mature, on the numerical optimization of the topology of the information network supported by fiber optics that will be created in Midtown Atlanta (especially close to the Belt Line).

A Non-Disclosure Agreement between Georgia Tech and Google Fiber was signed, in order to apply network optimization to information network systems.

**If relevant, commercialization impacts or course implementation information**
N/A

### 2.3.5 Thrust 3: Engineering Applications of Enzyme-Induced Carbonate Precipitation

**ERC Team Members**

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*Other Research Staff*
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*Graduate Students*
Miriam Wooley
Abdullah Almajed
Kimberly Martin

*Undergraduate Students*
Rachel Adams

**Project Goals**
The goal of this project is to develop sustainable ground improvement technologies for infrastructure construction using enzyme induced calcite precipitation (EICP). Technologies under investigation include ground improvement technologies that currently employ Portland cement as a binder for granular soil (e.g., soil-cement columns made by deep soil mixing), fugitive dust control, and mitigation of earthquake-induced liquefaction.

**The project's role in support of the strategic plan**
EICP plays a major role in the CBBG infrastructure construction methods and materials thrust and also contributes to the geologic hazard mitigation and environmental protection thrusts. As a replacement for Portland cement, EICP offers the potential for enhanced sustainability in infrastructure construction and, if a method for deriving urease enzyme from waste vegetation or agricultural wastes can be found, reduced construction costs. Portland cement is one of the least sustainable engineering materials commonly used in geotechnical construction, as its manufacture is estimated to be responsible for 4-5 of greenhouse gas emissions worldwide. Prior to the 2008 recession, Portland cement was in short supply and the price rose dramatically, still has not dropped to recession levels, and may be rising again. EICP also offers potential solutions for liquefaction mitigation under and around existing buildings, an important geologic hazard mitigation problem, fugitive dust control, an important environmental protection problem, and possibly surface water erosion control.

**Fundamental Research, Education, or Technology Advancement Barriers**
Fundamental barriers to deployment of this technology depend to some extent on the application. As a replacement for Portland cement for ground improvement and construction material purposes, the shear strength that can be achieved using EICP is an important issue. While an EICP-improved soil does not need to be as strong as a soil cement column made using Portland cement, it must have sufficient strength to carry substantial design loads. The speed of the precipitation reaction in EICP is a fundamental barrier for some applications. In percolation or injection-based application methods, the almost instantaneous reaction of carbonate and calcium ions in solution to form calcium carbonate when catalyzed by urease may lead to what is referred to in MICP as bio-clogging: rapid precipitation around the point where all of the reagents are brought together. This clogging causes a dramatic decrease in permeability and hindering further distribution of the reagents. The rapid rate of precipitation also hinders applications that employs mix and compact methods as laboratory testing suggests that rapid precipitation may hinder binding between successive layers of compacted soil. Rapid precipitation may also lead to smaller carbonate

crystals and to formation of less stable forms of calcium carbonate than calcite, e.g., Vaterite. Rapid precipitation also affects the means and methods for fugitive dust control, wherein an EICP solution is sprayed on the soil surface. Because of the rapid rate of precipitation, solutions containing the urease enzyme and the urea/calcium chloride mixture must be contained in separate containers and mixed at the nozzle of the sprayer, as combining these solutions before the nozzle will result in premature precipitation and clogging of the nozzle. Even if the reagents are mixed at the nozzle immediately prior to being sprayed onto the soil surface for fugitive dust control, rapid precipitation of the cementation solution at the soil surface can hinder penetration of the stabilizing solution into the soil. However, conversely, if the precipitation is too slow the precipitation solution may penetrate too deeply into the soil, reducing its effectiveness for dust control. Management of the ammonium chloride by-product of the EICP reaction is also an important barrier that must be overcome, as ammonium chloride is a recognized pollutant and acidification of groundwater by ammonium chloride could potentially degrade the precipitated carbonate. The cost and availability of agricultural urease is also an important issue, as available supplies are medical grade, produced in small quantities, and thus very expensive. Other fundamental research and technology advancement questions that must be answered to develop and commercialize this technique include: 1) what level of treatment necessary to achieve a specified level of improvement; 2) what is the permanence of the improvement that can be achieve using this technology; 3) what is the applicability of EICP to different soil types; and 4) what is the lifecycle cost of achieving a specified level of treatment?

**Any research aspect that involves foreign collaborations, especially indicating the length of time US faculty or students spent abroad conducting their work, and vice versa, and the value added of that work to the student's/faculty' work.**
N.A.

**Achievements in previous years**
Achievements during the first year of CBBG operation on this project included: 1) evaluation of an optimal "recipe" for EICP; 2) evaluation of the potential for reinforcing mix and compact EICP specimens with natural sisal fibers; 23 evaluation of the potential for use of hydrogels to enhance the strength of EICP-improved soil and facilitate fugitive dust control; and 4) a small scale demonstration of ground improvement via soil nailing using EICP.

The optimal recipe for EICP proved to be 1 part urea in solution to 0.67 parts calcium chloride solution. If the urease solution had a concentration of 1 molar, 3 gr/liter of enzyme was needed for complete utilization of the calcium substrate. Figure 78 shows stress-strain curves from sand improved by EICP using the mix and compact method with and without sisal fiber reinforcement. Mixing just 0.3% (by weight) sisal fibers with the sand resulted in a five-fold increase in the unconfined compressive strength of the soil. However, the resulting material was relatively brittle, with a strain at failure of approximately 0.5% in unconfined compression. Figure 79 is a scanning electron microscope photograph of sand improved using a mixture of Poly Acrylic Acid (PAA), a synthetic hydrogel, and EICP. This photo shows the PAA tendrils that wrap around the soil particles. When dried, the PAA-EICP specimens had even greater strength and ductility than the sisal fiber reinforced soils. However, upon re-hydration that strength was lost. Testing of spray application of a precipitation solution supplemented with a hydrogel showed that by retaining the cementation solution for a longer period of time at the soil surface the precipitation at particle contacts was enhanced due to increased viscosity. We also had success in creating a small-scale soil-nailed wall in the laboratory using EICP in Year 1.

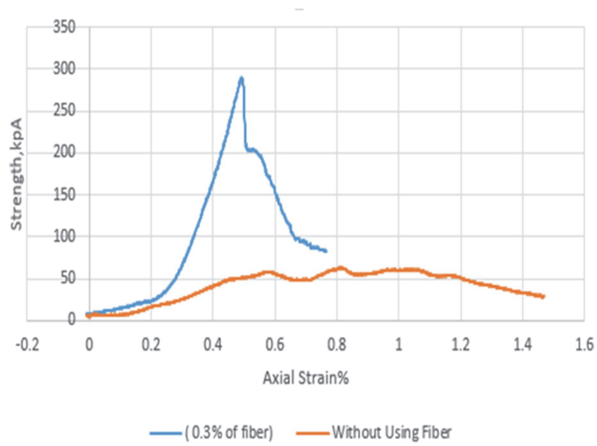


Figure 78. Impact of sisal fiber reinforcement on the stress strain behavior of EICP-improved soil

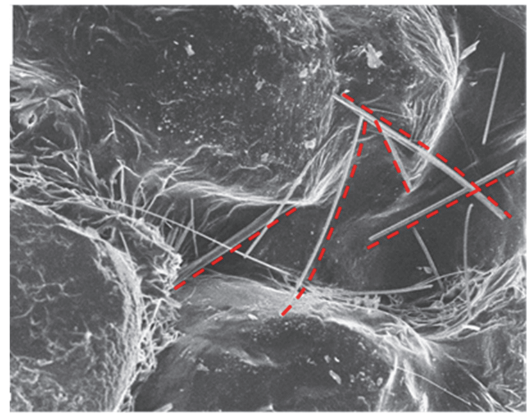

Figure 79. SEM image of sand improved by a PAA-EICP mixture showing PAA tendrils wrapping soil particle

**Achievements in past year**

Several notable achievements were obtained in Year 2 on this project. Perhaps most notable is that we were able to significantly increase the strength of EICP treated sand while reducing the amount of precipitated calcium carbonate. In prior EICP experiments, a single treatment yielded precipitation of 1 to 2 percent calcium carbonate and an unconfined strength on the order of 100 kPa. Multiple treatments to raise the carbonate content to 4 to 8 percent yielded strengths on the order of 400 kPa. However, with the addition of an organic stabilizer, powdered (dry) non-fat milk, to the EICP solution, we were able to achieve unconfined strengths of greater than 1 MPa with carbonate content of less than 1 percent in a single treatment. Figure 80 compares the strength and carbonate content achieved using a single treatment of an EICP solution using the stabilizer to EICP treatment without the stabilizer and to MICP treated soil. The significantly lower carbonate content necessary to achieve a substantial unconfined strength with EICP with a single treatment has multiple positive implications for commercial application of this technology, including reduced cost due to reduced quantities of substrate, reduced production of the undesirable ammonium chloride by-product, and simpler application due to the single step of treatment.

Other Year 2 achievements include demonstrating that EICP treatment by surficial spraying has substantial durability and demonstrating that EICP columns can be formed by injecting the EICP solution into a saturated soil. Durability testing was conducted using an accelerated aging chamber that increased the temperature and ultraviolet radiation to values well-above background. Specimens exposed to the equivalent of one year of outdoor exposure in Phoenix showed no degradation in wind erosion resistance over that period. EICP columns were formed by inserting an injection tube down the central axis of a cylindrical container fill of saturated soil and injecting EICP solution as the tube was withdrawn. Figure 81 shows the column that was formed in this manner. Two disappointing findings in Year 2 were that finer grained soils may require higher amounts of carbonate to achieve high strength and that some soils may be resistant to EICP treatment. Additional work is required to understand these effects.

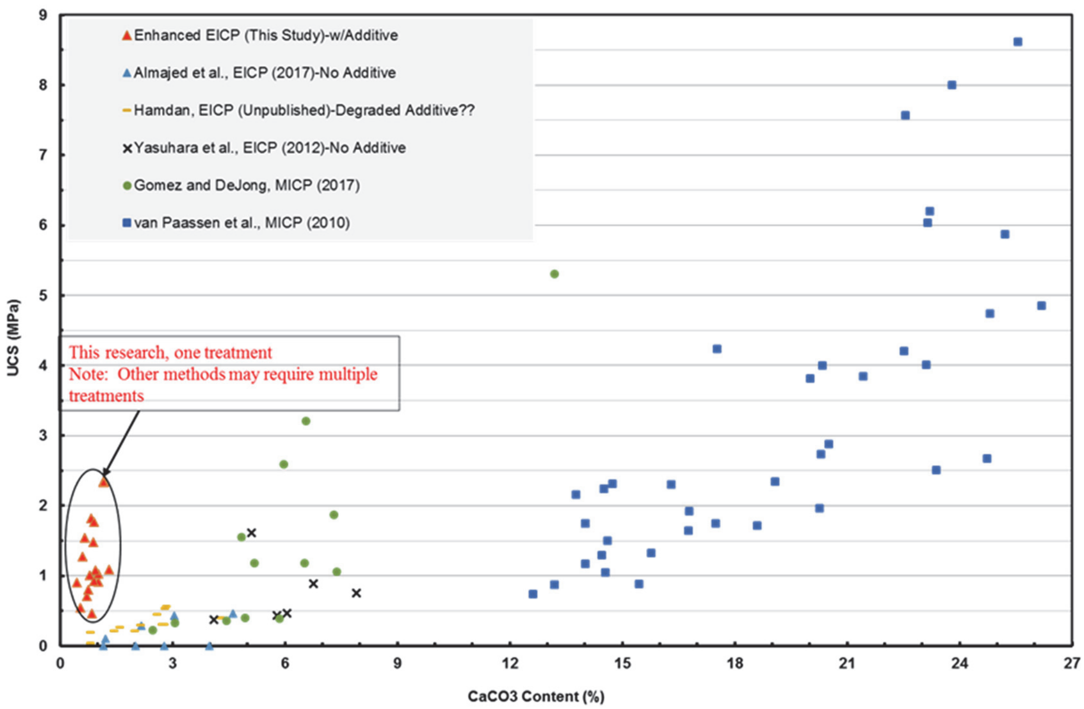


Figure 80. Relationship between unconfined compression strength (UCS) and calcium carbonate content for various treatment methods

Figure 81. EICP column formed by injection along the central axis of a cylindrical contained filled with saturated soil

**Summary of other relevant work being conducted within and outside of the ERC and how this project is different**

Related work being conducted within the ERC includes research on the application of hydrogels for a variety of purposes, including the development of hydrogel reinforcement resistant to hydration by cross-linking two different polymers. Also, as part of CBBG infrastructure development, a large test pit has recently been constructed on the ASU Polytechnic campus that will serve as a test bed for field scale development of all three carbonate precipitation technologies (MIDP, MICP, and EICP). Related work also includes a new project at NMSU on the applicability of EICP for erosion control on slopes.

**Plans for the next year**

Next year, this project will be split into two distinct projects, EICP for Soil Erosion Control and EICP Columns for Ground Improvement. Plans for the soil erosion control project include filed testing of EICP spray for fugitive dust control and of EICP via mix and compact for low volume road stabilization with a CBBG Industrial partners. Plans on the EICP Colum project for next year include additional investigation of grain size effects and of the resistance of certain soils to EICP treatment, additional benchtop laboratory experiments on EICP column formation, and full scale testing EICP soil column formation in the ASU biogeotechnical test pit. Work will also continue on a cost-effective way of extracting urease from waste vegetation.

**Expected milestones and deliverables for the project**

It is anticipated that field demonstration of the effectiveness of the technology for fugitive dust control and filed testing of EICP for low volume road stabilization will take place by the end of year 3 and by the end of year 4 these technologies will be ready for commercialization. Field scale testing of vertical soil columns should commence either by the end of year 3 or the beginning of year 4 if testing in the ASU biogeotechnical test pit is successful and these technologies could then be ready for commercialization by the end of year 5.

**Member company benefits**

A practical method for fugitive dust control is of significant interest and great benefit to member companies engaged in civil construction, including Hayward Baker, Nicholson Construction, Schnabel Construction, GeoPier ground improvement contractors, who could employ the technology to comply with dust control regulations. It is also of interest to the mine and landfill facility owners who are members of the Industrial Partner Program, including Republic Industries and Freeport McMoRan, and the public agencies who are Associate members, as they all have facilities at risk from this phenomenon. The EICP vertical column techniques are of benefit to the ground improvement companies cited above and to other civil construction contractors, who can market these techniques nationally and internationally.

**If relevant, commercialization impacts or course implementation information**

Information on this technique and its potential benefits has been incorporated in graduate classes on Ground Improvement at Arizona State University. EICP will also be included in the syllabus for a new graduate class on Biogeotechnical Engineering to be delivered at ASU in the fall semester of 2017.

### 2.3.6 Thrust 3: Tree Root Inspired Foundations

**ERC Participants**

*CBBG Faculty*
Dan Wilson, UC Davis
Jason DeJong, UC Davis
Alejandro Martinez, UC Davis

*Graduate Students*
Matt Burrall, UC Davis

*Undergraduate Students (REU)*
Kyle Doughty, UC Davis

**Project Goals**

The overarching goal of this project is to study and gain inspiration from natural biological anchorage systems, such as tree root systems, in order to create practical bio-inspired foundation/anchorage systems that are more resilient, efficient, and/or sustainable relative to conventional linear pile/anchor/nail systems utilized in practice. Achieving this goal will occur through collaboration with related ERC projects at Georgia Tech and NMSU as well as through collaboration with researchers at the University of Dundee. At UC Davis the project includes the following steps: (1) review and formulation of a bio-inspired engineering design research approach, (2) review of tree root literature in the plant physiology field, (3) design and execution of a full scale tree pullout test program of trees with different root architectures, (4) extraction of key observations/principles from the field test program and abstraction to conceptual anchorage designs, (5) DEM modeling of concepts to understand and quantify relative contributions of different mechanisms, and (6) centrifuge modeling of prototypical bio-inspired anchorage designs. Year 1 initiation of the project consisted of a survey across steps 1, 2, 3, and 6. Year 2 progress has included completion of step 1, producing a draft report of step 2, and initiation of step 3. Year 3 is expected to consist of completion of steps, 2, 3, and 4, and will target beginning step 5.

**Project Motivation & Role in Strategic Plan**

Deep foundation and anchorage systems used in industry are comprised, almost solely, of linear elements with a constant cross-section geometry. This functional form has remained the same for more than a century, primarily due to the materials available and the ease of installation. However, a comparison of some basic foundation systems against natural foundation/anchorage systems, tree root structures for example, reveal that the biological analog can perform up to 20x more efficiently under lateral or tension load when normalized to the material volume. Knowledge and understanding of what aspects of the natural, biological systems most contribute to this dramatic improvement in performance is currently unknown. The motivation for the current project is to identify and transfer concepts and principles from natural systems in order to realize similar performance gains in built foundation/anchorage systems.

Research into natural biological analogs to foundation/anchorage systems in order to gain bio-inspiration and develop more efficient, sustainable, and/or resilient infrastructure directly aligns with the bio-inspired theme of the ERC and the Infrastructure Construction thrust. This project, in combination with the others mentioned above at partner universities, comprise one theme within the ERC that is exploring the less studied bio-inspired discovery approach.

**Any research aspect that involves foreign collaborations, especially indicating the length of time US faculty or students spent abroad conducting their work, and vice versa, and the value added of that work to the student's/faculty' work.**

Collaboration with Prof. Jonathan Knappett and colleagues at the University of Dundee, Scotland, is in place. Prof. Knappett has a project funded by the Forestry Department that is focused on understanding how the root structures of trees on slopes adjacent to roadways help reinforce and increase the stability of constructed and natural slopes. While the goal of their project is not directly bio-inspired, the underlying work of how root systems provide geotechnical reinforcement to soils is relevant.

**Achievements in previous years**

As stated above, the launch of the project in Year 1 was designed to be a relatively high-level survey to explore, discover, and learn what research approach might be appropriate, how readily could performance gains in capacity or stiffness be realized, and what might a bio-inspired foundation/anchorage system look like. Thus, Year 1 focused on learning the literature on bio-inspired design and formulating a research approach for our research group, beginning a literature review in the biology / tree physiology research fields on tree root systems, performing a single full-scale tree pullout test, and designing and testing early conceptual bio-inspired foundation design in the small centrifuge at UC Davis.

**Achievements in the past year**

Year 2 activities have primarily focused on the following three areas.

***Development of Bio-Inspired Design Approach***

Bio-inspired engineering design is relatively young, with the bulk of literature discussing best practices, methods, and approaches for performing research in the field and being published in the past decade. Currently there is no firm consensus on best approaches and fundamental differences exist within the community regarding the extent to which nature itself represents an optimized system or solutions; camps of researchers differ widely on this issue. Review and distillation of the literature in Year 1 culminated in our research group articulating the research approach that we have decided to implement. This approach aligns with past work by Prof. Goel which articulated problem or solution driven research/development processes. In our view, neither is appropriate alone; rather, both problem and solution domain knowledge and experts should be engaged in a collaborative, iterative design process. For our project both engineering and plant science expertise is necessary. Further, we have adopted the position that solutions in nature likely do not represent completely optimized, ideal solutions. Instead, considering the natural constraints (e.g. limited water, sun light, nutrients, growth season), it is more likely that natural systems represent innovative, multi-functional, minimum energy systems that have developed a close-to-optimal solution to provide sufficient performance. This perspective has since guided the focus and distillation of content present in our literature review and in the design of the field scale test program that is now underway.

The design approach was published and presented at the ASCE GeoFrontiers 2017 as "A Bio-Inspired Perspective for Geotechnical Engineering Innovation". Graduate student Matthew Burrall presented the paper at the conference.


Figure 82. Graduate student Matthew Burrall presenting at ASCE GeoFrontiers 2017 conference.

***Review and Synthesis of Tree Root Literature in Biology/Plant Science Literature***

A literature review of over 250 articles/reports was performed with guidance and collaboration from faculty in the Plant Science Department. Distillation, in the context of our project focus, into the following sub-topics helped organize the content, though inevitably many inter-relations exist: (1) Individual root pullout behavior, (2) Root system pullout behavior, (3) Developmental processes and individual root architecture, (4) Defining root architecture, (5) Modeling of mechanical anchoring, and (6) Effect of environmental perturbations on root anchorage. This led to identification of relevant mechanisms/processes that exist at different length scales, including: structural root function varies with diameter with smaller roots primarily contributing to tensile capacity; root growth occurs primarily by radial expansion, which also results in soil densification; root tortuosity and branching to form nonlinear root structures has a first order effect on capacity generation; the tensile yield stress and root density can be incorporated into soil strength estimates; root cross-sectional shape change (such as elongation) is directly linked to structural loading conditions; root architecture variability inter- and intra-species is largely due to a direct dependence on surrounding environmental conditions; and the total anchorage capacity of a tree is largely dictated by the weight of the soil-root plate, the soil-root tensile capacity, the tensile resistance of the windward roots, and the bending resistance of the leeward hinge. The results of this study have guided development of the full-scale field testing program underway now and seeded ideas for root-inspired foundation/anchorage designs.

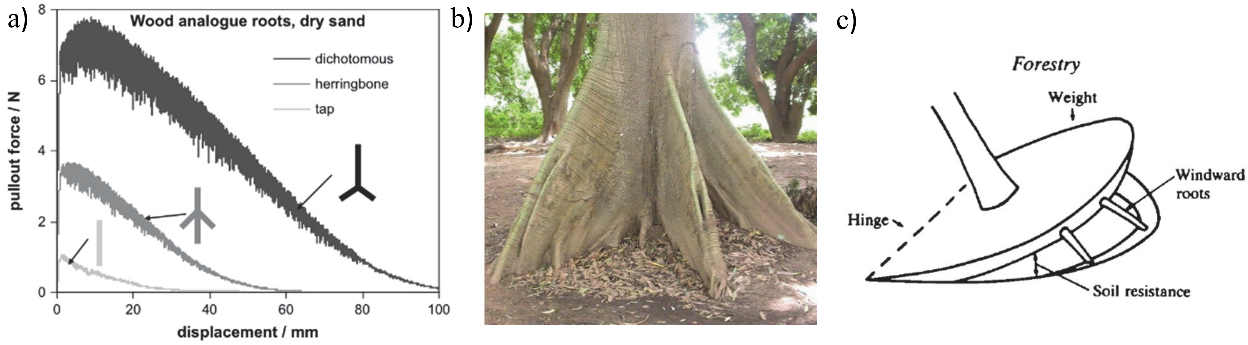


Figure 83. (a) change in pullout capacity as a function of branching (Mickovski et al. 2007), (b) extreme example of root elongation due to structural loading (http://www.eplantscience.com/index/root.php), and (c) components contributing to lateral pullout capacity.

***Design and Execution of Full-Scale Tree Pullout Test Program in UC Davis Orchards***

A unique full-scale field test program is currently underway at UC Davis. Through the development of our bio-inspired research approach and the literature review it became evident that (1) close study of the biological system (i.e. tree root systems) was important and (2) tree root systems vary tremendously with the surrounding environmental conditions. Collaboration with the Plant Science Department has provided access to an existing fruit orchard that is used for graduate teaching and research. This orchard, in which rows of six different fruit trees are planted yearly, provides access to a variety of different trees of the same age and under identical environmental conditions. Further, in current farming practices trees are typically grown by grafting a specific fruit species on to a root stock. In this orchard six different root stocks are used, and three of them vary substantially with respect to root architecture. The three root stocks that represent the range of architecture variations present are Myrobalan, Lovell, and Marianna.

The research program now underway is testing three year old trees. Three tests on each of the three different root stocks will be performed. A 5-ton gantry crane positioned over the tree provides displacement controlled uplift to gradually fail the trees in tension after the upper tree section has been cut off. Measurements during testing include axial load-displacement, surface displacement measurement to map the failure surface, surface accelerometer array to spatially monitor subsurface root failure in time, and photogrammetry to later reconstruct 3-D images of failure progression. After complete failure, the root mass and attached soil mass is weighed. Photogrammetry is then used for reconstruction of the root bulb architecture. Air-spade excavation will occur for a subset of the trees to exhume the surround root architecture remaining in the ground after testing of all trees is completed. Root samples will be obtained and tested in the laboratory to characterize the tensile root capacity. Mini-cone penetration testing and soil samplings are being performed adjacent to select trees as well.

The testing program is currently underway, with the load testing to be completed by end of September. Analysis will continue through much of Year 3. Figure 84 below shows an initial image during test setup.

Figure 84. Picture showing initial setup for field testing.

**Summary of other relevant work being conducted within and outside of the ERC and how this project is different.**

Related projects on bio-inspired root foundation systems are being performed at Georgia Tech (Frost) and at NMSU (Newtson). We have held several collaboration meetings during Year 2.

**Plans for the next year**

Year 3 activities will focus on the following:

- Complete report on literature review, highlighting concepts and ideas relevant to project goals.
- Execute full scale tree pullout test program of trees with different root architectures.
- Extract key observations/principles from field test program and abstract these ideas to conceptual anchorage designs.
- Begin DEM modeling of concepts to understand and quantify relative contribution of different identified mechanisms.

**Expected milestones and deliverables for the project**

Milestones and deliverables will include:

- Complete report on literature review.
- Completion and data report of field scale testing.
- Identification of conceptual ideas for bio-inspired foundation/anchorage systems.

**Member company benefits**

The development of more efficient foundation and anchorage solutions has the potential to increase performance efficiency, resulting in less material usage and fewer elements installed. Several of the current companies as well as others being courted to join the ERC work in the foundation/anchorage/retaining industries have expressed strong interest in the research program.

**If relevant, commercialization impacts or course implementation information**
None to date.

### 2.3.7 Thrust 3: Root-system Evaluation for Multi-function Foundation Bio-inspiration

**ERC Team Members**

*CBBG Faculty*
David Frost, GT
Jeannette Yen, GT

*Graduate Students*
Seth Mallett
Rodrigo Borela

*Undergraduate Students*
Caroline Colbert (REU)

**Project Goal**

The overarching goal of the proposed research is to provide insight into the performance of multi-function root systems which can lead to the development of novel construction configurations and techniques for the enhancement of common infrastructure systems, such as deep pile foundations and retaining structure anchorage systems.

**The project's role in support of the strategic plan**

This project aims to elucidate the anchorage and failure mechanisms of roots of varying architecture subjected to typical plant loading situations, including pullout extension (herbivores), compression (self-weight), and lateral (wind/earthquake) forces and use this insight to propose and develop new anchorage systems. Analogous synthetic root structures, instead of living roots, will be designed and utilized based on simplified optimal root architectures revealed in experimental studies. Test protocols and an associated taxonomy to characterize the behavior of typical root configurations on their own (no soil embedment) will be developed and then related to those of both model experiment results and discrete element method simulations of root-soil systems under various loading conditions.

**Fundamental Research, Education, or Technology Advancement Barriers**

Index tests will be developed to evaluate the response of various root systems under extension and compression loading conditions. Using an X-ray Computed Tomography (CT) system, soil samples with buried root structures will be imaged at various time increments during the loading procedure. Observation of the failure mechanisms will allow for a conceptual model to be formulated to predict the system capacity under the different loading scenarios for the various root architectures. The role of the root shape and surface characteristics will also be evaluated. Tests on real root systems as a function of time will also be constructed to provide insight into the evolution of capacity growth with time. The experiments on the analogue and real root systems will provide insight into the extent of the soil engagement in each of the cases. Experimental studies will be complemented by Discrete Element Model simulations of root-particulate systems.

**Any research aspect that involves foreign collaborations, especially indicating the length of time US faculty or students spent abroad conducting their work, and vice versa, and the value added of that work to the student's/faculty' work.**
A collaboration was established in year 1 of this project between Georgia Tech and researchers at the Port and Airport Research Institute (PARI) in Okosuka, Japan. This very productive collaboration enabled extensive X-ray CT testing to be performed during pull-out-tests on 3-D printed root analogues. A more recently established collaboration between Georgia Tech researchers and research from L3SR at Universite Grenoble Alpes, France is aimed at increasing international collaborations focused on studying root-inspired anchorage systems, particularly with respect to continuum based numerical simulations of root-soil anchorage systems. A third collaboration was established this year also with ENPC in Paris, France to focus on DEM numerical modeling of root anchorage systems. PhD student Seth Mallett spent 3 months at PARI in Summer 2016 supported on an NSF EAPSI Fellowship and 3 months in Summer 2017 at ENPC supported on an NSF IRES (International Research Experience for Students Fellowship. He also spent 2 weeks at L3SR working with researchers there on numerical modeling issues. Mr. Rodrigo Borela Valente attended a one week Winter School on computational micro geo-mechanics at L3SR in January 2017 supported by funds from the Higginbotham Chair.

**Achievements in previous years**
To begin to better understand the relationship between tree roots and the structural capacity of the roots as a foundation system, Year 1 studies involved both experimental and numerical simulations using root analogues. The analogues being used included un-branched and branched cables that incorporate many of the characteristics of tap roots as well as 3D printed roots that incorporate characteristics of fibrous roots. A selection of root analogues are shown in Figure 85.

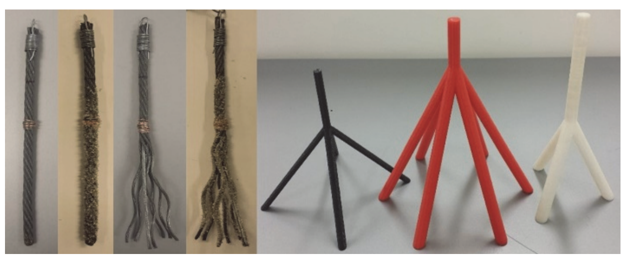

Figure 85. Selection of tap and fibrous root analogues.

Results from experimental pull-out tests conducted on un-branched and branched tap roots with and without friction (achieved by coating outside of root fibres with sand) show significant differences in terms of both peak and large displacement root resistance. Typical results are shown in Figure 86 and indicate that branched tap roots reach a larger peak than un-branched ones and also exhibit significantly less post-peak reduction in resistance. Further, roots with textured surfaces (higher friction) typically indicate higher pull-out resistance compared to their smooth-surfaced (lower friction) counterpart as seen in Figure 86.

Results from DEM numerical simulations of compression loading of fibrous root analogues further demonstrated differences between typical human-constructed and nature-constructed foundation systems. Figure 87 shows the force versus displacement response for different root analogues (straight, zig-zag, 15 degree splay and 30 degree splay). It can be seen that the common human implemented approach of using a straight shaft pile yields the lowest resistance while the large splay pile yields the largest resistance.

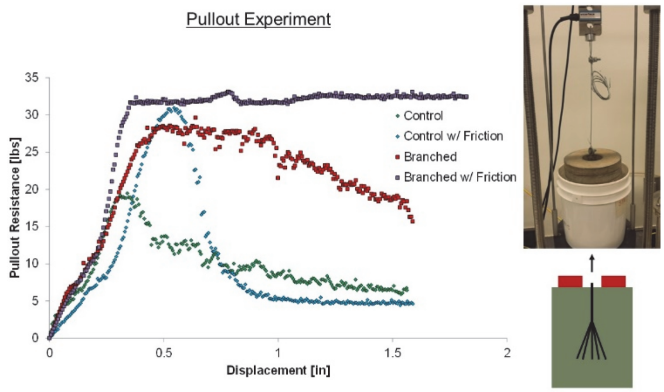


Figure 86. Pull-out resistance tests on tap root analogues.

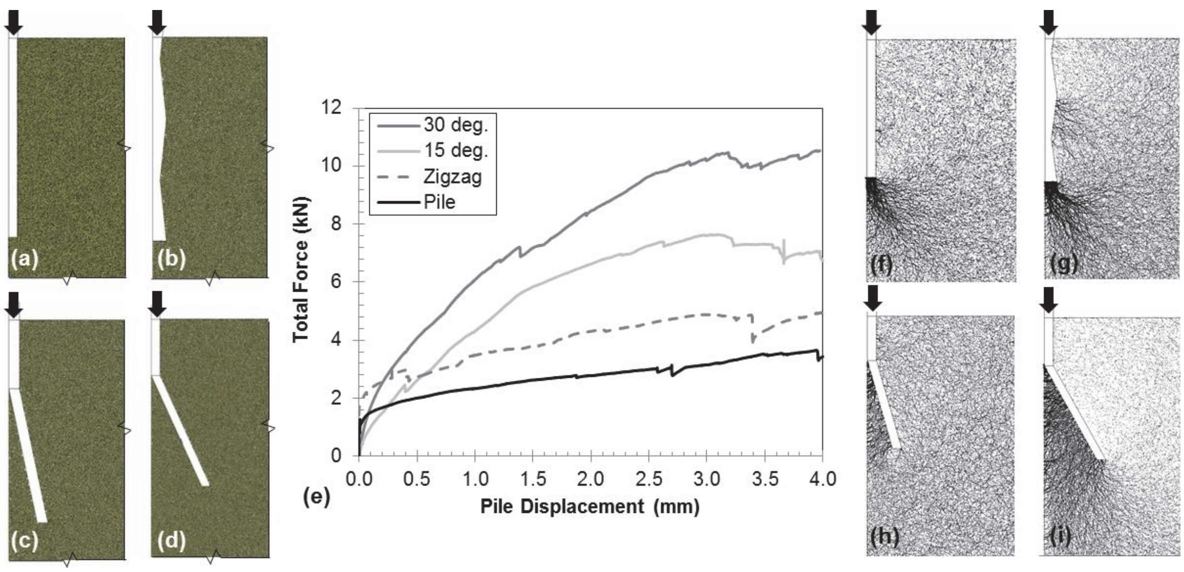


Figure 87. Close-up of setup (a) pile, (b) zigzag, (c) 15 degree and (d) 30 degree load test simulations. (e) Results of load tests. Force chain maps for (a) pile, (b) zigzag, (c) 15 degree and (d) 30 degree load test simulations.

## Achievements in past year

The pullout tests conducted in year 1 were completed with an extensive pullout testing program performed in an X-ray CT facility. The experimental set-up is shown below in Figure 88. Experiments performed using a range of root analog configurations including those with 3, 4 and 6 branches of different lengths at different orientations. A vertical section through one specimen along with the a horizontal CT scan showing concentric shear zones induced during the rot pull-out test are shown in Figure 89.

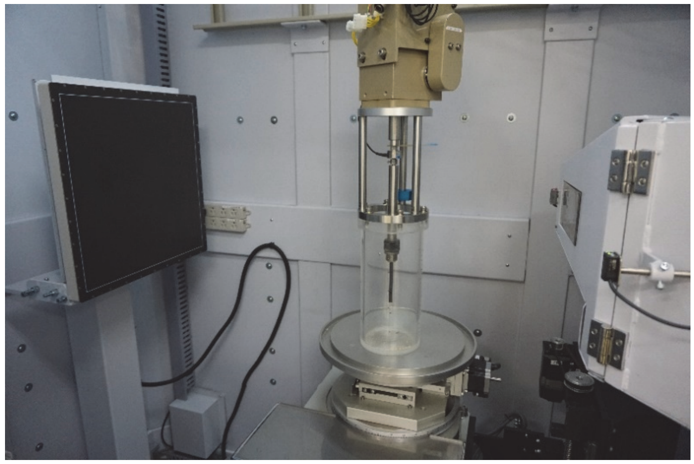

Figure 88. Root pullout chamber in X-ray CT scanner

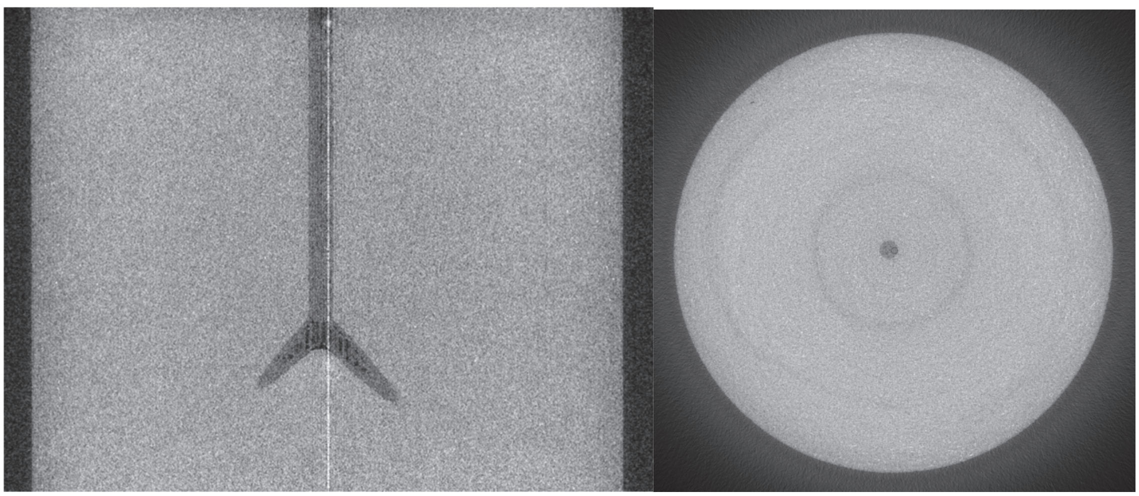

Figure 89. Vertical and horizontal sections through root analog in CT scanner.

Key project accomplishments in past year included:

- Completed preliminary characterization experiments on various root systems grown in lab including quantification of root topology and volume measurements.
- Conducted extensive program of pull-out tests on various root analogues using range of sands (sizes, angularity). Root analogues included 3-D printed roots as well as unbraided rope systems.
- Performed extensive program of compression/tension loading on 3-D printed root analogues to develop simple index test for root characterization.
- Performed 2-D DEM simulations of various root analogues in compression to demonstrate potential for non-straight (conventional) foundation elements to provide higher resistance.
- Initiated extensive pullout testing program on real root systems to develop understanding of evolution of root-soil anchorage mechanisms with time.
- Extensive analysis of time-lapse X-ray CT measurements to determine failure surfaces generated by root analogues with varying number of branches, length of branches, orientation of branches.

**Summary of other relevant work being conducted within and outside of the ERC and how this project is different**

Complementary research is being undertaken at UCD where the initial focus is on the study of full-scale root systems. In particular, natural root systems, such as trees, are providing the context for new bio-inspired foundation and anchorage systems. This is occurring through innovative capacity evaluation of full scale trees with different root topologies. Similarly, centrifuge testing of selected root analogues is scheduled and will be valuable to the further interpretation of the studies summarized herein.

**Plans for the next year**

These research tasks conducted during the next year of the project are expected to lead to a clear understanding of the interaction mechanics that occur between root analogues and soils and provide the basis for the develop of a rational theory which could be transferred to the design of a next generation of pile and anchor foundation systems that are bio-inspired and can yield a higher certainty of performance at a lower cost than current systems.

6. Complete lab pullout tests on 3-D printed root analogues including varying moisture and surcharge conditions.
7. Complete X-ray CT experiments including additional experiments on root analogues in compression.
8. Performed additional 2-D DEM simulations of various root analogues in extension to complement X-Ray CT experiments and demonstrate potential for non-straight (conventional) root inspired anchorage elements to provide higher capacities.
9. Perform analyses to identify optimal foundation/anchor configuration to yield highest capacities.
10. Begin development of concepts for installation of non-conventional foundation and anchor elements as critical -cursor to moving project from Fundamental Knowledge to Enabling Technology plane.

**Expected milestones and deliverables for the project**

The successful completion of this project is expected to lead to a number of contributions as follows:

Quantification of the extent of "bulb" contributing to root anchorage capacity in both tension and compression;

Development of new sensing systems to capture large scale response;

Improved understanding of root-soil interaction mechanisms;

Development of appropriate root analogues for model studies (bench scale, centrifuge and numerical).

**Member company benefits**

Longer-term benefits of the project will be the development of next-generation multi-function self-adaptive anchorage systems that yield sustainable, resilient geotechnical systems.

**If relevant, commercialization impacts or course implementation information**

None advanced at this stage of project.

## 2.4 Thrust 4: Cross-Cutting Research

### 2.4.1 Thrust 4: Geotechnics of Bio-locomotion and Self-Excavating Systems

**ERC Team Members**

| *CBBG Faculty* | *Graduate Students* |
|---|---|
| David Frost, GT | Mahdi Roozbahani |
| Dan Goldman, GT | Rodrigo Borela |
| | Karie Yamamoto (after May 2017) |
| | |
| | *Undergraduate Students* |
| | Karie Yamamoto (before May 2017) |
| | Sebastian Rico (REU) |

**Project Goal**

Traditional methods for exploration of the subsurface for site characterization and monitoring purposes have involved insertion of devices from the surface and thus development of a model of the subsurface is based on limited near vertical penetrations that traverse what are often predominantly near horizontal strata. Similarly, installation of subsurface infrastructure components and systems have typically relied on access to the subsurface from the surface although tunneling and other pipe-jacking systems allow for greater orientation control in developing underground spaces and conduits.

**The project's role in support of the strategic plan**

This project seeks to explore how subsurface bio-locomotion and self-excavating systems can provide new insights and thus concepts that can be ultimately leveraged to enhance the sustainability and resiliency of subsurface space development for infrastructure construction and hazard mitigation purposes.

**Fundamental Research, Education, or Technology Advancement Barriers**

The transformative contribution of this project is embodied in (i) the unique physical microscale experiments to be conducted and (ii) the complementary use of both physics-based particulate modeling approaches and network analysis methods. Through study of ant-tunnels and bio-interfaces, the study will seek to provide new unique insight into the efficiency with which biota explore and pervade different subsurface environments. The research team will use a combination of microscale experimental and observational methods in conjunction with DEM simulation systems to develop new insight into the geotechnics of bio-locomotion and self-excavating systems. The experimental methods will seek to characterize and understand what factors contribute to the geometry of the subsurface network of tunnels and chambers excavated by ants while the particulate modeling simulations will study issues such as the role of force chains in the overall stability of real subsurface ant structures.

**Any research aspect that involves foreign collaborations, especially indicating the length of time US faculty or students spent abroad conducting their work, and vice versa, and the value added of that work to the student's/faculty' work.**
A collaboration was established this year with ENPC in Paris, France to focus on DEM numerical modeling and network analysis to self-excavating systems. PhD student Mahdi Roozbahani spent 3 months in Summer 2017 at ENPC supported on an NSF IRES (International Research Experience for Students Fellowship. Mr. Rodrigo Borela Valente attended a one week Winter School on computational micro geo-mechanics at L3SR in January 2017 supported by funds from the Higginbotham Chair.

**Achievements in previous years**
It has widely accepted that ants use less than 0.1% of the energy that the most advanced human tunnelling machines do to excavate the same volume of soil. It is believed that ants are able to do so since they perform their tunnelling activities using a variety of approaches which seem to minimize the amount of energy expended at each step including tunnelling around obstacles, not removing particles that are deemed critical to supporting the surrounding soil particles (particles that are part of primary force chains) and creating clumps of several smaller particles as appropriate before removing them from the tunnel. These insights have been gleaned from both observing their behaviour while tunnelling as well as studying the characteristics of castings of the ant hill structures they create. An image with a "harvester-ant" nest casting is shown in Figure 90.

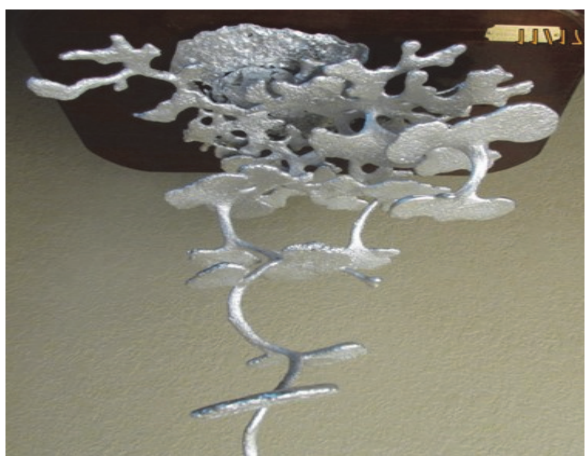

Figure 90. Harvester ant nest casting after removal of soil.

Discrete Element Modeling (DEM) simulations of the influence of soil arching in cavity stability have also been undertaken. In the current study, DEM simulations using the PFC2D software (Itasca, Inc.) were employed to model and analyze the effects soil arching on the stability of cavities within granular media. To construct the model, 10,000 particles were poured inside a rectangular container. Particles were randomly generated and their size varied between 0.004 and 0.01 (particle size/container width). Once the assembly reached a state of equilibrium after the pouring process, fixed parallel bonds were created between at particle contacts in order to simulate capillary forces that allowed for the creation of stable cavities of different sizes.

As shown in Figure 91, the stability of cavities was examined in 15 different cases, consisting of cavities of different sizes and in different locations within the assembly. The width of the cavities was varied in proportion to the Maximum Particle Size (MPS) in multiples of 10. The height of the cavities was fixed to 10*MPS, while their width was varied from 10 to 50*MPS. For the combined cavities simulations, the upper cavities had a fixed width of 40*MPS. As shown in the figure, the upper cavity collapsed when it reached a width of 50*MPS (Figure 91a), while the lower cavity collapsed when it reached a width of 40*MPS (Figure 91b). The decreased stability of the lower cavity as compared to the upper one is a result of the higher overburden stress acting at the cavity ceiling. For the combined case (Figure 91c), the lower cavity was more stable than for the lower only case (Figure 91b). In fact, the lower cavity for the combined case was stable at a width of 40*MPS and collapsed only when its width was enlarged to 50*MPS. The presence of the upper cavity altered the state of stresses in its vicinity, orienting the principal stresses horizontally around the rectangular cavity. This resulted in smaller vertical stress acting on the ceiling of the lower cavity as compared to the case when the upper cavity was not present.

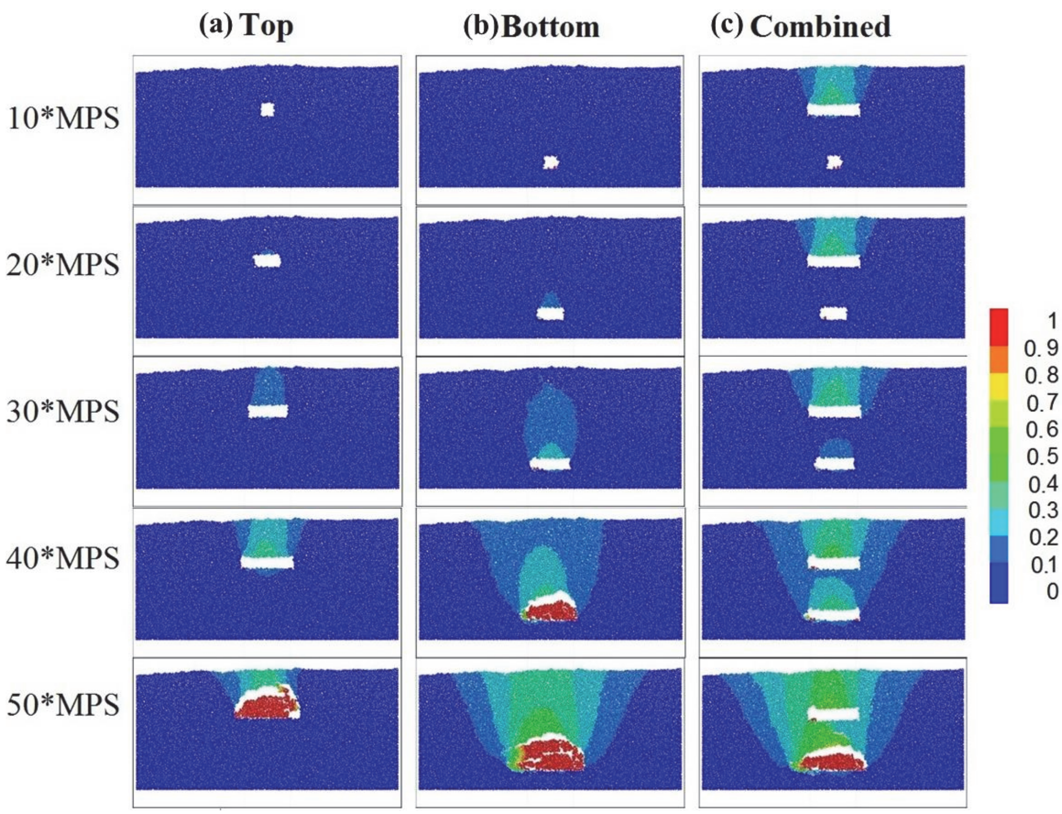


Figure 91. Particle displacements as a result of the presence of cavities at different locations.

The results of these simulations show that complex excavation geometries with overlying cavities promote stability by means of the modification of the state of stresses. It should be mentioned that the increase in stability was not observed when circular cavities were simulated, possibly because the zone of altered state of stresses was smaller. This is a compelling argument that can explain the reason why the chambers in ant nests have flat and elongated shapes instead of spherical shapes, as shown in Figure 90.

**Achievements in past year**

The work planned for the next year seeks to build on the initial experimental observations and DEM simulations performed to date. In particular, a time-lapse observational facility that was developed in Year 1 of the project is now being used extensively to study the tunneling behavior of several ant types in a variety of soil types with different moisture conditions and densities. These observations and measurements acquired under controlled laboratory conditions will be used to provide insight into the characteristics of ant hill structures recovered from the natural field environment. Quantitative characterization of the resulting laboratory and field structures will be used to inform additional DEM numerical simulations of the soil mechanics principles which ants may be practicing in their tunneling activities.

In addition to conducting physics based numerical simulations such as with a conventional DEM code, the research is expanding the exploratory study undertaken in Year 1 of the project that used network analysis as a possible approach to develop a more efficient computational approach to study force chains in a particulate subsurface medium. By considering the soil particles as nodes in a network similar to routers in a computer network and the contact forces between the soil particles as equivalent to the flow of information between routers in a network, it may be possible to develop a much more computationally efficient approach to determining the force distribution in the network (e.g. force chains). The advantages of a more computationally efficient approach and tool are significant in that they could enable simulations of much larger volumes of particles than currently feasible. The potential benefits of this could also extend far beyond the study of self-tunneling systems in the subsurface and lead to a new generation of computational tools for studying particle system response to external stimuli.

Key project accomplishments in past year included:

- Conducted preliminary physical experiments of ants tunneling in lab using 2-D time lapse photography system developed for project.
- Conducted detailed characterization of commercial 3-D ant hill structures to quantify topology of different structures as function of ant type, soil type and soil moisture.
- Conducted numerical simulations of ant tunnels in granular materials. Different combinations of tunnel sizes and configurations simulated to assess influences on force chain magnitudes and distributions.
- Performed initial study of applying network analysis to study of force chains surrounding ant tunnel structures.

**Summary of other relevant work being conducted within and outside of the ERC and how this project is different**

A related project is being undertaken at NMSU with a focus on worms. An annelid's body consists of a flexible membrane with circular and longitudinal muscles enclosing a relatively incompressible fluid (Trueman, 1978). The two muscle-groups work in synchrony with the fluid: contraction of the radial muscles displaces the fluid which causes longitudinal muscles to extend. Conversely, contraction of the longitudinal muscles displaces the fluid causing radial fibers to extend; thus, avoiding the need for an osseous structure. Earth worms move within the ground by expanding and contracting their body using the soil for reaction. Motion starts when the worm anchors (radial expansion) its back end against the soil. This allows it to use the soil for support so that when it extends (axial expansion) it can advance. The front then expands while the back tail relaxes allowing the worm to move forward, and the cycle is repeated. Since annelids are invertebrate, the internal volumetric changes involve hydro-mechanical coupling (peristaltic locomotion).

**Plans for the next year**

1. Complete and analyze 2-D lab experiments of ants tunneling in various subsurface conditions (variations in grain size, moisture content, subsurface anomalies/obstacles)
2. Perform several in-situ ant-hill experiments with detailed adjacent geotechnical characterization to correlate ant hill topology to geotechnical properties/conditions.
3. Perform 2-D and 3-D numerical simulations using DEM to explore stress fields around ant hill structures and assessing impact of structure geometry on tunnel/opening stability.
4. Expand network analysis studies and compare physics-based DEM findings with network analysis findings. Objective here is to develop analysis technique that can allow for study of larger structures with enhanced computational efficiency.

**Utilize results from textured and smooth surface sleeves to develop prototype multi-segment probe that can self-advance in subsurface through ratcheting process. Expected milestones and deliverables for the project**

The successful completion of this project is expected to lead to a number of contributions as follows:

An enhanced understanding of the soil mechanics of ant tunneling;

Understanding of the purpose of chambers and adits in ant tunnels and the degree to which these could be replicated in human tunnel systems to reduce energy consumption;

Insights into how to scale the low energy tunneling methods practiced by ants into human systems;

An improved understanding of the role of interface roughness in subsurface mobility;

Development of low energy self-motile devices that can lead to a new paradigm in the collection of subsurface information for characterization and mobility purposes.

**Member company benefits**

The long-term benefits of this study will be the development of next-generation sensors and devices that can allow for the efficient exploration and development of underground spaces to support human existence on earth.

**If relevant, commercialization impacts or course implementation information**

None advanced at this stage of project.

### 2.4.2 Thrust 4: Hydrogel-Enhanced EICP for Soil Stabilization

**ERC Team Members**

*CBBG Faculty*
Ximin He, ASU (currently UCLA)
Edward Kavazanjian ASU

*Other Research Staff*
Mo Sun, ASU (currently UCLA)
Hamed Khodadadi Tirkolaei

*Graduate Students*
Chiao-Yueh Lo, UCLA

*Undergraduate Students*

**Project Goals**
The goal of this project is enhance the performance of soil improved by polymer-assisted enzyme induced carbonate precipitation (EICP). The objective is to develop a high-performance soil strengthening method that has high and tunable mechanical strength and ductility, high stability under dry and wet condition, long-term sustainability, and is environment friendly (i.e., with minimum harmful by-products) at a low cost and with high throughput.

**The project's role in support of the strategic plan**
Enzyme induced carbonate precipitation (EICP) is one of biogeotechnical technologies being developed by the CBBG for stabilizing cohesionless soil. Stabilization of cohesionless soil with EICP is a cross cutting technology with applications in Hazard Mitigation, Environmental Protection and Ecological Restoration, and Infrastructure Construction.

Aggregation of loose cohesionless granular soils using EICP can reduce wind or water erosion at the earth surface, thereby mitigating not only soil erosion but also natural disasters such earthquake-induced liquefaction and mudslides. It can also be used to increase the bearing capacity of foundations, and instability in underground construction and excavations.

Furthermore, enhancement of EICP with a hydrogel (a water-loving polymer) can mitigate the generation of undesirable byproduct problems by EICP and provide an additional benefit by strengthening the EICP-treated soil. However, poor durability upon rehydration caused by the swelling behavior of the hydrogel in a hydrogel-enhanced EICP limits its application in humid environments and moist conditions. Therefore, we are designing and developing novel hydrophobic-hydrophilic copolymers to replace hydrogels to reduce the swelling effect caused by rehydration of the polymers. The enhanced resistance against rehydration makes our soil treatment method more promising for application in geotechnical practice.

**Fundamental Research, Education, or Technology Advancement Barriers**
Fundamental research and technology advancement questions that must be answered in our ongoing work include:

- What are the chemical and physical interactions at the complex hydrogel-EICP-soil interfaces?
- What are the respective roles of hydrogels and calcite in the structure, chemical, and mechanical properties of the improved soil?

- How do we prevent strength loss after treatment when the soil is rehydrated? Is polymer swelling the only factor contributing to strength loss?
- Can we fabricate new materials to mitigate the rehydration problem without adding harmful reactants or generating unnecessary byproducts?
- How do we precisely control the penetration depth of a precursor solution, which is the main advantage of using a liquid precursor rather than polymer powder?
- What is the long-term stability of the treated soil, in particular considering wind and UV exposure?
- What factors are crucial in the field that we have not yet considered in our bench-top experiments?
- What is the cost of achieving a specified level of treatment?

**Any research aspect that involves foreign collaborations, especially indicating the length of time US faculty or students spent abroad conducting their work, and vice versa, and the value added of that work to the student's/faculty' work.**
N.A.

**Achievements in previous years**
In the first year of CBBG operation, we developed an injectable precursor synthetic hydrogel, polyacrylic acid (PAA), as an alternative to use of a natural hydrogel powder for soil improvement. The injectable precursor we developed is advantageous over hydrogel powder treatment in terms of (1) it can be cured in-situ in soil over controllable time; (2) it facilitates the carbonate precipitating into composites to form a uniform gel-calcite-soil network; and (3) concurrent polymerization of root-like hydrogel with calcite precipitation considerably increased the mechanical strength of the improved soil, as illustrated in Figure 92.

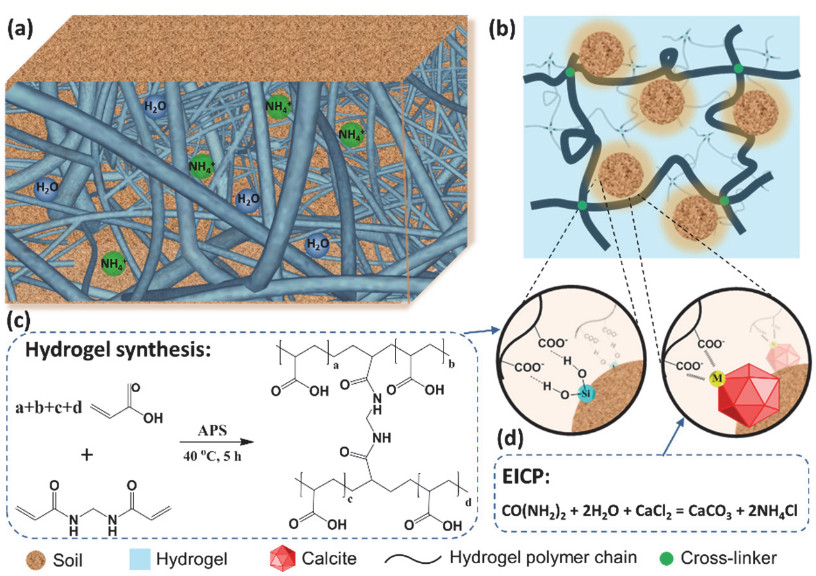


Figure 92. (a) A conceptual image of the hyper-branched hydrogel network formed by PAA with the soil matrix that resembles plant roots, providing good water retention and contaminant ($NH_4^+$) mitigation; (b) A schematic diagram showing the expected interactions between the hydrogel and soil particles or the calcite crystals from ECIP. Inset: zoomed in image of the hydrogel bonding (left) and complexation interactions (right); (c) The reaction formula of hydrogel synthesis; (d) The reaction formula of EICP.

**Accomplishments in the past year**

In the past year, we focused on improving the durability of treatment when the soil is rehydrated. Although the injectable polyacrylic acid (PAA) hydrogel showed promising result on soil treatment, we observed that some hydrogel-soil samples tend to crumble when the sample is rewetted and dried. This loss in soil strength upon rewetting obviously limits the applicability of this technique in the field. It was assumed that the swelling of the hydrogel upon rewetting damages the hydrogel-soil network, resulting in sample breakdown. To mitigate this limitation, in year 2 we: 1) Customized a hydrophilic-hydrophobic copolymer as an alternative to PAA; 2) Demonstrated that this copolymer greatly reduced the swelling ratio; and 3) initiated testing that showed the use of this copolymer can mitigate damage upon drying and re-wetting the soil.

*Customized hydrophilic-hydrophobic copolymer*

Based on the research above and our previous results on PAA enhanced EICP, we customized a new recipe specifically for our enhanced EICP soil stabilization system. We incorporated hydrophobic components, long-chain alkanes of different chain lengths, to copolymerize with hydrophilic monomers to form hydrophilic-hydrophobic copolymers by referring to the PAA-based copolymer work of Tuncaboylu (2014). By copolymerizing a hydrophobic monomer, stearyl methacrylate (C18), with hydrophilic acrylic acid (AA), the swelling ratio was reduced and energy damping ability was improved comparing to AA. Due to the low solubility of C18 in water, a surfactant, Sodium dodecyl sulfate (SDS), was added to conduct polymerization. In addition, a common electrolyte, NaCl, was added to increase the solubility of C18.

To facilitate practical application, we replaced AA by Acrylamide (AM) in our copolymer. Due to higher reactivity of AM, the copolymerization can occur at room temperature, as opposed to 40$^{o}$C for AA system. For further customizing, we changed the surfactant from an anionic SDS to a cationic Cetyl trimethylammonium bromide (CTAB). We proved that CTAB is capable of mediating hydrophobic C18 to copolymerize with hydrophilic AM as well as SDS.

*Reduced swelling ratio*

The swelling ratios of the hydrophobic-hydrophilic copolymers we created were found to decrease with increasing hydrophobic content, as illustrated in Figure 93 and in agreement with our expectations. However, a high surfactant concentration increased the swelling ratio, compensating for the improvement achieved by introducing hydrophobic content. In addition, the surfactant increases precursor solution viscosity, this may be beneficial when treating coarse grained soil but may cause problem when treating finer grained soil with a relatively low water permeability (e.g. silt). Thus, the surfactant concentration must be optimized for the particulars of any situation.

*Use of copolymers without surfactant*

In our studies on C18-AM copolymers, high hydrophobic content in the copolymer reduced the swelling ratio and a high surfactant (CTAB) concentration was essential to achieving a high hydrophobic content. However, high surfactant and electrolyte concentrations led to entanglement of surfactant micelles, which dramatically increases viscosity and forms white micelle aggregates in the precursor solution, blocking further reactions in the solution (Figure 94). This drawback limits our probable design of recipes with high hydrophobic content.

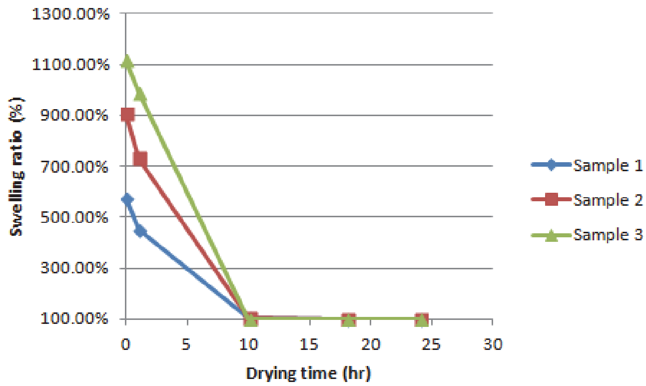


Figure 93. When CTAB concentration is at saturation (Sample 3), the swelling ratio increases compared to when it is not saturated (Sample 2). When both CTAB and C18 concentration are saturated (Sample 1), the swelling ratio decreases.

Figure 94. High surfactant concentration results in highly viscous, cloudy precursor solution.

To overcome the limitations associated with use of a surfactant, we introduced monomers such as HEMA and Dopamine, which are less hydrophilic than AM but have an acceptable solubility in water. Thus, we can avoid the need to add a surfactant to induce copolymerization. Preliminary mechanical test results on this category of copolymers show improved soil sample rehydration resistance (Figure 95).

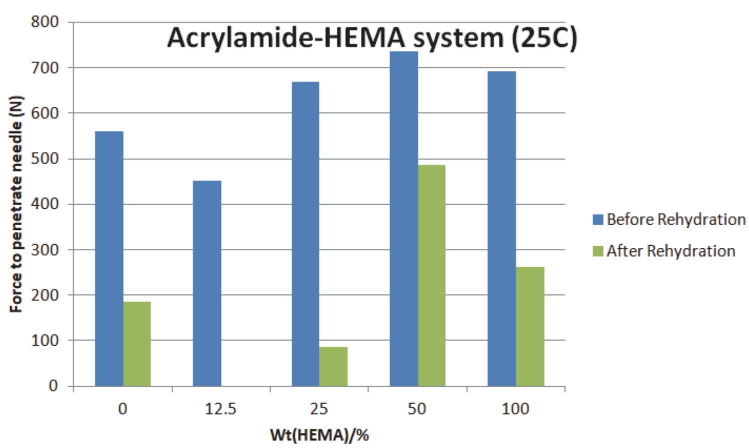


Figure 95. Reduced strength loss after rehydration of soil treated by copolymer with HEMA.

**Summary of other relevant work being conducted within and outside of the ERC and how this project is different**

Related work being conducted within the ERC includes research on ground improvement via microbially induced carbonate precipitation (MICP) and research on ground improvement via enzyme induced carbonate precipitation (EICP). Potential applications of both techniques include soil stabilization. As part of CBBG infrastructure development, a large test pit and a rainfall simulator are being constructed on the ASU Polytechnic campus that will serve as a test bed for field scale development of these carbonate precipitation technologies for soil improvement and erosion control. These tests can include enhancement of carbonate precipitation using hydrogels.

**Plans for the next year**

- Explore less hydrophobic monomers to copolymerize with PAA or PAAm, which can be polymerized without surfactant while retaining good rehydration resistance.
- Explore new copolymers with better adhesion with soil particles to enhance the mechanical strength.
- Conduct dynamic analysis on polymerization of liquid precursor, including the effect of temperature, reactant, and initiator, to achieve control on the penetration of the liquid precursor solution.
- Initiate field scale experiments to evaluate the interaction with and durability of soil under natural weather condition after treatment with copolymers for erosion control.

**Expected milestones and deliverables for the project**

It is anticipated that bench top evaluation of a series of hydrophobic-hydrophilic copolymers can be completed by year 3. The effectiveness of this technology at a field site and environmental impact evaluation will take place by the end of year 4. By the end of year 5, the technology will be available for deployment for erosion control on actual infrastructure projects.

**Member company benefits**

A practical technique for surficial and subsurface soil stabilization is of significant interest and great benefit to member companies engaged in ground improvement specialty contracting, including Hayward Baker, Nicholson Construction, Schnabel Construction and GeoPier, who could market the technology nationally and internationally. It is also of interest to the facility owners who are members of the Industrial Partner Program, including Republic Industries and Freeport McMoRan, and the public agencies who are Associate members, as they all have facilities at risk from fugitive dust emissions (an important application for this technology).

**If relevant, commercialization impacts or course implementation information**

Information on this technique and its potential benefits has been incorporated in graduate classes on Bioinspired Materials (senior and graduate level, lectured by Dr. He) at Arizona State University (2016 ASU) and currently at UCLA (2017 Spring). It will also be incorporated in a new graduate level class on Biogeotechnical Engineering at ASU next fall.

### 2.4.3 Thrust 4: Laboratory for Bio-mimetic and Bio-inspired Studies

**ERC Team Members**

*CBBG Faculty*
David Frost, GT
Chloe Arson, GT
Wendy Newstetter, GT

*Graduate Students*
Rodrigo Borela
Karie Yamamoto (after May 2017)

*Undergraduate Students*
Karie Yamamoto (before May 2017)

**Project Goal**

The goal of this project is to develop unique laboratory facilities at Georgia Tech to serve as a catalyst in understanding the processes by which nature achieves efficiency in design, form and function and to use this as the basis for identifying new avenues for bio-mimicry and bio-inspiration, particularly as it applies to geotechnical engineering.

**The project's role in support of the strategic plan**

The strategic plan of CBBG includes as a stated goal, the establishment of bio-geotechnical engineering as a sub-discipline. To achieve this requires a broad strategy that encompasses formal and informal education activities, research and outreach. A critical element to achieving this is a "space" where new concepts can be brought to life either by participating in physical experiments, engaging in numerical simulations and even leveraging the latest in immersive technologies where real and simulated experiences can be merged to advance learning and understanding.

**Fundamental Research, Education, or Technology Advancement Barriers**

An all too frequent challenge that is encountered when a new field is conceived is that it is envisaged at the intersection of existing fields of endeavor. In the case of bio-geotechnics, the challenge is one of bringing scientists (principally biologists) and engineers (principally geotechnical engineers) together. From the outset, they lack a common vocabulary, have different approaches to research and education and often have long-held opinions of how to advance their own field. The challenge is that they end up talking "at each other" and not "with each other". A strategic approach to resolving this type of impasse is to establish "new spaces" where both sides might be described as being equally uncomfortable or comfortable. This project seeks to develop just such a space for shared discovery.

**Any research aspect that involves foreign collaborations, especially indicating the length of time US faculty or students spent abroad conducting their work, and vice versa, and the value added of that work to the student's/faculty' work.**

None at this time.

**Achievements in previous years**
Efforts in Year 1 of CBBG had focused on identifying the space and requirements for the lab. This included engaging individuals from both biological science and geotechnical engineering disciplines to identify what types of equipment and environments could best achieve the desired goal of developing the new field of bio-geotechnics and at the same time co-locating a suite of experiments and technologies that could best support this goal.

**Achievements in past year**
This past year has seen significant developments in terms of the fabrication and acquisition of a range of devices that achieve the desired goals of engaging undergraduate and graduate students through both research and educational activities in developing an understanding of the new field of bio-geotechnics. Examples of test systems include:

- Development of a time lapse photography facility to allow for capture of ant-tunneling activities in 2-D chambers;
- Acquisition and adaptation of a load frame and data acquisition system to allow for precise measurements of load and deformation during pull-out tests on root and root analogue systems;
- Upgrading of a micro-scale X-ray CT system to allow for study of pore spaces in soils and their potential interactions with root systems;
- Mini-experiments that can be performed with Arduino kits for coding and electronics systems are being devised and developed to support research into bio-locomotion and self-excavating systems;

**Summary of other relevant work being conducted within and outside of the ERC and how this project is different**

Extensive efforts being led by the CBBG IDEA working group have led to the establishment of a range of education, diversity and outreach initiatives including NSF supported REV, RET, REU, and Young Scholars programs amongst others. Further, lecture slide decks have been prepared for use at all CBBG partner universities to introduce the new field of bio-geotechnics. Completing the development and commissioning of the lab for bio-mimicry and bio-inspiration will be valuable in furthering and complementing these efforts.

**Plans for the next year**
The plans for the next year are to complete the development of the lab for bio-mimicry and bio-inspiration through the acquisition of a number of additional devices as follows:

- Develop a large scale chamber system for use in scale-up pullout tests of new anchorage systems;
- Acquisition and testing of range of AR/VR systems for bio-geotechnical issues. This will likely include acquisition of devices including MS Hololens as well as other competing systems that are expected to be available in the next 6 months.
- Acquisition and commissioning of a digital confocal microscope to allow for study of plant root topography as well as other bio-inspiration studies;

**Expected milestones and deliverables for the project**

The Year 3 mid-year meeting will be held at Georgia Tech in April 2018 and this represents a firm deadline for completing the development and utilization of the various systems to be incorporated in the lab.

**Member company benefits**

While there may be some direct benefits to member companies to use the equipment in the bio-mimicry and bio-inspiration lab and results obtained with it in marketing potential new technologies being developed by CBBG researchers, it is likely that in the next couple of years, a greater benefit will accrue to them through the insights that CBBG students have as a result of being able to access the bio-mimicry and bio-inspiration lab.

**If relevant, commercialization impacts or course implementation information**

The lab will be used in an existing course on bio-inspired design that is cross listed in both the School of Biological Sciences as well as several of the engineering schools. CBBG is a core member of a working group at Georgia Tech that is exploring the potential role and benefits of AR/VR systems in STTEM education.

### 2.4.4 Thrust 4: Life Cycle Sustainability Assessment Framework for Geotechnical Engineering

**ERC Team Members**

*CBBG Faculty*
Alissa Kendall, UC Davis

*Other Research Staff*

*Graduate Students*
Alena Raymond
James Tipton

*Undergraduate Students*

**Project Goals**
The goal of this project is to develop a life cycle sustainability assessment (LCSA) framework for geotechnical engineering and to apply this framework to CBBG projects to encourage sustainability-oriented innovation in geotechnical solutions.

**The project's role in support of the strategic plan**
The LCSA framework is used to inform CBBG project selection and to guide innovation as projects mature through each of the 3-planes (i.e., fundamental knowledge, enabling technologies, and systems). The LCSA framework is also a mechanism for industry engagement through the development of benchmark LCSAs, which include cost assessments. Industry partners also inform assessment of feasibility and cost for proposed technologies (once research and development is sufficiently mature) as part of the LCSA process.

**Fundamental Research, Education, or Technology Advancement Barriers**
Fundamental research questions that must be answered to develop a standardized LCSA approach for evaluation of geotechnical systems include: 1) what is the appropriate scope and methods for environmental life cycle assessment (ELCA) of geotechnical systems; and 2) what level of detail and predictive capabilities are required for robust analysis outcomes at the research and development stage of technology development. Barriers to advancing this research include: 1) the maturity of CBBG projects, which affect the availability of data and information required for LCSA of a given technology; 2) the development of a life cycle inventory database and modeling approach to streamline assessment; and 3) collecting estimates of damage costs for pollutants to provide a mechanism for including pollution damage costs (i.e., externalities) in life cycle cost analysis (LCCA).

**Any research aspect that involves foreign collaborations, especially indicating the length of time US faculty or students spent abroad conducting their work, and vice versa, and the value added of that work to the student's/faculty's work.**
None to report.

**Achievements in previous years**

- Development, piloting, and dissemination of LCSA Questionnaire for CBBG project proposals.
- Development of two Example LCSA Questionnaires for instructive purposes.
- Completion of a comprehensive literature review of LCSA in the geotechnical field (with a focus on ELCA) to provide a critical review on the state of the practice, identify gaps,

and propose best practices for ELCA in the geotechnical engineering field. A manuscript for peer review was submitted in 2016.

**Achievements in past year**

- Revision and refinement of LCSA Questionnaire, which is now CBBG Annual Project Evaluation Report 2: Life Cycle Sustainability Assessment (Report 2). Development of a standardized approach to rating and feedback of submitted Report 2s, entitled *Summary LCSA Evaluation Statement* (referred to as "Outcomes Memo" in last year's project report).
- Completion of evaluation for all submitted Report 2s. This included two quantitative ELCAs for projects with enough data and information to support quantitative analysis (MICP and root-inspired foundations), and qualitative evaluations of all other submitted projects.
- Acceptance and online publication of one peer-reviewed journal paper entitled "Review of life-cycle-based environmental assessments of geotechnical systems" (http://dx.doi.org/10.1680/jensu.16.00073). This article critically reviews the body of previous work on LCA applied to geotechnical systems through a parametric assessment, summarizing the state-of-the-practice, identifying the sources of uncertainty and variability that lead to divergent results and conclusions, and developing recommendations for future LCAs of geotechnical systems. Figure 96 below summarizes our findings with respect to previous studies, and illustrates the limited number of infrastructure types assessed and the relatively small number of peer-reviewed studies that have been published:

Figure 96. Summary of Identified Literature of LCA applied to Geotechnical Systems

| Study No. | Primary Author | Year | Publication Type | Peer Reviewed | Infrastructure Type | Region of Study | Assessment Method |
|---|---|---|---|---|---|---|---|
| 1 | Chau | 2008 | CP | No | RW | UK | Process-Based |
| 2 | Storesund | 2008 | CP | No | RW | US | EIO-LCA |
| 3 | Rafalko | 2010 | CP | No | MSE RW | US | Process-Based |
| 4 | Inui | 2011 | JA | Yes | RW | UK | Process-Based |
| 5 | Soga | 2011 | JA | Yes | RW | UK | Lit. Review |
| 6 | Lee | 2015 | CP | No | MSE RW | -- | Process-Based |
| 7 | Giri | 2015 | CP | No | RW | US | Process-Based |
| 8 | Damians | 2016 | JA | Yes | RW | -- | Process-Based |
| 9 | Phillips | 2016 | CP | No | RW | US | Process-Based |
| 10 | Misra | 2010 | MT | Yes | DF | -- | Process-Based |
| 11 | Giri | 2014 | CP | Yes | DF | US | Process-Based |
| 12 | Spaulding | 2008 | CP | No | GI | US, AU | Process-Based |
| 13 | Pinske | 2011 | MT | Yes | GI | US | Process-Based |
| 14 | Shillaber | 2015b | JA | Yes | GI | US | Hybrid LCA |
| 15 | Walker | 2014 | CP | No | Other | UK, DE, DK | Lit. Review |
| 16 | Chau | 2012 | JA | Yes | Other | UK | Process-Based |

Note: CP = conference paper; JA = journal article; MT = Master's thesis; RW = retaining wall; MSE = mechanically stabilized earth; DF = deep foundation; GI = ground improvement; UK = United Kingdom; US = United States; AU = Australia; DE = Germany; DK = Denmark

Figure 97 describes the sources of variability and uncertainty in LCAs of geotechnical systems. Though some of these sources are common in LCAs of many types of systems, the site-specific nature of geotechnical solutions is a particular challenge for LCA.

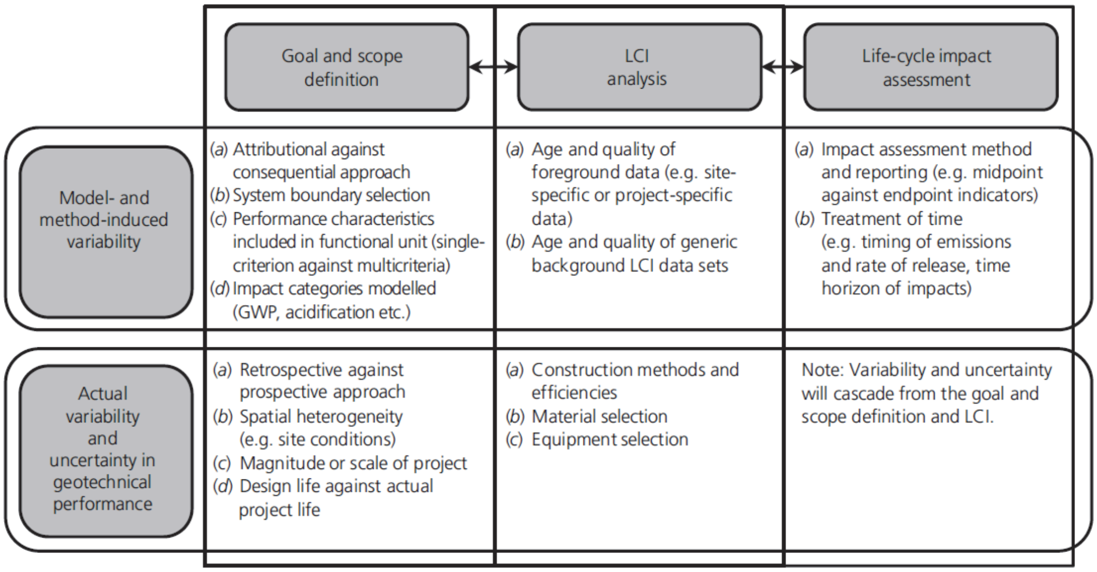


Figure 97. Sources of Variability and Uncertainty in Geotechnical LCA

- Acceptance and online publication of one conference paper entitled "Life-Cycle Assessment of Ground Improvement Alternatives for the Treasure Island, California, Redevelopment" (https://doi.org/10.1061/9780784480434.037) and accompanying presentation by Alena Raymond at the Geotechnical Frontiers 2017 conference in Orlando, Florida. This study compared the environmental and economic impacts of five ground improvement methods for the possible redevelopment of Treasure Island in San Francisco, California. For each improvement method, the study used LCA to assess the energy, global warming potential, acidification potential, smog formation potential, project cost, and social cost of carbon. The scope of analysis is illustrated in Figure 98.

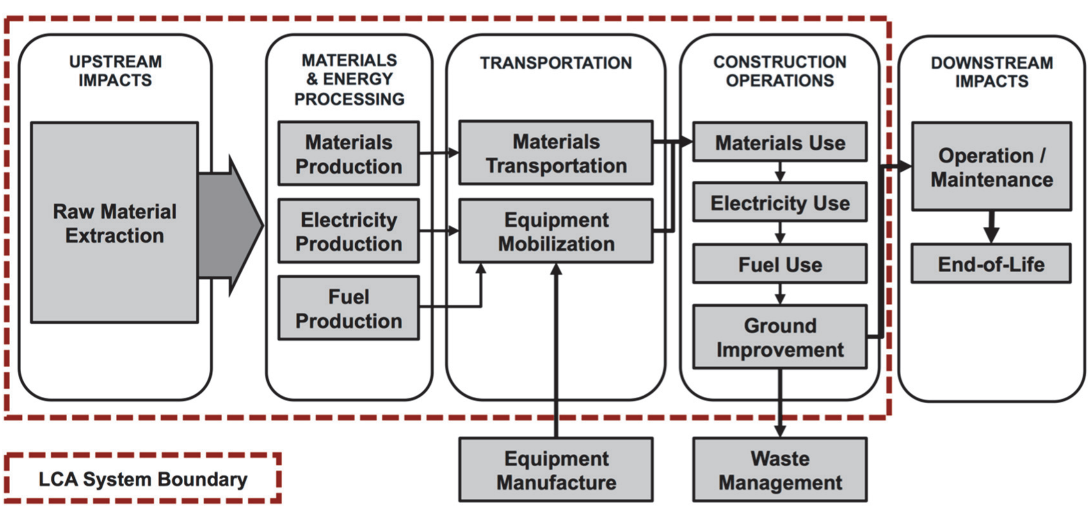


Figure 98. System Definition and Boundary of the Analysis

The study concluded that the most environmentally preferable combination of ground improvement methods does not include deep soil mixing, as illustrated in the comparison of scenarios in Figure 99.

Figure 99. Treasure Island Ground Improvement Scenario Analysis

| Ground Improvement Method | Proposed (ENGEO 2011) | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 |
|---|---|---|---|---|---|
| Deep Soil Mixing | 10.4% | -- | -- | -- | 10.4% |
| Vibro Replacement | -- | 10.4% | 10.4% | 10.4% | -- |
| Vibro Compaction | 9.1% | -- | 65.0% | 9.1% | 80.5% |
| Deep Dynamic Compaction | 80.5% | 80.5% | -- | 80.5% | -- |
| Earthquake Drains | -- | 9.1% | 24.6% | -- | 9.1% |
| **Primary Energy (GJ)** | 447427 | 158038 | 279035 | 122349 | 543447 |
| **GWP (tonnes $CO_2e$)** | 83047 | 10834 | 24512 | 10067 | 96187 |
| **AP (tonnes $SO_2e$)** | 200 | 1 | 61 | 36 | 210 |
| **Smog (tonnes $O_3e$)** | 5308 | 40 | 1692 | 974 | 5606 |
| **SCC - 3% Avg ($)** | $3,737,099 | $487,546 | $1,103,023 | $453,003 | $4,328,401 |

- Initiation of research for a second peer-reviewed journal article focusing on a critical review of environmental impact indicators for ELCA applied to geotechnical systems and technologies.

**Summary of other relevant work being conducted within and outside of the ERC and how this project is different**

Related work outside of the ERC is being conducted at UC Davis and elsewhere to develop a framework and guidelines for ELCA of related systems, such as pavements and complete streets. However, the pavement ELCA guidelines do not include the full scope of the LCSA (only environmental impacts, and not economic or social impacts), and cannot inform indicator development for geotechnical systems based on our critical review of the literature and existing guidelines. The work on complete streets includes environmental, economic and social components of sustainability within an LCA framework, which is aligned with the goals of the ERC LCSA process. However, the social and economic impacts of complete streets are not similar to those of geotechnical systems. Exploring indicators of social and economic impact for any infrastructure system could inform future indicator selection for geotechnical projects; however, the overlap is likely to be minimal as many of the impacts related to, for example, road and street infrastructure are the result of how the infrastructure is directly *used* by people, and most geotechnical systems are not directly used in the same way.

**Plans for the next year**

The following developments are planned for next year:

1) LCSA Questionnaire (now Report 2) dissemination and creation of Summary LCSA Evaluation Statement for all CBBG projects.
2) Continue development of a streamlined quantitative ELCA model for proposed projects.
3) Collaborate with industry to develop benchmarks of impacts of conventional ground improvement technologies for comparison with new biogeotechnologies (both for ELCA and LCCA).
4) Collect damage cost estimates for pollutants of interest.
5) Environmental sustainability indicator development (critical review of existing indicators and proposal of new/appropriate indicators for geotechnical technologies/projects).

6) Manuscript development and submission for environmental sustainability indicators for geotechnical technologies/projects.
7) Continuing to develop MICP ELCA model and evaluation of waste product scenarios for treatment.

**Expected milestones and deliverables for the project**
By the end of year three we expect to have an additional manuscript submitted for peer review addressing environmental sustainability indicators for geotechnical systems/projects. In addition, we will further refine Report 2 and revise the Summary LCSA Evaluation Statements for all CBBG projects. By the end of year five we expect to provide a database or tool for industry partners that documents the costs and environmental impacts of a suite of geotechnical solutions (both CBBG technologies and comparable alternatives that are commonly implemented).

**Member company benefits**
This project develops and implements a framework for evaluating the sustainability of existing and new geotechnical solutions. This has the potential to integrate LCSA-thinking at the innovation stage of research and development, where the greatest improvements may be identified. Member companies may benefit in two ways: 1) by engaging with the LCSA team on feasibility and cost assessment activities, member companies gain intimate knowledge of the innovative solutions being explored by CBBG research; and 2) member companies will have access to the resulting database of costs and environmental impacts associated with the many CBBG technologies evaluated with LCSA.

**If relevant, commercialization impacts or course implementation information**
None to report.

### 2.4.5 Thrust 4: GUSANO: Utilitarian Subterranean Annelid-Inspired Geo-probe

**ERC Team Members**

*CBBG Faculty*
Douglas D. Cortes, NMSU

*Graduate Students*
Sheldon John

*Undergraduate Students*
Cyrena Ridgeway
Russell (Kevin) Buehling

**Project Goal**
The goal of this project is to create a self-excavating geo-probe inspired on the evolutionary adaptations developed by the earthworm (*Lumbricus Terrestris*).

**The project's role in support of the strategic plan**
The development of an earthworm inspired geo-probe that can be driven into the ground without the need for surface reaction, and that can move within the soil in any direction could revolutionize in-situ geotechnical testing. It could facilitate the three dimensional delineation of liquefiable soil deposits (Hazard Mitigation thrust), and of spatial heterogeneities in general (Infrastructure Construction thrust). The probe could also be used as a disposable (in-place) environmental monitoring device (Environmental Protection thrust).

**Fundamental Research, Education, or Technology Advancement Barriers**
Fundamental research and technology advancement questions include:

*i.* what are the essential biomechanical adaptations developed by the earthworm for borrowing;
*ii.* how does the earthworm adapt to changes in soil type and properties;
*iii.* can an earthworm inspired geo-probe compete with available in-situ testing technologies in terms of depth, speed, and energy efficiency?

**Any research aspect that involves foreign collaborations, especially indicating the length of time US faculty or students spent abroad conducting their work, and vice versa, and the value added of that work to the student's/faculty' work.**
N.A.

**Achievements in previous years**
Work during the first year of this project concentrated in the bio-geo-mechanical analysis of earthworm burrowing. The primary objective was to determine the earthworm's evolutionary adaptations that are essential to moving underground. Earthworm locomotion involves its entire body which undergoes cycles of anchoring-extension-anchoring driven by peristalsis of coelomic fluid (Quillin 2000); penetration itself seems to be restricted only to the worm's anterior end (i.e., its 'head'). Experiments have shown that *Lumbricus terrestris* can exert higher pressures within the relatively wider anterior segments (segments 1 through 20). Pressures within the anterior end can be an order of magnitude higher than radial anchoring pressures along the body (Quillin 2000, Keudel and Schrader 1999). These pressures are developed as the worm ceases crawling and contracts the longitudinal muscles of several segments in an effort to enlarge the diameter of the tunnel (Quillin 2000). It has even been shown that the annelid worm *Nereis virens*, a different species from the same phylum as *Lumbricus terrestris*, purposely intensifies the stress field to

initiate and propagate cracks within the sediment, which allows the animal to move forward while reducing the energy needed for burrowing (Dorgan et al. 2005). It has also been proposed that multiple anterior expansions may serve to wedge open a crack while maintaining an O-ring type water seal so that the pore fluid pressure in front of the wedge remains high (Dorgan et al. 2006).

The combination of a soft body, a hydrostatic skeleton, and peristaltic waves provide the earthworm with a powerful mechanism for burrowing into a sediment, retracting, and changing direction. The maximum internal pressure an earthworm can develop is in the order of 200 kPa (Keudel and Schrader 1999, McKenzie and Dexter 1988, Newell 1950), which is equivalent to the geostatic stress at a depth of 15 m.

**Achievements in past year**

Experiments conducted as part of this study have shown that *Lumbricus terrestris* also uses crack propagation when attempting to borrow into a stiffer medium. Video recordings of earthworms burrowing trough a column of clear gelatin show differences in burrowing as a function of the gelatin stiffness. The overall cross sectional area of the worm remains circular as the worm burrows into the medium by volumetric expansion and contraction along its axis. In the case of stiff gelatin, as the worm moves forward its cross sectional shape changes from a circle to an ellipse. Figure 100 shows how the worm's body adjusts its burrowing strategy to the mechanical properties of the medium.

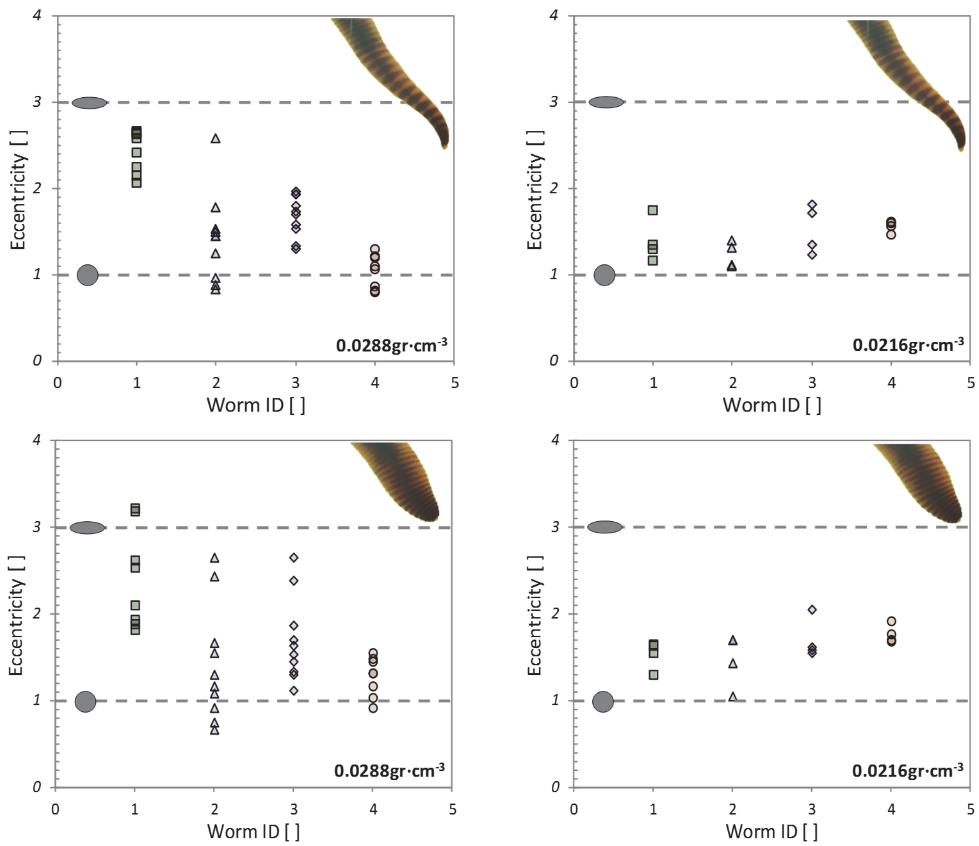


Figure 100. Cross sectional eccentricity of the 15 anteriormost rings of an earthworm burrowing in stiffer (left) and softer (right) gelatin. The top graphs show cross sectional area information during axial extension while the bottom graphs show the eccentricity during radial expansion.

The key evolutionary adaptation of the earthworm is the flexibility of its body. The soft body allows the worm to change its cross section, axial inclination and axial rotation. Thus, the worm is able to adapt to the soil fabric and/or the state of stresses in the medium to maximize the effect of its limited pressure.

Research activities in year 2 concentrated on the development of hybrid earthworm-inspired geoprobe prototypes. The primary objective being the development of robust self-excavating robots. Figure 101 shows a balloon-cone prototype designed to measure potential changes in cone-penetration resistance driven by the pressurization of the soft balloon. The probe design mimics the radial expansion of an earthworm prior to axial extension. Work on the prototype was completed in late July, and testing is currently underway. Preliminary results show substantial reductions in penetration resistance as a result of the radial expansion of the soft balloon. Figure 102 shows a root-inspired, rigid, self-excavating probe. Our prototype draws its inspiration from the plantoid robot develop by the Center for Micro-Biorobotics at the Instituto Italiano di Tecnologia (Sadeghi et al. 2014). Dr. Barbara Mazzolai and her research team at IIT have developed a clever method to mimic the growth behavior of plant roots using filament/cord deposition. Our aim is to explore the potential of incorporating the soft body adaptations of the earth worm into the rigid, root-inspired, self-excavator. The prototype has been designed and assembled in house. Data logging, sensors, and peripheral electronics were designed to work with the Arduino open source electronics platform. Final work on the prototype is currently in progress, the team expects to complete troubleshooting and start testing and data collection at the end of September, 2017.

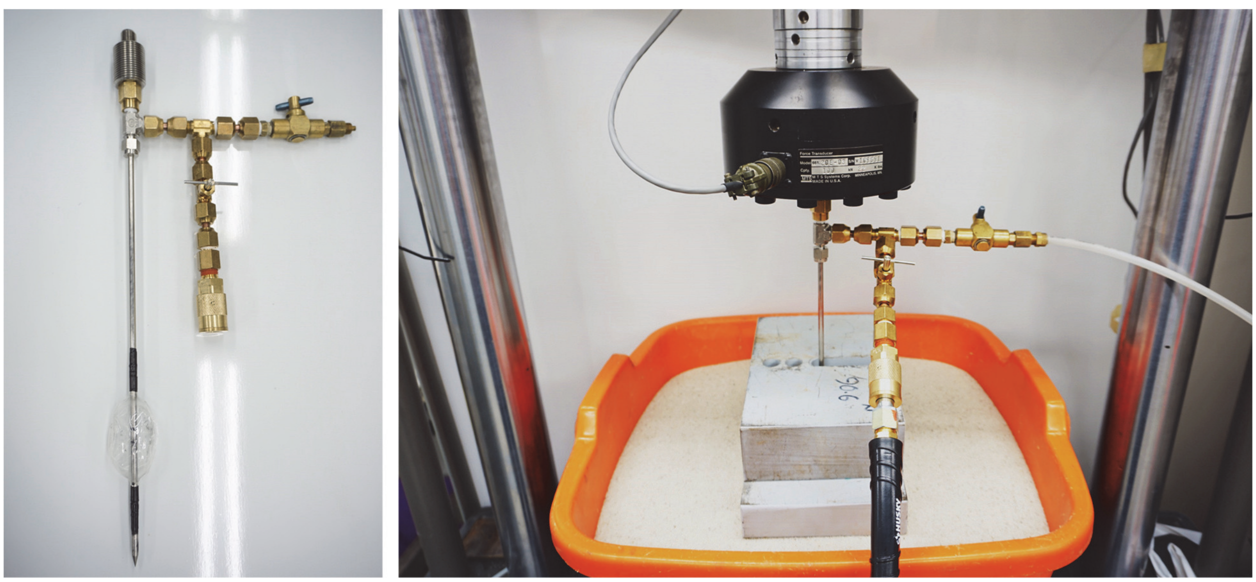

Figure 101. Balloon-cone prototype probe designed to mimic the radial expansion of an earthworm. The probe connects to the load cell in a universal loading frame. Valves connect the probe to an air compressor and a vacuum pump which are used for pressurization and deflation of the balloon.

Figure 102. Root-inspired, rigid, self-excavating probe.

References:

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Newell, G. E. (1950) The role of the coelomic fluid in the movements of earthworms. *Journal of Experimental Biology,* 27**,** 110-122.

Quillin, K. J. (2000) Ontogenetic scaling of burrowing forces in the earthworm Lumbricus terrestris. *Journal of Experimental Biology,* 203**,** 2757-2770.

Sadeghi, A., A. Tonazzini, L. Popova & B. Mazzolai (2014) A novel growing device inspired by plant root soil penetration behaviors. *PloS one,* 9**,** e90139.

**Summary of other relevant work being conducted within and outside of the ERC and how this project is different**

Related work being conducted within the CBBG includes research on the geotechnics of bio-locomotion and self-excavating systems. This project is led by Georgia Tech (Dr. David Frost) but involves researchers from the four partner institutions, including Dr. Cortes at NMSU. The collective effort involved in this Cross Cutting thrust project looks at locomotion and burrowing in general and across multiple types of organisms whereas this project concentrates on the earthworm and the development of an earthworm inspired geo-probe.

Work conducted by the Center for Micro-Biorobotics at the Istituto Italiano di Tecnologia concentrates on the development of bio-inspired robots and sensors. Their work includes both rigid and soft robots. While our work concentrates on subsurface characterization, the Italian group explores a wider range of applications including the development of biomedical devices. Dr. Cortes and Dr. Mazzolai are currently exploring a potential collaboration between the two groups.

**Plans for the next year**

Next year work will concentrate on: (1) data collection; (2) feasibility analysis; (3) incorporation of a soft body component into the root inspired self-excavating prototype; and (4) the development of a field probe prototype.

**Expected milestones and deliverables for the project**

It is anticipated that a proof of concept field prototype geo-probe will be completed next year. This will allow for an overall assessment of feasibility, which will lead to further refinement of the bioinspired geoprobe.

**Member company benefits**

The development of an instrumented probe that can be driven into the ground without the need for surface reaction (i.e., drill rig) and that can move within it in any direction could revolutionize in-situ geotechnical testing. In addition to the exploration potential, using the concept of peristaltic anchoring could transform deep foundations and geotechnical anchor systems.

**If relevant, commercialization impacts or course implementation information**

This technology has the potential to gain a competitive advantage in the field of geotechnical in-situ testing. As the project matures, the research team will seek patents on the prototypes and, if proven feasible, will move on to prototype refinement and commercialization.

## 2.5 Diversity and Education

### 2.5.1 Diversity and Education: Diversity and Integration

**ERC Team Members**

*CBBG Faculty*
Delia Saenz, ASU
Paola Bandini, NMSU
Felicia Benton-Johnson, GT
Colleen Bronner, UCD
Martha Mitchell, NMSU
Claudia Zapata, ASU

**Integrated Inclusion: A Diversity & Inclusion Strategic Plan for CBBG**
CBBG is a complex, multi-university center that aims to advance research on biogeotechnics, transform engineering education, and broaden participation of underrepresented persons in the field. With respect to the broadening participation, we propose to 1) foster understanding and awareness about, 2) promote skills-building in, and 3) engender an appreciation for the tangible value of diversity and inclusion within STEM disciplines. Accordingly, we have created a strategic plan in response to concerns raised by the SVT members during the year 1 evaluation cycle that engages transformational thinking and aspirations around diversity and inclusion across all areas/functions of the center. The **Integrated Inclusion** strategic plan was developed by Dr. Delia Saenz, CBBG director for diversity and inclusion, in consultation with assistant director Martha Mitchell, as well as members of the CBBG IDEA group and the leadership of the center. In addition to addressing concerns that were identified by the SVT, the strategic plan incorporates elements that broaden the impact of our work. The Integrated Inclusion framework is intended to guide our inclusion efforts in the short term as well as in the long term, as described below.

**Inclusion as a core value of CBBG**
CBBG is committed to two central inclusion goals--

- broadening participation of women, underrepresented persons, and persons with disability in the emerging field of biogeotechnics
- developing and disseminating best practices for creating and maintaining an inclusive culture in an engineering learning and discovery environment.

To achieve these goals, CBBG will engage Integrated Inclusion, such that issues relevant to diversity and inclusion, specifically, and effective group dynamics, more generally, ***will be integrated across all function areas*** of the Center. Further, all members of CBBG will play a role in promoting an inclusive environment.

**Implementing and measuring inclusion efforts**

A logic model reflecting the Integrated Inclusion Strategic Plan is depicted in the attached figure. Its implementation will be led by Inclusion core leads, Drs. Delia Saenz (ASU) and Martha Mitchell (NMSU). However, other members of the IDEA group, the PIs, and affiliated others within the Center will work collaboratively with them to ensure the success of the plan. The paragraphs that follow provide a summary of the components of the Integrated Inclusion model. The specific goals of the plan are highlighted on the left-most column of the graphic (Target Goal). These goals, listed under the heading 'Priorities,' are separated into 3 levels. More specifically, objectives are conceptualized as pertinent to 1) the person or individual level, 2) the Center or process level, and 3) a broader, more scalable level beyond CBBG specifically (inclusive of other ERC's, NSF, and industry partners). For each goal listed, the corresponding activities and target participants are identified (see middle heading 'Activities & Reach,') and so, too, are the desired short-, medium-, and long- term outcomes (under the heading 'Outcomes'). The model is both comprehensive and amenable to modification particularly as we measure and assess the effectiveness of the interventions. The foci and strategies are intended to be extensive in their reach (K-12, university, industry), and to be implemented sequentially through the life of CBBG rather than all at once. In addition, early progress or lack thereof on key outcomes is expected to inform the direction and specificity of subsequent diversity and inclusion efforts.

**Individual level.** At the core of Integrated Inclusion is the education of persons at all levels on matters related to understanding and addressing underrepresentation in biogeotechnics. Among the representative activities in this category are workshops delivered to CBBG members, outreach to underserved communities, development of target-specific recruitment materials, and professional development opportunities. To facilitate successful implementation, partnerships with relevant constituencies will be incorporated into these efforts (e.g., K-12 school partnerships, external presenters, graphic designers).

**Center level.** Individual-level activities (from category 1 above) are expected to contribute to and complement Center-level activities. The primary emphasis at this level is the development and reinforcement of practices at the group level that reflect a value of inclusion and further contribute to the development of an inclusive culture. Representative activities range from training of CBBG members to recognize and respond effectively to bias (as both a target and an ally) in group settings (e.g., classroom, lab, work settings), to embedding inclusion as a criterion for Center support (research funding, award recognition), as well as optimization of institutional collaborations (working with deans council members) to be recommend more expansive practices in the recruitment of diverse students and faculty.

**Broader level.** We anticipate that the CBBG Inclusive Integration methodology can inform a broader set of constituencies. For example, we intend to be synergistic with industry and other ERCs in the exchange of best practices around inclusion, and to share training materials and measurement tools. In this way, the benefits of Integrated Inclusion can expand well beyond the boundaries and lifetime of CBBG. Representative activities include convening of industry and university personnel with primary responsibility for diversity and inclusion in their respective settings, and collaborative efforts with other ERCs for the development of learning modules and climate measurement tools.

**Implementation**

All partner institutions (ASU, NMSU, UCD, GTech) will participate in the implementation of Integrated Inclusion. Elements that are part of the strategic plan well reflect both site-specific and common center-wide activities. As noted earlier, not all components of the strategic plan will be launched simultaneously. In part, this is due to the need to take time to develop some of the proposed interventions, and in part, because of the need to work within the parameters of funding availability. Nonetheless, CBBG leadership is committed to fleshing out the full model as quickly as possible.

**Other considerations**

Note that the Integrated Inclusion graphic, as a logic model, does not list the corresponding assumptions, external factors, and measurement tools or timeline that are often included in logic models. These omissions are mostly due to space considerations and partly, to the time required to flesh out each component. Nonetheless, these considerations are succinctly addressed in the next paragraph.

The primary assumptions guiding our Integrated Inclusion model is that CBBG will continue to receive support from NSF and that the Center director will continue to reinforce the importance of inclusion as a core value of the Center. External factors that may impact our proposed work relate to collaborative efforts and cooperation of outside entities such as university administrators and industry leaders. Insofar as measurement tools and timelines are concerned, CBBG inclusion leaders are working closely with the Center's external evaluators, College Research and Evaluation Services Team (CREST), to map out appropriate measurement intervals and instruments that will capture progress and inform our direction. The education core led by Dr. Wilhelmina Savenye has been working closely with CREST in the past year and reports that they have provided excellent guidance and objective feedback on that component. We anticipate that CREST will likewise provide professional services to the diversity and inclusion core. As per their progress to date, it is highly likely that tools and timelines will be more definitive by the next evaluation cycle.

**Activity in the past year**

Over the course of the past year, a number of the target goals listed in the logic model graphic have been pursued actively, including the following events/efforts:

- workshops on diversity and inclusion were delivered by diversity director Saenz to CBBG members;
- extensive outreach to underserved K-12 populations transpired at multiple sites;
- a workshop on mentoring was delivered by Dr. Erika Camacho (with online access to those off site);
- regular meetings between CBBG leadership and the ASU dean have been ongoing, and one session solely focused on diversity is upcoming;
- graduate students have developed a regular book club discussion series as a way to build community;
- multiple SafeZone trainings have been conducted;
- changes have been made to research project evaluation forms to utilize diversity as a dimension of evalution;
- the development of tracking of K-12 participants across the different levels of schooling (middle, high, college) and transition has begun;
- an electronic communication network (using SLACK) involving members from 5 ERC's nationwide has been established by a CBBG staff member to facilitate collaboration on instruments that measure climate;
- utilization of partner organizations (minority-serving schools, regional and national conferences, offices focused on services to veterans and persons with disability, respectively) yielded a diverse set of participants in our summer programs;
- outreach to Native American communities has facilitated plans to develop culturally-friendly curricular offerings;
- Young Scholars have learned about tools for academic success and about specific ways that they can effectively navigate college admissions requirements.

Notably, these efforts have spanned the Center's different function areas such as Research, Outreach, Education, Student Leadership, and university administrators, and have generated synergy with outside entities (other ERC's). Integrating inclusion into every function reflects our strategic approach going forward. Measurement efforts (evaluations) from individual events/initiatives further will be integrated into a database that is being created by CREST evaluators. Thus, we will have baseline measures from the early to later years of the Center's lifespan.

**Weaknesses, Threats, and Concerns from year 1**

In the last site visit, reviewers urged us to make changes in the personnel charged with guiding inclusion efforts, to develop a comprehensive strategic plan, and to ensure that designated funds were included in the budget for diversity and inclusion. All these recommendations were accepted. Likewise, the SVT identified the need for appropriate data collection, tracking, and assessment methodologies to assess effectiveness in our approach. D&I leaders have been working closely with CREST (evaluators) to ensure the ongoing data collection will lend itself to both short- and long-term evaluation (and will include measures beyond self-reports) so that progress can be measured accordingly. Above all else, we were informed that there was a 'lack of strategic cohesion with respect to education and diversity activities and management structure.' The leadership has been responsive to this critique by following the recommendations noted above, by providing consistent and strong messaging to all CBBG members that inclusion is a core value of our Center and a responsibility that must be embraced by each and every person. Further, the leadership has endorsed the view that inclusion is most effective when it is infused throughout all function areas. Notably, the same is true for our education component (please see that section for elaboration). There is significant work to be completed (e.g., formal recruitment plan, increasing participation of men of color, involvement of industry, increasing diversity at Georgia Tech). However, the development of a strategic plan, the skill set and academic expertise of the current director, the early progress across different arenas, and the enthusiasm of CBBG leadership toward the contributions of inclusion to the field, are good indicators that the Center will achieve success in advancing diversity and inclusion in alignment with NSF exigencies.

### 2.5.2 Diversity and Education: Education and Outreach

**ERC Team Members**

*CBBG Faculty*
Claudia Zapata, ASU
Wilhelmina Savenye, ASU
Susan Brown, NMSU
Colleen Bronner, UCD
Wendy Newstetter, GT
Delia Saenz, ASU
Martha Mitchell, NMSU
Alejandro Martinez, UCD
Felicia Benton-Johnson, GT
David Frost, GT
Jennifer Chandler, ASU

*Other Research Staff*
Jean Larson, ASU
Wendy Barnard, ASU
Megan O'Donnell, ASU

*Graduate Students*
Elizabeth Stallings, ASU
Kristin Elwood, ASU

**Project Goals**

Consistent with the CBBG's focus on bio-mediated and bio-inspired processes, our education program places the study of nature at the center of our activities. The CBBG links cutting-edge, innovative, high-tech research with tangible, knowable aspects of a student's natural world. We believe this engages students and encourages them to learn about the earth, soils, and how to design sustainable engineering projects.

**Project's Role in Support of the Strategic Plan**

CBBG's strategic focus is to develop an inclusive community of biogeotechnical engineers and innovative and creative scientist leaders, who are skilled in research, prepared for industry needs and trends, and ready to solve global and national biogeotechnical problems. Our programs and activities are designed to support the current generation workforce in the principles of biogeotechnical engineering, to educate and inspire a new generation of diverse and innovative biogeotechnical professionals, and to motivate and educate young people from all backgrounds to learn about, become interested in, and to consider careers in, biogeotechnical engineering and other STEM fields. We employ an iterative, learning systems approach to designing, developing, implementing, testing, and improving all aspects of the educational program.

**Fundamental Research, Educational, or Technology Advancement Barriers**

Advancement barriers to the education program are not different from those perceived in STEM careers and are primarily related to broadening participation of minority groups and climate of inclusion. Stereotypes about engineers and engineering, implicit biases towards women in engineering fields, lack of awareness by K-12 students and teachers of what civil engineers do, and lower self-efficacy levels by underrepresented groups with respect to their abilities in engineering are some of the barriers that CBBG are actively addressing.

**Description of Achievements**

*Partnerships*:

Long-term partnerships have been established at both the university and pre-college level. University-level partnerships include education and engineering colleges, veteran centers, community colleges, disability resource centers, and various community organizations. Pre-college partnerships are in place with schools and school districts in all four states, as well as the Phoenix Indian Center, science centers and community organizations. Relationships with the many partners are fostered through the online community, faculty and student exchanges, CBBG researchers visiting classrooms and STEM clubs, teachers and students participating in summer research programs, students visiting CBBG labs, as well as collaborative activities with community groups.

New partnerships were developed in Year 2, such as that of UC Davis with the Yolo County Office of Education in their effort to encourage girls in STEM fields, and a number of new schools. ASU is now partnering with new partners as well, such as ASU Prep Digital and Estrella Vista STEM Academy, from which we recruited four summer RETs. GT also formed new partnerships with five schools as well as Habitat for Humanity, the Georgia Mining Association, and the Georgia Construction Aggregate Association. NMSU extended its relationships with its many school district partners and also added partnerships with several new schools such as the Pueblo of Laguna Department of Education.

*Curriculum*:

Graduate Course Development – In Year 2, Dr. Leon van Paassen, who joined us this year from Delft University of Technology in the Netherlands, developed a graduate course on biogeotechnics, which he is teaching this fall. CBBG researchers at Georgia Tech are also currently at work developing a graduate course in biogeotechnical engineering. Dr. Colleen Bronner, again offered a two-course sequence to graduate students in *Engineering Educational Outreach Design*.

Undergraduate Course Development – In Year 2, CBBG made substantial accomplishments in developing undergraduate curriculum. Dr. Bandini at NMSU developed an undergraduate course on biogeotechnics, to be offered in hybrid format. Dr. Jeanette Yen at GT began planning for the adaptation of an undergraduate course on Bio-Inspired Design, which will include aspects of Biogeotechnics and adoption by at least one other CBBG university. A freshman-level module titled *Introduction to Biogeotechnical Engineering* was completed and iteratively assessed at ASU. Development was also started at ASU on three junior-level modules to be integrated into geotechnical fundamental courses. Two CBBG modules for community college courses were developed by Phoenix College faculty members participating in the RET summer program.
Biogeotechnical Engineering Demonstrations and Experiments **-** Cross-university CBBG research is shared through hands-on demonstrations, with additional information and at-home experiments for teachers, students, and families, provided in an accompanying handout. Demonstrations have been shared across all four universities to be used with outreach and

educational partners. Experiments in biogeotechnical engineering include creating a bio-based construction material, microscopy, soil liquefaction, and surficial soil stabilization.

Bio-inspired Geotechnical Engineering Modules - An earthworm module has been developed to introduce elementary and middle school students to worms through observation and hands-on activities. The Adobe Structure Module, created in Year 1 by Drs. Paola Bandini and Brad Weldon, was again delivered during a two-week summer residential camp for diverse, high-achieving students interested in engineering.

CBBG-Based Engineering Lessons for K-14 Classrooms – In Year 2, 11 complete lesson plans, all based on CBBG research and aligned with Next Generation Science Standards (NGSS), International Technology and Engineering Educators Association (ITEEA) standards, Arizona K-12 state standards, and Arizona MCC Course Competencies have been developed for use in partner schools. Two additional NGSS-aligned lessons, inspired by CBBG research performed at ASU and UC Davis, were created for middle school science courses. Once all lessons have been piloted and improved, they will be evaluated by the Curriculum Committee, and then submitted to TeachEngineering.org, LinkEngineering, and the American Geosciences Institute (AGI) Education Resources Network for dissemination nationwide.

*Outreach (a few examples)*:

Family Nights - New Mexico State University faculty participated in six family nights at partner schools by providing a booth with STEM activities that included CBBG content.

Civil Engineering Exhibit - CBBG students dedicated to sustainable geotechnical solutions and embodying school spirit engaged the local community through interactive activities that increased awareness of and knowledge in civil engineering at Picnic Day at UC Davis.

Hands-On Laboratory Experience - Summer 2016 RET from educational partner Charles R. Drew Charter School in Atlanta, brought 150 students to GT for hands-on experiences in various research labs.

A Day in the Life of…Field Trips – Local elementary and middle school students participated in an interactive biogeotechnics activity with CBBG researchers, who also discussed finding more sustainable solutions for some of the challenges that face biogeotechnical engineers.

*Internships, Exchanges, and Mentoring:*

Internships in Industry – In Year 2 CBBG began involving students in internships with the Center's industry members and existing programs at each partner university.

International Research Exchanges / Foreign Partnerships – This year the ERC's foreign partnerships have been extended, with several faculty partners having presented their research internationally, several international researchers presenting across the CBBG, and with several graduate students completing international research internships abroad.

Mentoring Program - The CBBG mentoring program was substantially deepened in Year 2. A comprehensive program for mentors and mentees was developed, including a mentoring booklet, mentoring workshop, and weekly drop-in mentoring sessions. Slack communities were established to connect mentors and mentees across CBBG.

*Career Development and Webinar Series:*

ASU ERC Consortium - In Year 2, one of our major initiatives was leveraging the power of the three ERCs at ASU. We formed the ASU ERC Consortium, comprised of Education leads from ASU's CBBG, QESST and NEWT ERCs. We meet bimonthly. The major work this year has been to share resources, including assessments, mentoring materials, outreach activities, and career development and outreach presentations.

Webinars, Seminars, and Interactive Activities - Center students, faculty, staff and postdoc researchers participated in over 103 webinars, seminars and interactive activities developed in collaboration by the leadership of the Center, researchers, Student Leadership Council and the Education and IDEA team in Year 2. All webinars, and most activities, crossed all four universities, with the universities rotating leadership on developing and delivering the webinars. It should be noted that our industry partners presented numerous webinars. Industry partners also told us they had others of their staff viewing some of the webinars. Dr. Colleen Bronner and her team at UCD presented SafeZone training for support of LGBTQ students at the Mid-Year Meeting. Dr. Wendy Newstetter presented on GT's existing bridge programs to aid the IDEA group in strengthening these types of programs. CBBG researchers, students and faculty also participated in workshops on Design Thinking and Problem-Based Learning and Design for Engineering.

Innovation, Entrepreneurship and Industry Discussions **-** In Year 2, the Center expanded activities and discussions related to innovation and entrepreneurship, particularly in partnership with industry members. Of note, was the presentation by Dr. Ann McKenna.

*Diversity and Inclusion:*

Engagement of Women, Differently-abled Students and Veterans – CBBG members represented the Center at meetings of the Society of Women Engineers (SWE), and the American Indian Society of Engineers and Scientists (AISES). Our partnership with AccessERC at the University of Washington, yielded CBBG-wide workshops and the opportunity for four CBBG graduate students to attend a two-day workshop on supporting students with disabilities in labs, instruction and research. Recruitment efforts yielded for summer 2017 one REU scholar and one RET who identified as having a disability, one veteran REU, and one veteran RET. Diversity Director Dr. Saenz led a center-wide inclusion workshop.

Cross-ERC National Climate Network and Climate-of-Inclusion Survey - After meeting with a group from various ERCs that have the common goal of creating an ERC-wide climate survey, members of CBBG education, diversity, and evaluation teams contributed to building a central collaboration space. Members of the "ERC Climate Network" come from CBBG, ReNEWIt, NEWT, NASCENT, TANMS, CSNE, and LESA. Individuals from various ERCs were able to join the "ERC Climate" Slack Team and share existing materials. Others contributed by offering expert feedback to improve assessment questioning.

*Summer Research Programs:*

Year-Round Research Experience for Undergraduates (REU) – The Center increased the number of undergraduates who were NOT part of our 8-week summer REU program. Thirty-three undergraduates had the opportunity to conduct research in CBBG labs at all four universities. Additionally, the Vertically Integrated Project (VIP) program at ASU and GT supports undergraduate students to engage in ongoing scientific research. Four students participated in the VIP program in Year 2.

Summer Research Experience for Undergraduates (REU) – Eight undergraduates participated in the Summer REU program and were immersed in technical research working in CBBG labs, and exposed to a broad scope of projects this summer. In addition, UCD's collaboration with Lafayette College included two additional REUs, who participated in all the REU activities and lab research. Eight of the 10 REUs spent the next seven weeks at the CBBG partner universities, but remained in contact through weekly webinars on innovation, inclusion, professional development, and research topics. During the last week, the REUs from the four campuses each shared their research via video conferencing.

Research Experience for Teachers (RET) – A total of nine base-budget funded K-12 STEM teachers and community college faculty were recruited to participate in a 5-week RET program located at ASU this summer. Eight of the nine engaged teachers were from CBBG educational partner schools and districts, which all serve a very high minority population of students. One of the middle school teachers, Mr. Steve Clemens, was one of the 2016 RETs and returned to serve as a mentor teacher for the 2017 team. Steve is also a U.S. veteran and is committed to assisting CBBG in forming support for recruiting students, especially from our partner community colleges, who have returned from serving and are interested in engineering research in CBBG labs. Participants will give poster presentations of their work at the Annual NSF CBBG Meeting in late October 2017.

Young Scholars Program (YSP) – All four of the highly qualified high school students selected for the 5-week CBBG Young Scholars Program were from an educational partner. Two of the 2016 Young Scholars were invited back this summer to continue their research. The four Young Scholars worked each day in the CBBG labs, and with the guidance of their mentors, created a research poster based on their project. All participants will be invited to participate in the NSF Site Visit to CBBG on October 19-20, 2017, and will continue collaborating as mentors in different outreach activities organized by CBBG.

**Summary of Other Relevant Work**

The newly created *CBBG Logic Model for Broadening Participation and Creating a Culture of Inclusion* will be used as a guide for planning educational activities and reaching diversity goals, both at the individual level and Center level.

CBBG-based curriculum materials are also being created with the *Outreach Strategies for Engagement of Women in Civil Engineering* Project, with a specific focus on women in engineering fields.

**Plans for Next Year**

Development and implementation of curriculum will continue into Year 3 at both the University and Pre-College level. Improvements will be made to the newly created graduate-level course, presently being implemented at ASU, and GT researchers will continue to develop another course at the graduate-level. The three junior-level modules will be completed, classroom-tested, and iteratively revised in Year 3. Development will begin on a fourth-year technical elective course in biogeotechnical engineering and a senior-level capstone design project with a biogeotechnical focus. There have also been discussions to include ASU's Innovation Space/Biomimicry group to collaborate on student capstone project demonstrations that allow industry involvement. All of the K-14 CBBG-based lessons created over the summer will be implemented, revised and vetted by the Curriculum Committee. Once finalized, the lessons will be adapted across the CBBG and nationally disseminated through TeachEngineering.org, Link Engineering, and as resources for the Curricula and Instruction section of the American Geosciences Institute's Education Resources Network.

In Year 3, CBBG will start a Research Experience for Veterans (REV) Program at three of the partner universities. Undergraduate Veteran students have been identified at GT, NMSU, and ASU.

In addition to continuing to offer summer research opportunities for high school students, K-14 teachers, and non-CBBG undergraduate students, the Education team will participate in outreach events across the Center, deepen long-term partnerships, and offer a webinar series over a variety of topics.

**Expected Milestones and Deliverables**

A complete list of expected milestones and deliverables for the project are contained in the CBBG Education Program Evaluation and Deliverables Timeline, found in in the Appendix of the CBBG Education Report in Volume 1.

**Member Company Benefits**

All developed educational materials are available for educational and/or training purposes by member companies.

**Commercialization Impacts or Course Implementation Information**

The first offering of the Biogeotechnics graduate course is being implemented in the fall of 2017, and will subsequently be evaluated and refined.

Based on the assessments of their implementation and effectiveness at NMSU and GT, the freshman undergraduate module will be prepared for national dissemination via our web site and several national organizations.

Once all CBBG-based K-12 lessons have been piloted and improved, they will be evaluated by the CBBG Curriculum Committee, and then submitted to TeachEngineering.org, LinkEngineering, and the American Geosciences Institute (AGI) Education Resources Network for dissemination nationwide.

### 2.5.3 Diversity and Education: Outreach Strategies for Engagement of Women in Civil Engineering

**Involved ERC Members**

Colleen Bronner, Faculty in UC Davis Dept. of Civil and Environmental Engineering
Annie Kirkwood, M.S. Student in UC Davis Dept. of Civil and Environmental Engineering
Matthew Burrall, Ph.D. Student in UC Davis Dept. of Civil and Environmental Engineering
Charles Graddy, Ph.D. Student in UC Davis Dept. of Microbiology
Jordan Greer, M.S. Student in UC Davis Dept. of Civil and Environmental Engineering
Sophia Palumbo, M.S. Student in UC Davis Dept. of Civil and Environmental Engineering
Alena Raymond, Ph.D. Student in UC Davis Dept. of Civil and Environmental Engineering
Jenna Kelmser, REU Student at UC Davis from Humboldt State University
Vivian Le, Undergraduate Student in UC Davis Dept. of Civil and Environmental Engineering

**Project Goals**

Projects goals include: 1) engaging girls and increase representation of women in civil engineering undergraduate and graduate programs by developing a series of activities that demonstrate societal benefits of civil engineering; 2) increasing awareness of the role of sustainable engineering in solving society's challenges (e.g., hazard mitigation, climate change, infrastructure needs) by creating educational modules for K-12 and undergraduate education; 3) assessing the effectiveness of the project's activities and educational modules on participant attitudes towards civil engineering and knowledge of the biogeotechnics field; 4) disseminating lessons learned and curriculum to ERC partners and interested educators.

**Project's Role in Support of the Strategic Plan**

This project aligns with the CBBG Educational & Outreach Strategic Plan's desired skillset for graduate students by enhancing the ability of graduate students to: convey complex content to non-technical audiences, create innovative activities for engaging younger generations, increase knowledge about engineering education, develop teaching philosophies and strategies, and work in teams with educators from diverse backgrounds. The project supports the Diversity and Inclusion Strategic Plan by encouraging participation of underrepresented groups in engineering. Although the project primarily targets girls and women, other target areas include students from lower socio-economic backgrounds and underrepresented minorities. Incorporating biogeotechnics educational modules into K-12 classrooms will allow students from lower socio-economic backgrounds to have experiences often restricted to students whose families can afford summer programs.

**Fundamental Research, Educational, or Technology Advancement Barriers**

*Barrier 1: Societal stereotypes about engineers and engineering.* There are the traditional stereotypes that engineers are white, nerdy, middle-aged men from middle- or upper-socioeconomic backgrounds who lack social skills and work alone in cubicles. Due to the large number of robotics camps, competitions and classes targeting K-12 students, engineering is often thought to be synonymous with robotics by some educators and students. This project challenges these stereotypes using a multiple lines of evidence approach. K-12 educators and students interact with graduate students of both genders from diverse ethnic and socio-economic backgrounds. The goal is to remove negative connotation of the words "engineer" and "nerdy" by demonstrating that the field has bright, enthusiastic individuals from diverse backgrounds. Hands-on educational modules created by graduate students and utilized in teacher workshops and K-12 outreach events demonstrate the breadth of civil engineering projects and provide an alternative pathway to engineering for students not passionate about robotics.

*Barrier 2: Lack of awareness by teachers, parents and other adult role models about implicit biases towards girls and women in engineering fields.* As teachers have frequent contact and form close relationships to students, they are the target group for addressing this barrier. Professional development workshops for teachers include presentations on imposter syndrome and implicit bias. During the workshop, faculty, graduate students and K-12 teachers discuss strategies and potential activities for decreasing this unintentional barrier.

*Barrier 3: Lack of awareness by girls and K-12 teachers of what a civil engineer does.* The educational modules and presentations by graduate students during professional development workshops and K-12 outreach events demonstrate the contributions of civil engineers to society. Additional public outreach events disseminate this information to a wider audience (e.g., UC Davis's Picnic Day, Yolo County Office of Education's STEM Conference for Eighth Grade Girls, etc.)

*Barrier 4: Lower self-efficacy levels by girls and other underrepresented groups with respect to their abilities in engineering.* Strategies for increasing self-efficacy include allowing students to build on small successes, learn to fail forward, and reject the dichotomy of "math people" vs "not-math-people." For all K-12 outreach events, CBBG faculty and students create an inclusive, positive environment. When a design fails or appears impractical, students are questioned on what they learned from their initial design and how they could improve it. Another theme at outreach events, especially the weeklong camp, is that the innovation and critical thinking skills needed by engineers are improved with practice, the same way that practice improves skills in athletes and musicians. Outreach activities are designed to replace the fixed-mindset that affects many students in underrepresented groups with a growth mindset. As some girls are more likely to take on leadership roles in design when separated from male peers, some of the outreach events will target female participants.

*Barrier 5: Limited evaluation on ability of outreach programs to recruit women into engineering.* In conjunction with the establishment of project activities and educational modules, CBBG faculty and students are developing assessment tools for evaluating impacts of activities on attitudes towards civil engineering and knowledge in civil engineering and biogeotechnics fields.

**Description of Achievements**

Recent project outcomes included a graduate course series in engineering education, a professional development workshop for middle school teachers, a weeklong day camp in biogeotechnics for elementary school students, draft biogeotechnics educational modules, and additional outreach events.

Graduate Course Series

A two-course series was developed for civil engineering graduate students in *Engineering Educational Outreach Design*. The first course (offered in Winter 2016) introduced students to engineering education topics (e.g., student learning outcomes (SLOs) and assessment, types of learning and communication styles, active learning strategies, project-based learning, and creating inclusive environments). Students were challenged to design an educational outreach activity related to their research that targeted specific age groups, aligned SLOs with K-12 education standards or undergraduate engineering curriculum, and included SLO assessment strategies. In the second quarter (Spring 2016), students began constructing physical components of their modules and piloting activities during K-12 outreach. *Eight students enrolled in the first quarter (5 females, 3 males) and five students in the second quarter (3 females, 2 males).*

Community Outreach

At Picnic Day, an annual open house event that commemorates the research, service, teaching, and campus life at UC Davis, Colleen Bronner, students of the Engineering Educational Outreach Design course, and CBBG students run geotechnical and water resources engineering hands-on activities for the public. Activities included retrofitting buildings for earthquakes, predicting where structures would fail during an earthquake, learning about seismic waves, and developing a watershed model. This activity began in 2016 and continued in 2017.

2016: Approximately, 365 people spent time at the exhibit (e.g., conversed with graduate students, participated or helped a child participate, listened to discussion for at least five minutes). It is estimated that 52% were male and 48% female; 15% were Hispanic/Latino; 45% Caucasian/White (Non-Hispanic), 38% Asian or Asian-American, and 2% were Black or African American. Approximately 174 participants were estimated to be less than 18, of these 56% were boys and 44% were girls.

2017: Throughout the four hours of the event, over 350 visitors, including about 160 girls and boys, interacted with the exhibits. We estimate that 17% of participants were underrepresented minorities, 32% were Asian or Asian-American, and 51% were Caucasian/White and not Hispanic. Visitors included local community members, current undergraduate students interested in geotechnical engineering, and several alumni – including a geotechnical engineering Ph.D. alumnus and his family. While most visitors spent between 15-60 minutes, some families spent over 3 hours becoming engrossed in discussions about designing resilient and cost-effective structures.

Development of Educational Modules

Current modules for the CBBG educational outreach activities are summarized in Table 1. All modules are in the development phase; versions were used in 2016 and 2017 activities. All K-12 activities are designed with NGSS alignment as a primary goal. Recently, Bronner and Le began a review of existing civil engineering modules from Engineering is Elementary and other curriculum developers – the goal is to adapt activities to needs of local students (e.g., make age-appropriate and include local case studies).

Figure 103. Educational Modules in Development (*denotes CBBG member)

| **Module** | **Target Age Group** | **Graduate Student Developer(s)** | **Description & Status** |
|---|---|---|---|
| Introduction to Engineering | K-12; general public | Used material from CBBG Student Leadership Council (SLC) | A series of activities and presentations to broaden notions on engineers and engineering (e.g., draw an engineer, draw/write civil engineering projects, name your favorite engineer, historical female engineers). |
| Sustainability | K-12 | Kelmser* and Kirkwood* | Material includes definitions of sustainability, three pillars of sustainability, tragedy of the commons, climate change, greenhouse gasses, UN Sustainability Development Goals, and examples of sustainability in civil engineering. Activities include defining sustainability (as individual and then team), tragedy of commons activity, and a Sustainability Development Goals game. |
| Life Cycle Assessment (LCA) | K-12 | Raymond* and Sara Pace, Ph.D. in Bio. & Ag. Eng. | Content includes overview of LCA and phases of LCA, important definitions, and examples of LCA in engineering. Current activities include developing a life cycle flow diagram on a common product and performing a simplified life cycle assessment on cupcakes. |
| Introduction to Soils | K-12 | Alex Sturm, Ph.D. in CEE | Material introduces soil properties used for classifying soils. Activities are tailored based on age group and include hands-on characterization of soils. |
| Watershed Modeling | 6-12 | Jeanette Newmiller, M.S. in CEE | Material introduces students to the concept of modeling and need for landscape and watershed analysis. Activities include creating 3-D models from 2-D topographic maps, surveying, coordinate systems, and predicting impacts natural hazards (e.g., sea level rise, tsunamis, and dam failures from earthquakes) on watersheds. Some activities require use of a portable Augmented Reality sandbox. |

| | | | |
|---|---|---|---|
| Designing for Earthquakes | K-12 | Diane Moug (Ph.D.) and Jaclyn Bronner (M.S.) in CEE | Building off previous outreach efforts by UC Davis Geotechnical Graduate Student Society, a module was developed with three main activities: creating earthquake waves with Slinkys, predicting impacts of earthquakes on K'nex structures, and retrofitting buildings. |
| Bio-mediated design in soils | 6-12, and undergraduate students | Graddy*, Greer*, and Kirkwood* | Material includes an introduction to microbe and bio-mediated design, and examples of bio-mediated designs in geotechnical engineering (e.g., biofilms, biocementation, etc.). Current activities include studying prepared slides under microscopes and an interactive Q&A with Graddy. |
| Bio-inspired Design | K-12 | Palumbo* and Kelmser* | Materials include examples of bio-inspiration, video from Monterey Bay Aquarium, classifying different levels/models of bio-inspired design, CBBG examples involving snakeskins and tree root systems, and a general introduction of the engineering design process. A hands-on activity guides students through the bio-inspired design process of designing pilings based on snakeskin. |
| Bio-films Activity | K-12 | Le*, Kelmser*, and Greer* | Material includes definition of biofilms, variety of places we find biofilms, important of context for determining if they are good or bad, and potential use for biofilms in geotechnical engineering. Initial activity involves students working as cells in teams of four to build a "biofilm" using cups and string. |
| Women in Engineering and Imposter Syndrome Module | K-12, undergraduate, and graduate students | N/A | Material includes statistics about percentage of STEM professionals by gender, race, and ethnicity; hypothesized reasons for lower numbers of URGs in STEM, impacts of stress, imposter syndrome, stereotype threat, and history of women in engineering. Activities range based on age group – examples include drawing imposter monsters and plans for how to defeat them, |

| | | | |
|---|---|---|---|
| | | | determining goals before 35 and breaking down into achievable steps, group discussions on fears, bullying, and support networks, reading graphs, and practicing coping skills. |

Professional Development Workshops for Middle School Teachers

In 2016, nine teachers participated in a professional development workshop on sustainable engineering at UC Davis. Primary objectives included: 1) providing assistance to teachers for meeting the engineering components of the Next Generation Science Standards (NGSS); 2) collecting feedback on CBBG educational modules; 3) and creating partnerships with local educators. The workshop focused on geotechnical and environmental engineering content with each day representing its own theme. Initial activities introduced participants to the topics of engineering, civil engineering, geotechnical engineering, sustainability, and underrepresented groups in engineering (especially women). The majority of technical content was provided by the educational modules listed in Table 1. Tours of UC Davis's Bohart Museum of Entomology and Botanical Conservancy were included to: 1) as a brainstorming exercise (participants were asked to think about which plant and insect functions engineers should mimic in their designs), and 2) demonstrate available UC Davis resources available. At the end of each day, Dr. Colleen Bronner facilitated discussions with teachers to: 1) develop strategies for integrating workshop activities and content into lesson plans; 2) strategize methods for involving URGs in outreach activities; 3) identify potential partnerships between UC Davis and local schools; and 4) obtain feedback for graduate students on the modules they presented.

For summer 2017, last year's participants were invited to attend a four-day workgroup to discuss challenges of applying knowledge from last year's workshop and for general achievement of NGSS. Graduate students provided reviews and updates on their research topic and a couple of new modules were discussed (e.g., biofilms and bio-inspiration lessons). Using the experience of the five participating teachers, the workgroup spent time critiquing current modules and brainstorming ideas for new modules. Additionally, the workgroup developed realistic plans for maintaining contact throughout the 2017-2018 academic year. After evaluating activities from the past two years, an adjustment has been made to encourage more continuous interactions with K-12 teachers (e.g., student visit to UC Davis, teachers attending some of the classes in the improved graduate student course, visit to science classes in the teachers' schools, shared folder for editing of CBBG precollege education modules).

Programs to Engage Girls in Biogeotechnics Fields

In July 2016, an all-day camp was held for 24 local elementary school students entering grades 3 to 5. The goal of the workshop was to provide a safe space in which girls could explore geotechnical and environmental engineering topics. In addition, to technical topics the camp program included discussion of female role models in engineering (e.g., Emily Roebling), strategies for overcoming imposter syndrome, and the need to support each other (i.e., prevent bullying). Each day focused on a different technical topic. To practice teamwork and communication skills, the students created one presentation using Google Slides on six different computers to summarize what they had learned during the week on the last day of camp. The final activity was a presentation made to their parents, which served a secondary purpose of introducing parents to civil engineering. There were 24 female participants and 2 volunteers that were under 18: a sixth grader and senior in high school. While the material was well-received by the students and several positive parental reviews received, it was posited by the project team that five days may be too long and that older students would allow the curriculum to integrate more advanced concepts.

The curriculum was adapted to a four-day format and to target girls entering seventh to ninth grade in the following fall. The recruitment strategy, based on conversations with middle school teachers, was modified to have teachers nominate students. In July 2017, nine female students participated in the Engineering for Sustainable Societies Academy. Students came from five different schools and three different grades. Students were more racially and ethnically diverse than in 2016; 33.3% of students in the 2017 cohort were from URMs. Two of the students had disabilities (one had Asperger Syndrome and the other ADHD), that required more individual feedback of UCD students and faculty, which was possible due to the smaller cohort size of girls and is important to the project team that the academy be accessible to all students. Assessment of the activities have led plans for a modified recruitment plan, changing the duration back to five days, adjusting the target number of participants to 15, and modifying activities for the summer of 2018. The target age group was appropriate as students had the fundamental math skills desired for some activities (e.g., LCA activity). The older students also had a larger attention span and were all highly interested in science.
Pictures of activities are located on UCD's CBBG Facebook page (https://www.facebook.com/ucdcbbg/) and Instagram page (https://www.instagram.com/cbbg_ucdavis/).

**Summary of other relevant work being conducted within and outside of the ERC and how this project is different.**
Curricular materials for CBBG topics are being developed at ASU, GT, and NMSU; however, these activities are different and do not follow the same module development and review process as this project. The SLC produced presentations for Biogeotechnics 101, which have been useful to this project during the workshop and camp activities.

**Plans for Next Year**
Programmatic events for next year include: a) participation in Yolo County's Office of Education STEM Conference (fall 2017); b) Continue to hold and improve community outreach event during UCD's Picnic Day (e.g., improve assessment of activity, add bio-inspired activities) in spring 2018; c) Sustainable Engineering Academy for Middle School Girls; d) Sustainable Engineering Professional Development Workshop for Middle School Teachers; e) a seminar series highlighting women in geotechnical engineering; and f) a collection of smaller educational outreach events.

Two undergraduate students will be funded to help with the collection and analysis of assessment data from the above events. These students will also work with K-12 teachers to help plan classroom events during the school year in our goal to strengthen relationships between UC Davis and the local middle school teachers.

**Expected Milestones and Deliverables for the Project**

Expected milestones for Year 3 (2017-2018) include: submitting two modules to teachengineering.org, implementing a revised graduate course, a teachers' workshop, a sustainable engineering academy for middle school students, and refining assessment protocols for project activities.

Final deliverables for the project will include:

- Refined two-quarter course series for graduate students in engineering education and outreach design
- Annual professional development workshop for teachers
- Annual bio-inspired geotechnical engineering academy for middle school girls
- Annual outreach activities in local K-12 schools through educational partners
- 10 CBBG educational modules for K-12 or undergraduate education, including all supplementary curricular information

**Member Company Benefits**

Materials developed will be accessible to all member companies to use for educational or training purposes.

**Commercialization Impacts or Course Implementation Information**

Educational modules developed through this project will be used in undergraduate and/or K-12 curricular activities. The CBBG curriculum committee will review the final version of educational modules, including supplementary curricular materials. All K-12 learning content will be piloted in a local K-12 classroom and then submitted to teachingengineering.org, where it will undergo a peer-review by an engineer and K-12 educator. All curricular content will be freely accessible to all interested parties.

### 2.5.4 Diversity and Education: Tribal Initiative

**ERC Team Members**

| *CBBG Faculty* | *Graduate Students* |
|---|---|
| Martha Mitchell, NMSU | Rashidatu Ossai |
| Paola Bandini, NMSU | |

**Project Goal**
The goal of this project is to engage Native American students in Center Activities.

**The project's role in support of the strategic plan**
The theme of the Center, ecologically friendly, cost-effective solutions, inspired by nature, for development and rehabilitation of resilient and sustainable civil infrastructure systems, is an ideal avenue to introduce Native American students interested in the environment, engineering and science, to the emerging field of biogeotechnics.

**Fundamental Research, Education, or Technology Advancement Barriers**
The participation of Native Americans in the areas of expertise that CBBG researchers have is very low. Increasing participation of Native Americans in Science, Technology, Engineering and Math (STEM) careers is a high priority. New Mexico has two year and four year colleges and universities with a larger number of Native American students, so CBBG has the opportunity to translate its research into course materials that can be delivered to the students at their institutions in order to encourage their interest in biogeotechics.

**Any research aspect that involves foreign collaborations, especially indicating the length of time US faculty or students spent abroad conducting their work, and vice versa, and the value added of that work to the student's/faculty' work.**
N.A.

**Achievements in previous years**
In year 1, initial plans were made with personnel at Southwestern Indian Polytechnic Institute (SIPI). SIPI is a National Indian Community College and Land Grant institution serving American Indian and Alaskan Native Students. It is a two-year institution located in Albuquerque, New Mexico. This is a proposal for New Mexico State University personnel to develop and deliver a course on biogeotechnics that incorporates research results from the Center. The course is planned to be an online course with on-site mentoring and guidance. The course will have college algebra as prerequisite and will count as the engineering elective course (3 credits) in the engineering curriculum for SIPI students. Students from non-engineering majors may also enroll in the course. An outline of the course was developed in year 1 by an NMSU graduate student, Mrs. Rashidatu Ossai, with her advisor (Paola Bandini).

**Achievements in past year**
In year 2, the course outline was further refined. The course starts with a general introduction on bio-inspired design principles. Then we will discuss relevant geological processes and natural hazards that affect our society and infrastructure and bio-mediated processes used to solve engineering problems. The remaining course modules focus on select topics taken from the core

CBBG research projects that apply bio-mediated and bio-inspired principles, such as bio-cementation, bio-inspired motile probes for soil investigation, root-inspired soil reinforcement, bio-enhanced landfills, bio-mediated soil restoration, and bio-enhanced water and soil decontamination. Part of the evaluation of the content of the course with respect to cultural compatibility will include the involvement of Native American persons with whom we have established a relationship.

In order to fund the costs of delivering the cost, a white paper was submitted to Dr. James Moore, a Program Director at the National Science Foundation, for supplemental funding. A discussion with Dr. Moore led us to redirect our efforts. We now understand that we need to submit our supplemental funding request through the ERC Program Directors. In addition, we now recognize that the budget requested from SIPI was not feasible. Given these constraints, we are now reworking our plan, and are refocusing our efforts on connecting with other two year and four year colleges and universities in New Mexico, as well as high schools with large Native American populations, to encourage students to consider summer research experiences at New Mexico State University, with the goal of facilitating enrollment or transfer from two year institutions to NMSU.

**Summary of other relevant work being conducted within and outside of the ERC and how this project is different**

Course modules have been developed for implementation in engineering courses. These modules are different in their focus on a particular population with an emphasis on cultural compatibility.

**Plans for the next year**

In the coming year we will continue to develop contacts, with the help of the American Indian Program at NMSU, to increase recruiting of Native American students to CBBG-related disciplines at NMSU. We will rework the course outline into shorter course modules that could be presented to a high school or college course as a visiting lecture by a CBBG faculty member.

**Expected milestones and deliverables for the project**

Expected milestones include recruitment of Native American students as undergraduate student researchers into the Center as well as course modules with CBBG-research content that have been evaluated with respect to cultural compatibility.

**Member company benefits**

Member companies may also benefit from best practices in recruiting and retaining Native American students, and in what we learn about the issues that the students we recruit face as they pursue higher education.

**If relevant, commercialization impacts or course implementation information**

The culturally compatible course modules could be appropriate for delivery in other settings.

# 3 Associated Projects

## 3.1 Groundwater Detoxification through Combined Remediation and Zero-Valent Iron Reduction

Rosa Krajmalnik-Brown (Arizona State University)

Summary: Contamination of soil and groundwater with anthropogenic chlorinated chemicals is of major concern nationally and locally. To date, there are ~1300 US Superfund sites polluted with organic and inorganic chlorinated compounds requiring decontamination (US EPA 2013). Of particular interest for this proposal is a Superfund site located in an area of the desert southwest. The main contaminants are trichloroethene (TCE > 1000 µg/L in source zone) and perchlorate ($ClO_4^-$ > 150 µg/L) (US EPA 2012b).

TCE and perchlorate are known to cause adverse health effects. Currently, perchlorate is not regulated by EPA. Some states, however, have established regulatory levels or cleanup targets: e.g., Arizona 14 µg/L and California 6 µg/L (US EPA 2012a). On the other hand, TCE is highly regulated by EPA (MCL of 5 µg/L), classified as a top Priority Pollutant, and a proven human carcinogen (ATDSR 2011; US EPA 2013). It is imperative to remediate sites contaminated with chlorinated compounds such as TCE and $ClO_4^-$ to improve the quality of water supplies, to provide clean land, and to reduce human exposure.

The goal of the proposed bench-scale study was to evaluate the potential for using in situ bioremediation enhanced by zero-valent iron (ZVI) abiotic reactions as a feasible strategy for reduction of TCE and perchlorate in groundwater at the Superfund site. The bench-scale study includes assessing micro- and nano-scale ZVI varieties in combination with bioaugmentation and biostimulation options using site specific soil and groundwater. This bench-scale study will also include evaluating the chemical and microbial interactions of the various amendments. The results of this study will provide key information for the design of a pilot-scale study, if appropriate.

**Objectives**. In aerobic sub-surfaces, zero-valent iron (ZVI) can be injected to establish anoxic conditions, beneficial for biostimulation/bioaugmentation. However, the benefits and challenges of combined abiotic reduction by ZVI and microbial reduction of TCE and ClO4- for remediation of aquifers are not well understood.

**Approach/Activities**. We used bench scale semi-batch microcosms with soil and groundwater from a contaminated Superfund site. We studied conditions representing an injection zone of ZVI followed by a combination of biostimulation and bioaugmentation, and a downgradient zone influenced by Fe (II) derived from ZVI oxidation.

**Results/Lessons Learned**. In experiments representative of the ZVI and biostimulation/bioaugmentation injection zone, high concentrations of ZVI (16.5 g L-1) effectively reduced TCE to ethene and ethane, but $ClO_4^-$ concentrations remained mostly unchanged. Microbial reductive dechlorination of both contaminants was hindered by the presence of ZVI or Fe (II). For TCE, rapid abiotic dechlorination provided by ZVI made TCE unavailable for the bioaugmented dechlorinating bacteria. For $ClO_4^-$, ZVI did not reduce ClO4-, and inhibited the indigenous perchlorate-reducing bacteria associated with the aquifer material. Furthermore, $H_2$

generated by ZVI reactions stimulated competing microbial processes such as sulfate reduction and methanogenesis. In experiments representing the downgradient conditions (Fe (II) and biostimulation/bioaugmentation with dechlorinating enrichment cultures), cis-dichloroethene (cis-DCE) and vinyl chloride (VC) accumulated after 56 days of microcosm operation.  In the absence of ZVI or Fe (II), the bioaugmentation culture achieved complete TCE dechlorination to ethene and $ClO_4^-$ reduction rates were faster. These results illustrate some limitations imposed by combining ZVI with microbial reduction of chlorinated compounds and provide useful information relevant to bioremediation of chlorinated compounds in subsurface environments.

## 4 Data Management Plan

*Roles and responsibilities*

Intellectual property and data generated under this project is administered in accordance with the Arizona State University (ASU) and National Science Foundation (NSF) Data Management Guidelines. The objective of the data management plan is to maximize data access for researchers, collaborators, and the public, now and in the future.

CBBG Center Director, Dr. Edward Kavazanjian has overall responsibility of the Center's data management. The Center seamlessly connects to the partner Universities through a virtual presence, coordinated through the CBBG headquarters space in the Goldwater Center for Science and Engineering (GWC) building on Tempe's campus. The entry point to this virtual space is the CBBG web site: http://biogeotechnics.org. The CBBG Project Coordinator ensures the implementation of the data management plan for each reporting period and that the Senior Investigators are fulfilling their responsibilities. The Project Coordinator also is the public contact for providing access to the data upon request by emailing biogeotechnics@asu.edu.

On the CBBG web site, visitors and interested stakeholders are able to review the Center's mission, industry membership program, research projects, education and diversity activities, lists of participants, project related data/information and access protocols, and news related to the Center activities. The Center web site promotes its education and diversity programs and allows for tracking of inquiries, especially with regards to the available Young Scholar, Research Experience for Undergraduates (REU), and Research Experience for Teachers (RET) opportunities and the industry partnership program. There are password-protected pages on this ASU-hosted web site which permit the Leadership Team, the Industry Advisory Board (IAB), and the Scientific Advisory Board (SAB) to use it for document management, calendaring, teaming, and task management. The CBBG web site is in compliance with the Web Accessibility Review and Recommendations prepared by AccessERC at the University of Washington. The benchmark for that evaluation was the Web Content Accessibility Guidelines 2.0, published by the World Wide Web Consortium (W3C).

An internal, password protected SharePoint site is hosted by the School of Sustainable Engineering and the Built Environment (SSEBE) but is managed by the CBBG Administrative Director. The Center Director has ultimate authority and responsibility for the content and permissions for the site. CBBG also has an Education Dropbox hosted by ASU that is used for a variety of purposes (sharing documents, housing photos, etc.).

The SharePoint site allows for multiple sub-sites to be created, with various levels of permissions. The site was designed such that there is easy access, reference, and full transparency across the thrusts and universities involved in conducting the work. This arrangement is in keeping with the focus on a highly integrated and creative team. However, there is tiered access to the site that is actively managed at the group level. For example, the Industry Partners Program and the related Industry/Practitioner Advisory Board have limited access to the SharePoint site (i.e., excluding preliminary data or confidential center information), but is able to draw on particular resources, e.g. contact information for team members and a contact list of industry partners. The site provides versioning for documents and data uploaded.

The Center Director (Dr. Kavazanjian) chairs a data stewardship committee comprised of the thrust leaders (Drs. DeJong, Bandini, Krajmalnik–Brown and Frost) and the Administrative Director, as well as a technical point of contact at each university (appointed by the thrust leaders). The committee is responsible for linking university electronic and physical infrastructure with CBBG. The committee reviews the use, curation, and distribution of Center data via the web site quarterly. This committee monitors the data management plan to ensure that it reflects the Center's best practice and the ERC network's best practice and incorporates the best practice policies of the National Science Foundation and all partner universities.

At the CBBG mid-year meeting, which was held at the University of California, Davis in April 2017, the CBBG team decided to use the services of DesignSafe (www.designsafe-ci.org) for data archiving and curating beginning in Year 3. DesignSafe allows researchers to effectively share, publish, and find data; perform numerical simulations using high performance computing; and integrate diverse datasets DesignSafe embraces a cloud strategy, with all data, simulation, and analysis taking place on the server-side resources of the cyber infrastructure (CI), accessible and viewable from the desktop. A webinar demonstrating how to use DesignSafe is scheduled for the CBBG team at the beginning of the Fall 2017 academic year, and a presentation by an advanced user of DesignSafe is scheduled for the October 2017 Annual Meeting, with implementation taking place immediately after.

*Expected types of research data*

Table 1 describes the data types expected to be produced by CBBG. Each university and thrust generates raw data separately and together. The internal structure of the DesignSafe site is designed to make data collection, retrieval, and sharing easy, yet maintain the integrity of the data. The data stewardship committee has a standard operating procedure that outlines the process for data input into DesignSafe.

Physical data that is not transferable or amenable to digital formats (e.g., laboratory notebooks) are archived in a secure location within the office of each thrust leader. This data will be maintained for up to five years after archiving, or five years after the termination or dissolution of the Center. Data produced by the partner Universities will adhere to the inter-university agreement. Data that is produced in conjunction with industry also will adhere to the industry member agreement, including all provisions for intellectual property assignment. At ASU, this data is stored in a fire-proof cabinet that is bolted to the wall in the CBBG Storage Room (GWC 135). The Administrative Director and Project Coordinator have the keys to this file cabinet on their key rings, with a third key maintained by the ASU Lock Shop, which is overseen by the ASU Police Department.

*Data archiving*

Data produced as part of the NSF-funded Center will be archived for the duration of the award, and up to five years after the project completion. The Center web site and email address for data requests will be active for the entire duration of the award, and for up to five years post project close out, irrespective of NSF funding continuation. In conjunction with the data stewardship committee, the Center will provide a persistent URL for retrieval of the most useful data sets. ASU's University Technology Office (UTO) will be the emergency administrator for the site, and will be responsible for all disaster preparedness protocols. In addition to the above, the Center has contracted with Michael Nolan of Cerium LLC to provide a data collection tool, ERC 360, which helps the Center prepare the Excel spreadsheets used to upload data into the ERC Web Database. Nolan is a former graduate student at the Center for Biorenewable Chemicals (CBiRC) Engineering Research Center (ERC) at Iowa State University, who worked solely on data collection, manipulation, and storage for that Center's information for their Annual Report. ERC 360 is the data collection tool that CBBG uses for the preparation of the Annual Report. The data in this tool will be kept for the duration of the award.

**Expected Data Types**

| Expected data | Type | File formats | Storage |
|---|---|---|---|
| **Laboratory & Field Experiments** | Element, model, and full scale 'test bed' experiments | Excel, CSV, JPG, MOV, Binary, Mathcad, Matlab, Grapher | Laboratory notebooks, local computers, DesignSafe |
| **Biological samples** | Live/dead/preserved cellular material, kinetic growth, consumption and production rates | Excel, CSV, Plain Text | Laboratory, laboratory notebooks, local computers, DesignSafe |
| **Genetic Sequencing** | Raw sequence data | Excel, CSV, Plain Text | Laboratory notebooks, local computers, DesignSafe |
| **Modeling** | Biogeochemical (COMSOL, TOUGHREACT) and geotechnical modeling (FLAC), programs, user guides, input files, developed software | Excel, CSV, Mathcad, Matlab C++, fortran scripts, MOV, technical notes, publications, plain text files, image files (e.g., JPG, GIF, PNG), word files, video files | Local computers, university servers, documents assigned a permanent URL on SmartTech (Georgia Tech), repository for digital resources ASU, DesignSafe. |
| **Student Participation** | Discrete and continuous data points, survey | Excel, Word, video, technical notes | DesignSafe, ERC 360 |
| **Protocols** | | Word, technical notes | Laboratory notebooks, local computers, DesignSafe |
| **Education Program Activities** | Training videos, webinars, interviews | Video files, Word, PDF, text files | Local computers, Sharepoint site, CBBG website, DesignSafe, ERC 360 |

*Data re-use and re-distribution*

The Center's web site provides information on currently available data sets and physical specimens, along with a procedure and contact information for requesting the information, appropriate use, and citation for resources obtained through CBBG. The data stewardship committee reviews, prioritizes, and executes data requests submitted to cbbg@asu.edu . Data used in student theses, other publications and presentations include appropriate reference to the award and any stipulation for subsequent use. Genomic sequences generated will be submitted to Genbank. In the event that discoveries or inventions are made in direct connection with Center data, access to data will be granted upon request once appropriate invention disclosures and/or provisional patent filings are made. Key data relevant to the discovery will be preserved until all issues of intellectual property are resolved.

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## 5 Biographical Sketches

**(In alphabetical order by last name)**

## Chloé Arson

### Professional Preparation:

| | | |
|---|---|---|
| University Paris I Panthéon-Sorbonne (France) | Philosophy | 2003 |
| École Nationale des Ponts et Chaussées (France) | Civil Engineering | M.Eng. 2006 |
| École Nationale des Ponts et Chaussées (France) | Soil &Rock Mech. | M.Sc. 2006 |
| École Nationale des Ponts et Chaussées (France) | Geomechanics | Ph.D. 2009 |

### Appointments:

| | | |
|---|---|---|
| 2016-now | Associate Professor Tenured position | School of Civil and Environmental Engineering Georgia Institute of Technology |
| 2014-now | Adjunct Professor Courtesy appointment | School of Earth and Atmospheric Sciences Georgia Institute of Technology |
| 2012-2016 | Assistant Professor Tenure-track position | School of Civil and Environmental Engineering Georgia Institute of Technology |
| 2009-2012 | Assistant Professor Tenure-track position | Zachry Department of Civil Engineering Texas A&M University (TAMU) |
| 2006-2009 | Research Assistant | Navier Lab., Ecole Nat. Ponts & Chaussées (France) |
| 2004-2005 | Engineer Assistant | Vinci Construction (Monaco) |
| 2003 | Research intern | RWTH - Aachen (Germany) |

### Products:

1. C. Zhu, A. Pouya, C. Arson, 2016. Prediction of viscous cracking and cyclic fatigue of salt polycrystals using a joint-enriched Finite Element Model, *Mechanics of Materials*, DOI: 10.1016/j.mechmat.2016.09.004
2. W. Jin, H. Xu, C. Arson, S. Busetti, 2016. A Multi-Scale Computation Tool Coupling Mode II Fracture Propagation and Damage Zone Evolution, *International Journal of Numerical and Analytical Methods in Geomechanics*, DOI: 10.1002/nag.2553
3. C. Zhu, A. Pouya, C. Arson, 2015. Micro-macro analysis and phenomenological modeling of salt viscous damage and application to salt caverns, *Rock Mechanics and Rock Engineering*, DOI: 10.1007/s00603-015-0832-9
4. H. Xu, C. Arson, 2015. Mechanistic Analysis of Rock Damage Anisotropy and Rotation around Circular Cavities, *Rock Mechanics and Rock Engineering*, DOI: 10.1007/s00603-014-0707-5
5. C. Arson, B. Gatmiri, 2012. Thermo-Hydro-Mechanical Modeling of Damage in Unsaturated Porous Media: Theoretical Framework and Numerical Study of the EDZ, *International Journal for Numerical and Analytical Methods in Geomechanics*, vol.36, pp.272-306, DOI: 10.1002/nag.1005

**Other Relevant Publications**:

1. W. Jin, C. Arson, 2017. Micromechanics based discrete damage model with multiple non-smooth yield surfaces: theoretical formulation, numerical implementation and engineering applications, *International Journal of Damage Mechanics,* DOI: 10.1177/1056789517695872
2. W. Jin, C. Arson, 2017. Discrete Wing Crack based Damage Model for Brittle Solids, *International Journal of Solids and Structures,* DOI: 10.1016/j.ijsolstr.2016.12.025
3. P. Wang, C. Arson, 2016. Discrete Element Modeling of shielding and size effects during single particle crushing, *Computers and Geotechnics*, DOI: 10.1016/j.compgeo.2016.04.003
4. C. Arson, T. Vanorio, 2015. Chemo-mechanical evolution of pore space in carbonate microstructures upon dissolution: linking pore geometry to bulk elasticity, *Journal of Geophysical Research*, DOI: 10.1002/2015JB012087
5. C. Arson, 2014. Generalized Stress Variables in Continuum Damage Mechanics, *Mechanics Research Communications*, DOI: 10.1016/j.mechrescom.2014.06.006

**Synergistic Activities:**

1. **Recipient of the Early CAREER Award from the U.S. National Science Foundation, 2016.** Title: 'Multiphysics Damage and Healing of Rocks for Performance Enhancement of Geo-Storage Systems - A Bottom-Up Research and Education Approach'. Total budget: $500,000.
2. **Lead organizer of an NSF-funded International Educational Workshop, University of Cambridge (UK) on September 5-6, 2014.** The workshop addressed the new skill set needed by geotechnical engineers to solve the multi-scale, multi-physics problems faced by modern technology. 44 faculty and graduate students participated in this workshop, with a balanced representation of U.S. and European leading institutions.
3. **Member of the "Future Leaders Program" of the American Rock Mechanics Association, 2013- 2016.** The group gathers motivated younger ARMA members of "outstanding promise" that discusses issues and ideas to develop the ARMA and become engaged in ARMA leadership.
4. **Lead-PI of the geomechanics Vertically Integrated Program (VIP) at Georgia Tech, since 2013.** Undergraduate students are mentored by Dr. Arson and her graduate students, and by each other, to work on bio-inspired network dynamics, rock damage and healing, computational geomechanics and geostorage. Undergraduate students earn course credit that counts towards their degree. The size and structure of a VIP team enable continuity in the project and students participating from all disciplines.
5. **Creator and leader of the "CEE Gateways to France" program, since 2012.** Program aimed to promote scientific collaborations between Georgia Tech School of Civil & Environmental Engineering (GT CEE) and Ecole des Ponts Paris Tech (ENPC), a top European program in civil engineering and theoretical mechanics.

**Paola Bandini**

**Professional Preparation:**

| | | | |
|---|---|---|---|
| Universidad de Oriente | Geological Eng. (*Summa Cum Laude*) | B.S. | 1993 |
| Universidad de Oriente | Geology (*Summa Cum Laude*) | B.S. | 1993 |
| Purdue University | Civil Engineering, Geotechnical | M.S.C.E. | 1999 |
| Purdue University | Civil Engineering, Geotechnical | Ph.D. | 2003 |

**Appointments:**

| | |
|---|---|
| 2017 – Present | Wells-Hatch Family Endowed Professor of Civil Engineering, Department of Civil Engineering, New Mexico State University |
| 2008 – Present | Associate Professor, Department of Civil Engineering, New Mexico State University |
| 2008 – Present | Licensed Professional Engineer, New Mexico, #18663 (Civil Engineering, Geotechnical) |
| 2002 – 2008 | Assistant Professor, Department of Civil Engineering, New Mexico State University |
| 2002 | Instructor, School of Earth Sciences, Universidad de Oriente, Venezuela |
| 1993 – 1996 | Instructor, School of Earth Sciences, Universidad de Oriente, Venezuela |
| 1992 – 1993 | Research Assistant and Engineer Intern, PDVSA (formerly CORPOVEN, S.A.), Department of Petroleum Geology, Venezuela |

**Products:**


1. Mostafazadeh-Fard, S., Samani, Z., and Bandini, P. (2017). Production of liquid organic fertilizer through anaerobic digestion of grass clippings. *Waste and Biomass Valorization* (Technical paper, accepted August 2017).
2. Bandini, P., and Al Shatnawi, H. H. (2017). "Discussion of 'Fines Classification Based on Sensitivity to Pore-Fluid Chemistry' by Junbong Jang and J. Carlos Santamarina." *J. Geotech. Geoenviron. Eng.*, 143(7): 07017011, 10.1061/(ASCE)GT.1943-5606.0001692
3. Al Aqtash, U., Bandini, P., and Cooper, S. (2017). Numerical approach to model the effect of moisture in adobe masonry walls subjected to in-plane loading. *Inter. J. Architectural Heritage*, 1-11, 10.1080/15583058.2017.1298010
4. Gebremariam, T., Weldon, B., and Bandini, P. (2017). Experimental evaluation of two small-scale adobe walls under lateral loading. *Earth USA 2017, 9th Inter. Conf. on Architecture and Construction with Earthen Materials*, Santa Fe, New Mexico, September 29-October 1 (Accepted).
5. Al Aqtash, U., Bandini, P., and Cooper, S. (2017). Effect of moisture on the out-of-plane lateral strength of residential adobe masonry walls. *Earth USA 2017, 9th Inter. Conf. on Architecture and Construction with Earthen Materials*, Santa Fe, New Mexico, September 29-October 1 (Accepted).
6. Al Aqtash, U., and Bandini, P. (2015). "Prediction of unsaturated shear strength of an adobe soil from the soil-water characteristic curve." *Constr. Build. Mater.*, 98(11): 892-899, 10.1016/j.conbuildmat.2015.07.188
7. Wosick, E., Gebremariam, T., Weldon, B., Bandini, P., and Al-Aqtash, U. (2014). Strength characteristics of typical adobe material in the Southwestern United States. *Proc. 9th International Masonry Conference*, Guimarãe, Portugal. July 7-9.
8. Dung, T., Bawazir, A.S., Shukla, M.K., and Bandini, P. (2011). Some hydraulic and

wicking properties of St. Cloud zeolite and zeolite-soil mixtures. *Applied Engineering in Agriculture*, 27(6): 955-967, 10.13031/2013.40624

9. Diaz-Rodriguez, J.A., Antonio-Izarras, V.M., Bandini, P., and Lopez-Molina, J.A. (2008). Cyclic strength of a natural liquefiable sand stabilized with colloidal silica grout. *Canadian Geotechnical Journal*, 45: 1345-1355, 10.1139/T08-072
10. Bianchini, A., and Bandini, P. (2010). Prediction of pavement performance through neuro-fuzzy reasoning. *Computer-Aided Civil and Infrastructure Engineering - An International Journal*, 25(1): 39-54, 10.1111/j.1467-8667.2009.00615.x

**Synergistic Activities:**

1. Chair of Transportation Research Board's (TRB) Standing Committees: AFS50 "Modeling for the Design, Construction and Management of Geosystems" (2011-2015) and AFS20 "Geotechnical Instrumentation and Modeling" (2015-2017). Member since 2005 to present. As Committee Chair, I organized and/or co-chaired 9 paper and/or lectern sessions for dissemination of research, 2 half-day technical workshops and 1 webinar, and co-developed Research Needs Statements RNS) for TRB.
2. Co-Editor of Conference Keynote Proceedings, Technical Program Co-Chair, Chair of Panel Discussions of Geo-Institute's 2014 Geo-Congress: American Society of Civil Engineers (ASCE), 2011-2014. I co-organized the Geo-Congress 2014's technical program (keynote lectures and technical sessions) with over 400 papers submitted and seven panel discussions on geotechnical and geoenvironmental engineering.
3. REU (Research Experience for Undergraduates), 2016 and 2017: Coordinated the CBBG-sponsored REU summer activities, mentorship and webinars at NMSU; served as research mentor of 2 REU students (summers), 2 REU minority community college participants in SCCORE program (Summer Community College Opportunity for Research Experience) (summers), 6 undergraduate research students (2 female, 5 minority students) (academic year/summer). PI ($1M) of NSF S-STEM grant: Increasing the Success of Low-Income, Academically Talented Students in Engineering (2016-2021), providing $600K in scholarship support; research on increasing self-efficacy and metacognition on student performance.
4. Former Member of the Board of Directors, New Mexico Section of the ASCE: holding leadership positions at the state levels since 2005 as ASCE New Mexico Section's Director, Vice President, President Elect, President, Past-Presidents Committee Chair and Co-Chair of Transportation, Geotechnical and Construction Technical Group. I co-organized/chaired the technical program and keynote lectures of 10 conferences of the ASCE NM Section (2005-2012) for the civil engineering community.
5. Co-author of Invention Disclosure. Currently preparing submission of provisional patent application through NMSU Arrowhead Center, resulting from research. Co-mentor of graduate student who was finalist of NMSU Arrowhead's 2017 LAUNCH entrepreneurship program, awardee of 2017 Aggie I-Corps entrepreneurship and commercialization program ($2,000), and awardee of 2017 NSF I-Corps ($50,000).

**Wendy Miedel Barnard**

**Professional Preparation:**

| | | | |
|---|---|---|---|
| Rutgers University | New Brunswick, NJ | Psychology | B.A., 1992 |
| Rutgers University | New Brunswick, NJ | Counseling Psychology | M.Ed., 1995 |
| University of Wisconsin | Madison, WI | Human Development | Ph.D., 1995-2001 |

**Appointments:**

| | |
|---|---|
| Director, Arizona State University | 2012-Present |
| Research Professional, Arizona State University | 2011-2012 |
| Adjunct Professor, Buena Vista University | 2007-2011 |
| Evaluation/Research Specialist, University of Pittsburgh | 2001-2006 |

**Products:**

**Barnard, W.M.** (2015). *Beyond the pre- and post-test: Evaluating an international education program.* In the Monograph: International Development in Indian Teacher Education: Conceptual and Empirical Issues, C.M. Clark (Ed.).

**Barnard, W. M.** & Fu, H. (2015). *Examining mentor teacher professional success in a value-added evaluation framework.* Paper presented at the Annual Conference of the American Educational Research Association (AERA), Chicago, Ohio.

**Barnard, W.M.**, Fu, H., & Wang, B. (2016). *Using an Integrated Design to Evaluate a Complex Statewide Educational Initiative.* Presented at the American Evaluation Association Conference, Atlanta, GA.

Vagi, R., Pivovarova, M., **Barnard, W.M.** (in press). *Keeping our best? A survival analysis examining pre-service teacher quality and teacher attrition.* Journal of Teacher Education.

Lawton, K.C., & **Barnard, W.M.** (2015). *Improving Science Achievement through Content Learning and Collaborative Inquiry: Math Science Partnership Grant.* Technical Evaluation Report.

**Synergistic Activities:**

Evaluation Grants Funded in STEM and Higher Education:

- *Center for Bio-inspired Bio-mediated Geotechnics (CBBG).* The evaluation focuses on the CBBG education component (students and teachers' knowledge, skills, attitudes, and engagement levels).
- *Nanotechnology Collaborative Infrastructure Southwest (NCI-SW).* Evaluation efforts include program implementation as well as the impact of the center's education efforts.
- *Teacher Quality Partnership NEXT Evaluation Project.* This longitudinal evaluation examines the impact of a teacher preparation program on teacher effectiveness in the classroom.
- *Improving Science Achievement through Content Learning and Collaborative Inquiry.* The evaluation used a matched comparison group to examine whether participants

increased their content knowledge, increased their confidence in teaching science over time.

- *Adaptive Learning Evaluation.* This evaluation examined learning trajectories of student success in adaptive learning courses compared with traditionally taught courses.

**Colleen E. Bronner**

**Professional Preparation:**

| | | | |
|---|---|---|---|
| State University of New York at | Environmental Engineering | B.S. | 2005 |
| University of California at Berkeley | Water Resources Engineering | M.S. | 2006 |
| State University of New York at Buffalo | Environmental Engineering | Ph.D. | 2014 |

**Appointments:**

| | |
|---|---|
| 2015 – present | Lecture with Potential for Security of Employment in Civil Engineering, University of California at Davis |
| 2014 – 2015 | Assistant Professor of Civil Engineering, California State University, Chico |

**Products:**

1. Savenye, W., Larson, J., Zapata, C., Kavazanjian, E., Elwood, K., Reed, A., Mitchell, M., Brown, S., **Bronner,** C., Saenz, D., Newstetter, W., Benton-Johnson, F., Dalal, M., Gomez, M., & Delgado. (2016). The ultimate higher education start-up: Building education / outreach / diversity for an NSF Engineering Research Center. Paper presented at the annual meeting of the Associate for Educational Communications and Technology, Las Vegas, NV, October 17-21, 2016
2. **Bronner, C. E.** (2014). *Critical evaluation of stream restoration practice: A Western New York case study*, doctoral dissertation, State University of New York at Buffalo, ProQuest, UMI Dissertations Publishing. http://gradworks.umi.com/36/12/3612934.html.
3. **Bronner, C.E.,** A.M. Bartlett, S.L. Whiteway, D.C. Lambert, S.J. Bennett, and A.J. Rabideau. (2012). An assessment of U.S. stream compensatory mitigation policy: Necessary Changes to Protect Ecosystem Functions and Services, *Journal of American Water Resources Association (JAWRA)*: 1-14. DOI:10.1111/jawr.12034
4. Bennett, S.J., A. Simon, J.M. Castro, J.F. Atkinson**, C.E. Bronner**, S.S. Blersch, and A.J. Rabideau. (2011). The evolving science of stream restoration, in Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools, edited by A. Simon, S.J. Bennett, and J.M. Castro*, Geophysical Monograph* 194, pp. 1-8, American Geophysical Union, Washington, D.C.
5. Rabideau, A.J., **C.E. Bronner**, D. Milewski, J. Golubski, and A.S. Weber. (2007). Background Concentrations of Polycyclic Aromatic Hydrocarbon (PAH) Compounds in New York State Soils, *Environmental Forensics*, 8(3): 221 – 230. DOI: 10.1080/15275920701506219

**Synergistic Activities:**

1. *Development of Civil and Environmental Engineering Programs and Modules*. Current activities include an geotechnical engineering summer camp for girls, sustainable engineering workshop for middle school teachers (connect K-12 standards to engineering content), and development and implementation of a graduate course series in which civil engineering graduate students studied education engineering topics and then designed educational modules related to their research for K-12 or undergraduate audiences (modules used in

engineering camp and teachers workshop).

2. *Promotion of Inclusion and Diversity in Engineering Education.* As an active member in several American Society of Engineering Education divisions dedicated to diversity and inclusion in engineering (Pre-college; Women in Engineering; Engineering and Public Policy; and Minorities in Engineering divisions), I participate in activities designed to open engineering education from pre-college to post-graduate levels. Examples include: 1) Participation in Fall 2015 workshop for LGBTQ Safe Zone Facilitator Training as part of the ASEE Leadership Virtual Community of Practice; 2) Facilitation of Safe Zone workshop at national 2016 ASEE Conference; 3) Serving as a Director at Large for Pacific Northwest Section 2016-2017; 4) Assisting in creation of more inclusive logo for pre-college division; and 5) Serving on committee for 2016 K-12 Teachers Workshop at ASEE Conference. Through involvement with Society of Women Engineers (SWE) as a past faculty advisor at CSU Chico, past Scholarship Chair, current Section Representative of Sierra Foothills Professional Section, and mentor for UC Davis SWE section, I have participated in numerous outreach events, activities to empower female students, and given presentations on women in engineering. Examples include: 1) a collaboration with principal and science teachers at Inspire High School of Arts and Sciences (Chico, CA) led to establishment of club for high school girls in their engineering track and involve students in engineering outreach activities. It became one of the first SWENext Clubs and 2) presentations, including those with undergraduate student co-authors, at local, regional and national SWE events for preparing women entering the engineering profession.
3. *Mentorship of Students on Engineering Projects*. As faculty advisor of UC Davis Engineers Without Borders (EWB) chapter, I mentor three student teams working on international and domestic design projects (e.g., water distribution system in Peru, water treatment project for tribal college) and help students create sustainable designs that consider economic, social and environmental constraints, as well as the technical (e.g., geotechnical and water resource factors).
4. *Activity on Committees focused on Civil and Environmental Engineering Education*. Active members of three Environmental and Water Resources Institute (EWRI) focused on civil engineering students in college and immediately upon graduation: Education Council (incoming Chair, current secretary); Students Council (member); New Professionals Council (incoming Vice-Chair). Activities in which I am active include increasing awareness of need for diversity in engineering (e.g., moderate panel sessions, presentations at conferences), encouraging student and new professional participation in professional organizations (action to create new EWRI graduate student chapters, organizing events at annual Congress), and disseminating information on educational strategies and tools in civil engineering education (developing EWRI educational blog). Additionally, I am currently serving on the 2017 Congress Organizing Committee to represent student interests and organize activities to increase their participation.
5. *Co-PI on Preparing Engineering Graduate Students for the 21st Century (PEGS21).* Co-organizing seminar for first generation, low-income graduate students. Activities include development and presentation of material on imposter syndrome and anxiety in graduate school.

**Susan Wightman Brown**

**Professional Preparation:**

| | | | |
|---|---|---|---|
| New Mexico Highlands University | Las Vegas, New Mexico | Education | Bachelor of Arts 1970 |
| New Mexico State University | Las Cruces, New Mexico | Curriculum and Instruction | Master of Arts in Education 1981 |
| New Mexico State University | Las Cruces, New Mexico | Elementary | Certification 1988 |
| New Mexico State University | Las Cruces, New Mexico | Curriculum and Instruction Minor: Multicultural Education | Ph.D. 2000 |

**Appointments:**

2016 – Present Interim Associate Dean of Research, College of Education, NMSU
2006 – Present Research Associate Professor, College of Education, New Mexico State University
2006 – Present Director of STEM Outreach, College of Education, New Mexico State University
2006 – Present Project Director, Scientifically Connected Communities ($SC^2$), New Mexico State University
2002 – Present Project Director, Southern New Mexico Science, Engineering, Mathematics, and Aerospace Academy (SNM SEMAA), NASA and NMSU
2008 – Present Online Course Instructor, University of Texas at El Paso
1994 – Present Instructor of Science Methods for Early Childhood, Elementary and Secondary Teachers, College of Education, New Mexico State University
1970 – 1972; 1987 – 2000 Middle and High School Teacher, several schools, New Mexico

**Products:**

1. S. Brown and L. Chacon. *Current Perspectives on School/University/Community Research, STEM education in Afterschool Rural NM, Chapterpending.* Information Age Publishing: Charlotte, North Carolina.
2. KM Wiburg and S Brown. *Lesson Study Communities: Increasing Achievement with Diverse Students*. Corwin, *224p* (2006).
3. S Brown. Let's observe. *Journal of Mathematics and Science: Collaborative Explorations*, Virginia Mathematics and Science Coalition (VMSC): 2009.
4. SW Brown. The gender differences: Hispanic females and males majoring in sciences or engineering. *Journal of Women and Minorities in Science and Engineering,* Vol 14(2): 205-223 (2008).
5. SW Brown. Hispanic students majoring in science or engineering: what happened in their educational journeys? *Journal of Women and Minorities in Science and Engineering,* Vol 8(2) (2002).
6. SW Brown. Emily and Rebecca: A tale of two teachers. *Teaching and Teacher Education,* Vol 21(6): 637-648 (2005).
7. SW Brown and TM Hansen. Connecting Middle School, Oceanography, and the Real World. *Science Scope*, Vol 24(3) (November 2000).

8. SW Brown. *NES Guide to Developing Partnerships & Sustainability: Utilizing a Systems Approach*, 2007.
9. SW Brown. A human system debate. *Science Scope*, Vol 23(5) (February 2000).

**Synergistic Activities:**

1. K-12 education and outreach. Her outreach focus is increasing student participation and achievement in the STEM fields. Her K-12$^{th}$ grade after school programs touch the lives of over 4500 students each year as well as her working with K-12$^{th}$ grade teachers by providing high quality professional development opportunities that include increasing the teacher's content knowledge and use of brain researched teaching strategies.
2. Research focused on science and engineering education of minority students. Her research focus is science education and the underrepresentation of minority students and females in the fields of science, math, and engineering as shown by her grants and the national awards she has received. She is the recipient of the Presidential Award for Excellence in Science Teaching, NMSU Outstanding Research Award, NMSU Research Achievement Award, NASA's Space Flight Awareness Trailblazer Award, NASA Innovative Program Award, the Walt Disney/McDonald's American Teacher Award, AAAS Robert I. Larus Award, Who's Who Among America's Teachers, and a special recognition from the New Mexico Legislature.
3. Grant writing with emphasis on education and outreach programs. She has obtained more than $7.5 million in funding for STEM outreach efforts. She is the Principal Investigator of the following grants: NSF Stone Age to Space Age; NSF Noyce; NSF GK-12; NASA SEMAA; Scientifically Connected Communities (SC$^2$) Program; and several other foundation grants.
4. Teacher and student scientific training programs. She is the founder and director of Scientifically Connected Communities (SC$^2$) Program, dedicated to improving the scientific literacy of southern New Mexico students by providing professional development to K-12$^{th}$ grade teachers emphasizing critical-thinking strategies and pedagogy to enhance scientific inquiry for all students. SC$^2$ program collaborates with a network of teachers, scientists, administrators, and district leaders to increase teacher science content knowledge, promote scientific inquiry curriculum, and to provide resources and materials for the classroom. http://stem.education.nmsu.edu/sc2/
5. Broadening the participation of groups underrepresented in science, mathematics, engineering and technology. She is a Principal Investigator and Program Director of Southern New Mexico Science, Engineering, Mathematics, and Aerospace Academy (SNM SEMAA), which is designed to encourage normally underrepresented groups into the fields of science, engineering, mathematics, and technology through hands-on, inquiry based science activities. The program is a collaboration of NASA, NMSU Colleges of Engineering and Education, Gadsden Independent School District, Las Cruces Public Schools, parents and volunteers.

   http://stem.education.nmsu.edu/semaa/

**Hinsby Cadillo-Quiroz**

**Professional Preparation:**

| | | | |
|---|---|---|---|
| Univ Nacional Mayor de San Marcos, Peru | Biology | B.S. | 2000 |
| Univ Nacional Mayor de San Marcos, Peru | Microbiology | MS. | 2001 |
| Cornell University | Microbiology | Ph.D. | 2008 |

**Appointments:**

*2011-present* *Assistant Professor,* School of Life Sciences, Arizona State University.
*2010-2011* *Postdoctoral Assoc.*, Institute of Ecology and Evolution, University of Oregon.
*2008-2010* *Postdoctoral Assoc.*, Dept of Microbiology, Univ. of Illinois Urbana-Champaign.
*2002-2008* *Graduate Research Assistant*, Department of Microbiology, Cornell University.

**Publications**:

1. Browne, P, Li, Z., Chongle P., and **Cadillo-Quiroz, H**. **2017**. Transcriptomic structure and response to pH stress of novel *Methanoregulacea* methanogens from peatlands. **Journal of Applied and Environmental Microbiology** (***Submitted***).
2. C.X. She, Z.C. Zeng, ***H. Cadillo-Quiroz***, C. Tong. **2017**. Changes of community structure and abundance of methanogens in soils along a freshwater–brackish water gradient in subtropical estuarine marshes. Geoderma 299: 101:110.
3. Browne, P., Kyrpides, N., Woyke, T., Goodwin, L., Detter, C., Tamaki, H., Liu, W., Zinder, S., **Cadillo-Quiroz, H**. **2016.** Genomic composition and dynamics among *Methanomicrobiales* predict adaptation to contrasting environments. ***ISME J.*** 11:87-99.
4. Yamamoto, K., Tamaki, H., **Cadillo-Quiroz, H.,** Imachi, H., Kyrpides, N., Woyke, T., Goodwin, T., Zinder, S., Kamagata, Y., Wen-Tso, L. **2014**. Complete genome sequence of *Methanoregula formicica* SMSPT, a mesophilic hydrogenotrophic methanogen isolated from a methanogenic upflow anaerobic sludge blanket reactor. **Genome Announcements** 2(5): e00870-14.
5. Nelson, J.L., Fung, J.M. **Cadillo-Quiroz, H**., Cheng X., Zinder S.H. **2011**. A Role for *Dehalobacter spp*. in the Reductive Dehalogenation of Dichlorobenzenes and Monochlorobenzene. ***Environmental Science & Technology*** *45* (16), 6806-6813.

*Other significant publications*

6. Wang, S., Zhuang, Q., Lähteenoja, O., Draper, F., and **Cadillo-Quiroz, H**. **2017**. A potential shift from a carbon sink to a source in Amazonian peatlands under a changing climate. ***Nature Communications***. (***Submitted*)**.
7. Bridgham, S., **Cadillo-Quiroz, H**., Keller, J., Zhuang, Q. **2013**. Contemporary and future methane emissions from wetlands: biogeochemical, microbial, and modeling perspectives from local to global scales. ***Global Change Biology*** 19:1325-1346
8. Sun, C., Brauer, S., **Cadillo-Quiroz, H**., Zinder, S., Yavitt, J. **2012**. Seasonal Changes in methanogenesis and methanogens in three peatlands New York State. **Frontiers in Terrestrial Microbiology**. **3**(81), doi: 10.3389/fmicb.2012.0008
9. Baran, R., Brodie, E., Mayberry-Lewis, M., Hummel, E. Nunes Da Rocha, U., Chakraborty, R., Bowen, B., Karaoz, U., **Cadillo-Quiroz, H**., Garcia-Pichel, F., Northen, T. **2015**. Exometabolite niche partitioning among sympatric soil bacteria. ***Nature Communications*** 6: 8289.

10. **Cadillo-Quiroz, H**., Yavitt, J., Zinder, S.H., and J. E. Thies. **2010**. Diversity and community structure of methanogens and related *Archaea* inhabiting the rhizoplane of two contrasting plants in an acidic bog. ***Microbial Ecology*** 59 (4): 757-767.

**Synergistic Activities:**

*1.* ***Mentor.*** Dr Cadillo-Quiroz, has a long record of expanding research experiences into undergraduate (UG) education, he mentored 16 UG students even as a PhD student. As an Assistant professor, he has formalized his UG effort into an Inquiry-based learning class called MENTOR@ASU mentoring ~10 students per semester. He also co-advises 3 honors theses in the Universidad de la Amazonia Peruana, and mentors 3 PhD and 2 Master students and 2 postdoctoral researchers. Specific programs where he participates as mentor are: ***a)*** Founder and Lead of the ***M****icrobial* ***E****ducatio****N****,* ***T****raining and* ***O****ut****R****each (MENTOR@ASU)*, ***b) ASM Mentor for International Students, c) Mentor of local chapter of the Society for the Advancement of Chicanos and Native Americans in Sciences (SACNAS) mentor*** for undergraduate and graduate students.

*2.* ***Faculty Member of the Center for Fundamental and Applied Microbiomics (CFAM), and Sweety Center for Environmental Biotechnology (SCEB) at the Biodesign Institute.*** *Arizona State University.* PI is a founding member of CFAM, a newly formed center where transdisciplinary research is developed among 15 faculty from five different Schools at ASU. The center's research focus is to identify emergent properties of microbial biology and PI is an active member involved in two active projects. PI is a member of SCEB where he contributes his expertize on methanogenesis and currently leads a project on the ASU Engineering Research Center on enhancing $CH_4$ production from landfills.

***3.*** ***Visiting Researcher at the Research Center for Natural Resources, Universidad de la Amazonia Peruana (UNAP)****.* Dr. Cadillo-Quiroz has developed a strong partnership with UNAP for research and training of undergraduate "thesistas" students and has recently been nominated under visiting researcher status in the UNAP Natural Resources Institute.

4. **Instructor** of: **a) "Bacterial Diversity (MIC470)" class** implementing creative Microbial Power instructional project to be executed in local high schools lead by ASU students; b) **Frontiers in Microbial Biology symposium,** organizing, developing and evaluating research talks and discussions for overly 25 PhD students and invited external speakers.

5. ***Member. Research Experience for Peruvian Undergraduates (REPU) program. REPU is a peer-organized program that trains and unites the next generation of Peruvian and Peruvian-american scientists.*** *P*rogram to complement undergraduate scientific education with a 3-month research-intensive internship in laboratories in the US for students from Peru. Dr Cadillo-Quiroz, is substantially involved in training programs for minorities at ASU, nationally and internationally, and is involved in active international educative and research international collaborations.

**Douglas D. Cortes**

**Professional Preparation:**

| | | | | |
|---|---|---|---|---|
| Georgia Institute of Technology | Atlanta, Georgia | Civil & Environmental | B.S. | 2006 |
| Georgia Institute of Technology | Atlanta, Georgia | Civil & Environmental | M.S. | 2008 |
| Georgia Institute of Technology | Atlanta, Georgia | Civil Engineering | Ph.D. | 2010 |

**Appointments:**

| | |
|---|---|
| 2017 – Present | Associate Professor of Civil Engineering, New Mexico State University |
| 2011 – 2017 | Assistant Professor of Civil Engineering, New Mexico State University |
| 2011 | Senior Staff of Geotechnical Engineering, Geosyntec Consultants |

**Products:**

1. Rascon, R., Cortes, D. D., and Pasten, C., 2015. “Reclaimed asphalt binder aging and its implications in the management of RAP stockpiles” Construction and Building Materials, v 101, Part 1, pp 611-616, doi:10.1016/j.conbuildmat.2015.10.125
2. Nasirian, A., Cortes, D. D., and Dai, S., 2015. “The physical nature of thermal conduction in dry granular media.” Géotechnique Letters, v 5, n January-March, pp 1-5, doi.org/10.1680/geolett.14.00073
3. Garcia, N. F., Valdes, J. R., and Cortes, D. D., 2015. “Strength characteristics of polymer-bonded sands” Géotechnique Letters, v 5, n July-September, pp 212-216, doi.org/10.1680/geolett.15.00089
4. Williamson, S., and Cortes, D. D., 2014. "Dimensional analysis of soil-cement mixture performance." Géotechnique Letters, 4, (Jan-Mar), pp 33-38.
5. Cortes, D. D., A. I. Martin, T. S. Yun, F. M. Francisca, J. C. Santamarina, and C. Ruppel, 2009. “Thermal conductivity of hydrate-bearing sediments.” Journal of Geophysical Research, 114, B11103, doi:10.1029/2008JB006235.
6. Miranda, L. V., Valdes, J. R., and Cortes, D. D., 2017. "Solar bricks for lunar construction." Construction and Building Materials, v 139, 15 May 2017, pp 241-246, doi.org/10.1016/j.conbuildmat.2017.02.029
7. Papadopoulos, E., Cortes, D. D., and Santamarina, J. C., 2016. "In-situ assessment of the stress-dependent stiffness of unbound aggregate bases: application in inverted base pavements." International Journal of Pavement Engineering, v 17, n 10, pp 870-877, doi.org/10.1080/10298436.2015.1022779
8. Pasten, C., Garcia, M., and Cortes, D. D., 2015. "Physical and numerical modelling of the thermally induced wedging mechanism" Géotechnique Letters, v 5, n July-September, pp 186-190, doi.org/10.1680/jgele.15.00072
9. Cortes, D. D., Shin, H., Santamarina, J. C., 2012. "Numerical Simulation of Inverted Pavement Systems." Journal of Transportation Engineering, v 138, n 12, pp 1507-1519, doi:10.1061/(ASCE)TE.1943-5436.0000472.
10. Fragaszy, R. J., Santamarina, J. C., Amekudzi, A. A., Assimaki, D., Bachus, R., Burns, S. E., Cha, M.-S., Cho, G.-C., ?Cortes, D. D., 2011."Sustainable Development and Energy Geotechnology - Potential Roles for Geotechnical Engineering." KSCE Journal of Civil Engineering, v 15, n 4, pp 611-621, doi: 10.1007/s12205-011-0102-7.

**Synergistic Activities:**

1. Senior Personnel:
   Center for Bio-mediated & Bio-inspired Geotechnics (Aug/2015 – Present).
2. President:
   American Society of Civil Engineers. New Mexico Section (Sep/2013 – Sep/2015).
3. Chair:
   ASCE-NM Spring Seminar (Sep/2013 – Sep/2015).
4. Reviewer:
   ACI Materials Journal, Revista Internacional de Desastres Naturales, Accidentes e Infraestructura Civil, ASCE Journal of Geotechnical and Geoenvironmental Engineering, ASTM Geotechnical Testing Journal, Transportation Research Record, Geomechanics and Engineering (ongoing).
5. Invited lecturer:
   Congreso Internacional de Ingeniería Civil 2011 Universidad la Gran Colombia. Bogotá, Colombia (Oct/2011).

**Sheng Dai**

**Professional Preparation:**

| | | | |
|---|---|---|---|
| Tongji University, Shanghai, China | Civil Engineering | B.S.C.E. | 2005 |
| Tongji University, Shanghai, China | Civil Engineering | M.S.C.E | 2008 |
| Georgia Institute of Technology, Atlanta, Georgia | Geosystems Engineering | M.S.C.E | 2011 |
| Georgia Institute of Technology, Atlanta, Georgia | Geosystems Engineering | Ph.D. | 2013 |

**Appointments:**

| | |
|---|---|
| 2015 – present | Assistant Professor, School of Civil and Environmental Engineering, Georgia Institute of Technology |
| 2013 – 2015 | Postdoctoral Researcher, National Energy Technology Laboratory, US Department of Energy |
| 2008 – 2013 | Graduate research assistant, School of Civil and Environmental Engineering, Georgia Institute of Technology |

**Products:**

1. Jeong, B., Dai, S. (2017). Permeability reduction due to bio-clogging in porous media. *2nd Pan American conference on Unsaturated Soils*, Nov 12-15, 2017, Dallas, TX.
2. Dai, S., Boswell, R., Waite, W.F., Jang, J., Lee, J.Y., and Seol, Y. (2017). What has been learned from pressure cores. *9th International Conference on Gas Hydrates*, Jun 25-30, 2017, Denver, CO.
3. Mahabadi, N., Dai, S., Seol, Y., Yun, T.S. and Jang, J. (2016). The water retention curve and relative permeability for gas production from hydrate-bearing sediments: Pore-network model simulation. *Geochemistry, Geophysics, Geosystems*, 17(8), 3099-3110.
4. Cao, S. C., Dai, S., Jung, J. (2016). Supercritical CO2 and brine displacement in geological carbon sequestration: Micromodel and pore network simulation studies. *International Journal of Greenhouse Gas Control*, 44, 104-114.
5. Dai, S., Cha, J., Rosenbaum, E., Zhang, W., Seol, Y. (2015). Thermal conductivity measurements in unsaturated hydrate-bearing sediments. *Geophysical Research Letters*, 42(15), 6295-6305.
6. Dai, S., Seol, Y., Wickramanayake, S., Hopkinson, D. (2015). Characterization of hollow fiber supported Ionic liquid membranes using microfocus X-ray computed tomography. *Journal of Membrane Science*, 492, 497-504.
7. Dai, S., Y Seol (2014). Water permeability in hydrate-bearing sediments: A pore-scale study. *Geophysical Research Letters*, 41(12), 4176-4184.
8. Dai, S., JY Lee, JC Santamarina (2014). Hydrate nucleation in quiescent and dynamic conditions. *Fluid Phase Equilibria*, 378, 107-112.
9. Dai, S., JC Santamarina (2014). Sampling disturbance in hydrate-bearing sediment pressure cores: NGHP-01 expedition, Krishna-Godavari Basin example. *Marine and Petroleum Geology*, 58(Part A), 178-186. DOI: 10.1016/j.marpetgeo.2014.07.013.
10. Dai, S., JC Santamarina (2013). Water retention curves for hydrate-bearing sediments. *Geophysical Research Letters*, 40 (21), 5637–5641.

**Synergistic Activities:**

6. *Research Areas:* Energy geotechnics: gas hydrate-bearing sediments, geological carbon sequestration, enhanced geothermal system, nuclear waste disposal; Wave-based geomaterials characterization: stiffness, thermal and electrical properties, X-ray computed tomography; Offshore science and engineering: oceanic sediments, pressure core testing, microbial degradation of hydrocarbon.
7. *Education Related Activities:* Affiliated faculty of Ocean Science and Engineering and Strategic Energy Institute, Georgia Institute of Technology (2015 - ); Class of 1969 Teaching Fellows, Georgia Institute of Technology (2016/2017); Tech to Teach Program, Center of Enhanced Teaching and Learning at Georgia Tech (2012).
8. *Honors and Awards (Recognitions of Significant Contributions to Research and Education):* 'Spotlight of Research', featured in the *Fire in the Ice* newsletter of US Department of Energy (2017); Class of 1969 Teaching Fellows, Georgia Institute of Technology (2016); ORISE Fellowship, US Department of Energy (6/2015; 10/2014); George F. Sowers Distinguished Graduate Students, Georgia Institute of Technology (2013).
9. *Professional Service:* GOM2 Marine Test Science Advisory Board, DOE/UT (2016 - present); ISSMGE TC308: Energy Geotechnics – Member (2015 – present); Advisory Board of Pressure Core Analyses, USGS, U.S. Dept. of the Interior (2015 – present); American Geophysical Union – Life Member (2014 - ); Society of Exploration Geophysicists – Member (2010 - ); Reviewer for journals of ASCE JGGE, Geoph. Res. Lett., J. Geoph. Res., Mar. Petr. Geol., Env. Sci. Tech., Geochem. Geophy. Geosys., Adv. Wat. Res. etc.

**Jason T. DeJong**

**Professional Preparation:**

| | | | |
|---|---|---|---|
| University of California, Davis, California | Civil Engineering | B.S.C.E. | 1996 |
| Georgia Institute of Technology, Atlanta Georgia | Geotechnical Engineering | M.S.C.E. | 1997 |
| Georgia Institute of Technology, Atlanta Georgia | Geotechnical Engineering | Ph.D. | 2001 |

**Appointments:**

| | |
|---|---|
| 2012 – present | Professor of Civil Engineering, University of California at Davis |
| 2016 | Overseas Fellow, Churchill College, Cambridge, England |
| 2016 | Visiting Scholar, Department of Engineering, University of Cambridge, England |
| 2010 | Gledden Research Fellow, University of Western Australia |
| 2007 – 2012 | Associate Professor of Civil Engineering, University of California at Davis |
| 2005 – 2007 | Assistant Professor of Civil Engineering, University of California at Davis |
| 2002 – 2005 | Assistant Professor of Civil Engineering, University of Massachusetts Amherst |
| 2001 | NSF International Research Fellow, Univ. of Western Australia, Perth, Australia |

**Products:**

11. DeJong, J.T., Burrall, M., Wilson, D.W., Frost, J.D., "A Bio-Inspired Perspective for Geotechnical Engineering Innovation", ASCE Geotechnical Frontiers 2017 Conference, Orlando, Florida, March 2017.
12. Gomez, M.G., Graddy, C.R.M., DeJong, J.T., Nelson, D.C., Tsesarsky, M. (2017). "Stimulation of Native Microorganisms for Bio-cementation at Field Scale Treatment Depths." *Journal of Geotech. and Geoenviron. Eng.,* Submitted in Review.
13. Gomez, M.G., Anderson, C.M., DeJong, J.T., Nelson, D.C., Graddy, C.M.R., and Ginn, T.R. (2016). "Large-scale Comparison of Bioaugmentation and Biostimulation Approaches for Bio-cementation of Sands." *Journal of Geotech. and Geoenviron. Eng.,* Published.
14. DeJong, J.T, Gomez, M.G., Waller, J.T., Viggiani G. (2017). "Influence of Bio-Cementation on Shearing Behavior of Sand using X-ray Computed Tomography", GeoFrontiers 2017 Technical Papers, 12 pp.
15. Gomez, M.G., DeJong, J.T (2017). "Engineering Properties of Bio-cementation Improved Sandy Soils", Grouting 2017 Technical Papers, 11 pp.
16. Proto, C.J., DeJong, J.D., Nelson, D.C., and Sturm, A.P. "Bio-Mediated Permeability Reduction of Saturated Sands", ASCE J. Geotechnical and Geoenvironmental Engineering, 2014, Vol. 142(12).
17. Gomez, M.G., Martinez, B.C., DeJong, J.T., Hunt, C.E., deVlaming, L.A., Major, D.W., and Dworatzek, S.M. "Field Scale Bio-cementation Tests to Improve Sands", *Ground Improvement*, 2014, 11 pgs.
18. Dumlao, M.R., Ramananarivo, S., Goyal, V., DeJong, J.T., Waller, J., and Silk, W.K. "The role of root development of Avena fatua in conferring soil strength", American Journal of Botany, 2015, Vol. 102, No. 7, pp. 1050-1060.
19. DeJong, J.T., Soga, K.S., Kavazanjian, E., Burns, S., van Paassen, L., Al Qabany, A., Aydilek, A., Bang, S.S., Burbank, M., Caslake, L., Chen, C.Y., Cheng, X., Chu, J., Ciurli,

S., Fauriel, S., Filet, A.E., Hamdan, N., Hata, T., Inagaki, Y., Jefferis, S., Kuo, M., Laloui, L., Larrahondo, J., Manning, D.A.C., Martinez, B., Montoya, B.M., Nelson, D.C., Palomino, A., Renforth, P., Santamarina, J.C., Seagren, E.A., Tanyu, B., Tsesarsky, M., Weaver, T. (2013) Biogeochemical processes and geotechnical applications: progress, opportunities, and challenges, *Geotechnique*, 63(4): 287-301.

20. Mortensen, B.M., Haber, M.J., DeJong, J.T., Caslake, L.F., and Nelson, D.C. (2011) Effects of Environmental Factors on Microbial Induced Calcium Carbonate Precipitation, *Applied Microbiology* 111 (2): 338-349.

**Synergistic Activities:**

10. *Research Areas:* Bio-mediated soil improvement; Embodied energy of geotechnical systems: opportunities for sustainable design; Integrated site characterization methodology; Laboratory characterization of intermediate soils; iBPT for characterization of liquefaction potential of gravels.
11. *Education Related Activities:* Development of Unified Tablet PC – Classroom Communication System for Enhanced Learning in Large Engineeering Classrooms; Lilly Teaching Fellowship – Young Faculty Educational Development (2003-2004), University of Massachusetts Amherst Center for Teaching; DeJong, J.T. and Boulanger, R.W. (2000) "Introduction to Drilling and Sampling in Geotechnical Practice", Educational Video, 2nd Edition. 35 min.
12. *Honors and Awards (Recognitions of Significant Contributions to Research and Education):* ASTM Hogentogler Award (2015), ICE TK Hsieh Prize (2014), ASCE Huber Research Prize (2013), Shamsher Prakash Research Award (2011), Gledden Visiting Senior Fellowship, University of Western Australia (2009-2010), ASCE Casagrande Award (2008), ASTM Hogentogler Award (2003), Lilly Teaching Fellow, University of Massachusetts (2003-2004)
13. *Professional Service:* ISSMGE TC102 Committee – Secretary (2012 – present), ASCE Soil Properties Committee – Chair & Member (2003 – 2012); ASCE Engineering Geology and Site Characterization – Member (2003 – present); Editorial Board Member for ASCE JGGE and Geotechnique Letters; Reviewer for ASCE JGGE, ASTM GTJ, CGJ, Geotechnique, Geotechique Letters, TRB, Advanced Microbiology, ES&T, Const. Mats.; Vice Chair, Organizing Committee – GeoCongress 2006 - Atlanta

**Anca G. Delgado**

**Professional Preparation:**

| | | |
|---|---|---|
| Arizona State University, Tempe AZ | Microbiology | B.S. 2008 |
| Arizona State University, Tempe AZ | Microbiology | PhD. 2013 |
| Arizona State University, Tempe AZ | Environmental Engineering | Postdoctoral Fellow 2013-2016 |

**Appointments:**

**Assistant Professor of Environmental Engineering**, School of Sustainable Engineering and the Built Environment, Arizona State University, *position starting in August 2017*

**Assistant Research Scientist**, Biodesign Swette Center for Environmental Biotechnology, ASU, 2016-2017

**Associate Faculty**, School of Sustainable Engineering and the Built Environment, ASU, 2015-2017

**Postdoctoral Research Associate**, Arizona State University, 2013-2016

**Graduate Research Assistant**, Arizona State University, 2008-2013

**Teaching Assistant**, School of Life Sciences, Microbiology Department, 2008-2010

**Undergraduate Researcher**, School of Life Sciences, Microbiology Department, 2007-2008

**Products – Select Publications:**

Esquivel-Elizondo S, Delgado AG, Krajmalnik-Brown R. 2017. Evolution of microbial communities growing with carbon monoxide, hydrogen and carbon dioxide. FEMS Microbial Ecology. 93 (6): fix076.

Chen T, Delgado AG, Maldonado J, Zuo Y, Kamath R, Westerhoff P, Krajmalnik-Brown R, and Rittmann BE. 2017 Interpreting the interaction between ozone and residual petroleum hydrocarbons in soil. Environmental Science & Technology 51 (1): 506–513.

Esquivel-Elizondo S, Parameswaran P, Delgado AG, Maldonado J, Rittmann BE, Krajmalnik-Brown R. 2016. Archaea and Bacteria acclimate to high total ammonia in a methanogenic reactor treating swine waste. Archaea Special Issues on "To Cooperate or Compete? Archaea in Symbiosis". http://dx.doi.org/10.1155/2016/4089684.

Apul OG, Delgado AG, Kidd J, Alam F, Dahlen P, Westerhoff P. 2016. Carbonaceous nano-additives augment microwave-enabled thermal remediation of soils containing petroleum hydrocarbons. Environmental Science: Nano. 3: 997-1002.

Chen T, Delgado AG, Yavuz BM, Proctor AJ, Maldonado J, Zuo Y, Westerhoff P, Krajmalnik-Brown R, Rittmann BE. 2016. Ozone enhances biodegradability of heavy hydrocarbons in soil. Journal of Environmental Engineering and Science. 11(1): 7-17.

Delgado AG, Fajardo-Williams D, Kegerreis KL, Parameswaran P, Krajmalnik-Brown R. 2016. Impact of ammonium on syntrophic organohalide-respiring and fermenting microbial communities. mSphere 1(2):e00053-16.doi:10.1128/mSphere.00053-1.

Delgado AG, Fajardo-Williams D, Kegerreis KL, Parameswaran P, Krajmalnik-Brown R. 2016. Impact of ammonium on syntrophic organohalide-respiring and fermenting microbial communities. mSphere 1(2):e00053-16.doi:10.1128/mSphere.00053-1.

Delgado AG, Fajardo-Williams D, Popat SC, Torres CI, Krajmalnik-Brown R. 2014. Successful operation of continuous reactors at short retention times results in high-density, fast-rate *Dehalococcoides* dechlorinating cultures. Applied Microbiology and Biotechnology 98(6): 2729-2737.

Delgado AG, Parameswaran P, Fajardo-Williams D, Halden RU, Krajmalnik-Brown R. 2012. Role of bicarbonate as a pH buffer and electron sink in microbial dechlorination of chloroethenes. Microbial Cell Factories 11(128).

**Products – Patent Applications:**

Krajmalnik-Brown R, Torres CI, Delgado AG, Popat SC, Fajardo-Williams D. Methods, system, and culture medium for production of dechlorinating microorganisms. PCT application #14/204,058; filed 03/14/2013.

Rittmann BE, Lee H-S, Torres CI, Delgado AG, Halden RU, Krajmalnik-Brown R. Reduction of chlorinated compounds and toxic substances in groundwater and soils by $H_2$ supply generated from microbial electrolysis cells (MECs). Nationalized PCT # 13/583,322; filed 03/08/2011.

Krajmalnik-Brown R, Halden RU, Delgado AG, Ziv-El M. Microbial cultures and methods for anaerobic bioremediation. Nationalized PCT #13/386,386; filed 07/23/2010.

**Synergistic Activities:**

- Involved in several projects on bioremediation of chlorinated solvents and petroleum hydrocarbons, including projects sponsored by industries
- Manuscript reviewer for Applied and Environmental Microbiology, Applied Microbiology and Biotechnology, Biodegradation, Environmental Engineering and Management Journal, Environmental Science & Technology, ISME Journal, Journal of Hazardous Materials, Journal of Visualized Experiments (JoVE), Science of the Total Environment, Water Research
- Advising and mentoring students from the following programs: Environmental Engineering, Chemical Engineering, Microbiology, Biology, Biochemistry, Biological Design

**J. David Frost**

**Professional Preparation:**

| | | |
|---|---|---|
| Trinity College, Dublin, Ireland | Civil Engineering | BA.I. (Honors) 1980. |
| Trinity College, Dublin, Ireland | Mathematics | B.A. 1980. |
| Purdue University, Indiana, USA | Civil Engineering | M.S.C.E. 1986. |
| Purdue University, Indiana, USA | Civil Engineering | Ph.D. 1989. |

**Appointments:**

2016-present Elizabeth & Bill Higginbotham Professor, Georgia Institute of Technology, Atlanta
2000-present Professor of Civil Engineering, Georgia Institute of Technology, Atlanta
2006-2011 Vice Provost, Georgia Institute of Technology, Atlanta
2000-2012 Director, Regional Engineering Program & Georgia Tech Savannah Campus, Savannah
1993-2000 Geosystems Engineering Group Leader, Georgia Institute of Technology, Atlanta
1992-2000 Associate Professor of Civil Engineering, Georgia Institute of Technology, Atlanta
1989-1992 Assistant Professor of Civil Engineering, Purdue University, West Lafayette
1984-1989 Graduate Assistant, Purdue University, West Lafayette
1981-1984 Geotechnical Engineer, Golder Associates, Calgary, Alberta, Canada

**Products (Related to Proposed Activity):**

Martinez, A., Frost, J.D., and Hebeler, G.L., (2015), Experimental Study of Shear Zones Formed at Sands-Steel Interfaces in Axisymmetric Axial and Torsional Shear Tests, ASTM Geotechnical Testing Journal, Vol. 38, No. 4, pp. 409-426.

Martinez, A, and Frost. J.D., (2016), “Particle-Level Effects on the Global-Scale Behavior During Axial and Torsional Interface Shear”, International Journal of Analytical and Numerical Methods in Geomechanics, published on-line.

Martinez, A., and Frost, J.D., (2017), “The Influence of Surface Roughness Form on the Strength of Sand-Structure Interfaces”, Geotechnique Letters, published on-line.

Frost, J.D., Roozbahani, M., Peralta, A.F., Mallett, S.D., and Hanumasagar, S.S., (2017), “The Evolving Role of Materials in Geotechnical Infrastructure Systems”, Journal of Structural Integrity and Maintenance, published on-line.

Frost, J.D., Martinez, A., Mallett, S.D., Roozbahani, M.M., and DeJong, J.T., (2017), “The Intersection of Modern Soil mechanics with Ants and Roots”, Proceedings of ASCE-GI Geotechnical Frontiers Conference, Orlando, CD-ROM.

**Products (Other):**

Frost, J.D., and Karademir, T., (2015), “Shear Induced Changes in Smooth Geomembrane Surface Topography at Different Ambient Temperatures”, Geosynthetics International, Vol. 23, No.2, pp. 113-128.

DeJong, J.T., Burrall, M., Wilson, D.W., and Frost, J.D., (2016), "A Bio-Inspired Perspective for Geotechnical Engineering Innovation", submitted for possible publication in Proceedings of ASCE Geo-Institute Geotechnical Frontiers Conference 2017.

Atalay, F., and Frost, J.D., (2017), "Engineered Transition Zone for Enhanced Heat Transfer in Energy Pile Foundations", in press for publication in Proceedings of 19th International Conference on Soil Mechanics and Geotechnical Engineering, Seoul, Korea.

Frost, J.D., Roozbahani, M.M., Martinez, A., Jackson, K., Leonard, L., Yamamoto, K., and Jones, M., (2017), "Biologically-Inspired Insights Into Soil Arching and Tunnel Stability from Topology of Ant Nests", in press for publication in Proceedings of 19th International Conference on Soil Mechanics and Geotechnical Engineering, Seoul, Korea.

Liu, F.Z., Atalay, F., Frost, J.D., Li, Y.S and Huang, R.Q., (2017), "Long-Term Gravitational Deformation and Reactivation of a Gigantic Paleo-Landslide", Proceedings of 3rd North American Symposium on Landslides", Roanoke, Virginia, pp. 222-232.

**Synergistic Activities:**

Invited Opening Plenary Keynote Lecture, "The Evolving Role of Materials in Infrastructure Engineering", 1st Transportation Research Congress (TRC 1), Beijing, China, June, 2016.

Invited Seminar, "Infrastructure Engineering Innovations and Inspirations", Port and Airport Research Institute (PARI), Yokosuka, Japan, August, 2016.

Invited Lecture, "The Evolving Role of Geomaterials in Infrastructure Systems", ASCE Seattle Section Geotechnical Group and Geo-Institute Seattle Chapter, Supported by ASCE Geo-Institute Speaker Series, May 2017.

Invited Presentation, "The Evolving Role of Geomaterials in Infrastructure Systems", Georgia Mining Association Annual Convention, Purchasing Managers Breakfast, Ponte Vedra, Florida.

Chair, ISSMGE TC105, International Symposium on Geomechanics from Micro to Macro in Research and Practice, Atlanta, GA, 2018.

**Timothy R. Ginn**

**Professional Preparation:**

| | | | |
|---|---|---|---|
| University of Virginia | Classics, Environmental Science | B.A. | 1982 |
| Purdue University | Civil Engineering | M.S. | 1985 |
| Purdue University | Civil Engineering | Ph.D. | 1988 |

**Appointments:**

| | |
|---|---|
| 2016- present | Professor of Civil & Environmental Engineering, Washington State University |
| 2001-2015 | Professor of Civil & Environmental Engineering, UC Davis. |
| 1999-2001 | Associate Professor of Civil & Environmental Engineering, UC Davis |
| 1997-1999 | Acting Associate Professor of Civil & Environ. Engineering, UC Davis |
| 1994-1997 | Senior Research Scientist, Battelle Pacific Northwest National Lab |
| 1991-1994 | Research Scientist, Battelle Pacific Northwest National Lab |
| 1989-1991 | Alexander Hollaender Distinguished Postdoctoral Fellow, Battelle PNNL |
| 1988-1989 | Visiting Assistant Professor, Civil Engineering, Purdue University |

**Products:**

Ginn, T. R., L. G. Schreyer, and K. Zamani (2017) Phase exposure-dependent exchange, Water Resour. Res., 53(1):619–632.

Babey, T., J.-R. de Dreuzy, and T. R. Ginn (2016) From conservative to reactive transport under diffusion-controlled conditions, Water Resour. Res., 52, 3685-3700.

Kamai, T., M.K. Nassar, K.E. Nelson, T.R. Ginn (2015) Colloid filtration prediction by mapping the correlation-equation parameters from transport experiments in porous media, Water Resources Research 51 (11), 8995-9012.

Le Borgne, T., T. R. Ginn, and M. Dentz (2014) Impact of fluid deformation on mixing-induced chemical reactions in heterogeneous flows, Geophys. Res. Letters, 41(22):7898–7906, 2014.

Martinez, B., J.T. DeJong, and T. R. Ginn (2014) Bio-geochemical reactive transport modeling of microbial induced calcite precipitation to predict the treatment of sand in one-dimensional ÀRZ, *Computers and Geotechnics*, 58:1-15.

Ginn, T. R., M. K. Nassar, T. Kamai, K. Klise, V. Tidwell, and S. McKenna (2013) On a recent solute transport laboratory experiment involving sandstone and its modeling, *Water Resources Research*, 49(11): 7327–7338.

Ginn, T. R. (1999) On the Distribution of Multicomponent Mixtures over Generalized Exposure Time in Subsurface Flow and Reactive Transport: Foundations, and Formulations for Groundwater Age, Chemical Heterogeneity, and Biodegradation, *Water Resources Research* 35(5): 1395-1408.

Martinez, B. C., J. T. DeJong, T. R. Ginn, B. Montoya, T. H. Barkouki, C. Hunt, B. Tanyu, and D. Major, (2013) Experimental optimization of microbial-induced carbonate precipitation for soil improvement, *J. Geotechnical and Geoenv. Eng*. 139(4):587-598

Seeboonruang U., and T. R. Ginn (2006) Upscaling Heterogeneity in Aquifer Reactivity via Exposure- time Concept: Forward Modeling, J. *of Contaminant Hydrology*, 84 (3-4): 127-154.

Murphy, E. M. and T. R. Ginn (2000) Modeling Microbial Processes in Porous Media, Hydrogeo. J. 8(1):142-158.

**Synergistic Activities:**

1. ***Research Areas*** Upscaling subsurface reactive transport, Groundwater Age, Ureolytic calcite precipitation, Colloid filtration, Bioreductive immobilization of dissolved metals, Multidomain diffusion in structured porous media, Fish population dynamics, Multimedia risk assessment for alternative fuels, Inverse modeling for calibration of groundwater flow and reactive transport
2. ***Education Related Activities***
   Prof. Ginn has delivered freshman seminars in "Pollution and Populations" introducing effects of metals and other contaminants on marine and freshwater population dynamics, and has given on-campus short- courses during summer quarters (2002; 2003) in advanced topics related to transport. He has delivered international short courses at Univ. Milan (2010), at the CNRS Summer School on Flow and Transport in Porous and Fractured Media (http://osur.univ-rennes1.fr/cargese2010/), and at Univ. Tübingen Short Course on Reactive Transport Modeling October 2013 in Bad Boll, Germany. In curriculum development, Prof. Ginn has developed a new class at the graduate level in "Quantitative Geochemistry" (ECI272C) in which students are taught use of commercial computer programs for simulation of reactive transport processes affecting solutes and colloids in groundwater. Codes taught include PHREEQC, TOUGHREACT, PHT3D and Geochemists' Workbench. Prof. Ginn works continually with two groups representing underrepresented groups, as follows. WEL Women Engineering Link: extensive recruiting of female research assistants leading to matriculation in graduate studies. NBE National Black Engineering society: mentored undergraduate research assistant Titus Garrett, president of UC Davis chapter of NBE Society, supported fundraising with Titus.
3. ***Honors and Awards***
   UC Davis College of Engineering Outstanding Engineering Mid-Career Award for Research, 2010 Alexander Hollaender Distinguished Postdoctoral Fellow, Battelle PNNL, 1989-1991
4. ***Professional Service***
   Editor, Groundwater Section, ASCE J. Hydrologic Engineering, 2004-9.

   Associate Editor: Advances in Water Resources (2000-2010), Water Resources Research (1994-2003); Stochastic Env. Res. and Risk Assessment (1995-2009); ASCE J. Hydrologic Engineering, 1999-2004

   Special Issue Editor: Stochastic Hydraul. & Hydrol. Vol. 12, Nos. 3, 5 (1998), "Inverse Problems" Advances in Water Resources, with B. D. Wood and D. Tartakovsky, "Macrodispersion in Heterogeneous Porous Media," 2007/8, and Journal of Hydrology, "Quantitative Methods for Groundwater Age Distributions" with J.-R. de Dreuzy.

**Michael G. Gomez**

**Professional Preparation:**

| | | | | |
|---|---|---|---|---|
| University of California, Davis | Davis, CA | Civil & Env. Engineering | B.S. | 2011 |
| University of California, Davis | Davis, CA | Civil & Env. Engineering | M.S. | 2013 |
| University of California, Davis | Davis, CA | Civil & Env. Engineering | Ph.D. | 2017 |

**Appointments:**

2017 – Present Assistant Professor, Civil and Env. Engineering, University of Washington

**Publications:**


**Gomez, M.G.**, Graddy, C.M.R., DeJong, J.T., Nelson, D.C. (2017). "Biogeochemical Changes During Bio-cementation by Stimulated and Augmented Ureolytic Microorganisms." *Environmental Science and Technology*, (In Final Preparation).

**Gomez, M.G.**, DeJong, J.T., Anderson, C.M. (2017). "Effect of Bio-cementation on Geophysical and Cone Penetration Measurements in Sands." *Canadian Geotechnical Journal*, (In Review).

**Gomez, M.G.**, Graddy, C.M.R., DeJong, J.T., Nelson, D.C., Tsesarsky, M. (2017). "Stimulation of Native Microorganisms for Bio-cementation in Samples Recovered from Field Scale Treatment Depths." *Journal of Geotechnical and Geoenvironmental Engineering*, (Accepted in Final Formatting).

**Gomez, M.G.** (2017). Up-scaling of Bio-cementation Soil Improvement Using Native Soil Microorganisms. Doctoral dissertation, Department of Civil and Environmental Engineering, University of California, Davis, 334 pp.

**Gomez, M.G.**, & DeJong, J.T. (2017). "Engineering Properties of Bio-Cementation Improved Sandy Soils." Grouting 2017 Technical Papers, ASCE, Reston, VA. 23-33.

DeJong, J. T., **Gomez, M. G.**, Waller, J. T., & Viggiani, G. "Influence of Bio-Cementation on the Shearing Behavior of Sand Using X-Ray Computed Tomography." Geotechnical Frontiers 2017 Technical Papers, ASCE, Reston, VA. 871-880.

**Gomez, M.G.**, Anderson, C.M., Graddy, C.M. R., DeJong, J.T., Nelson, D.C., and Ginn, T.R. (2016). "Large-Scale Comparison of Bioaugmentation and Biostimulation Approaches for Biocementation of Sands." *Journal of Geotechnical and Geoenvironmental Engineering*, 143(5).

**Gomez, M.G.**, DeJong, J.T., Anderson, C.M., Nelson, D.C., Graddy, C.M. (2016). "Large-Scale Bio-cementation Improvement of Sands", Geotechnical and Structural Engineering Congress 2016 Technical Papers, 941-949.

**Gomez, M.G.**, Martinez, B.C., DeJong, J.T., Hunt, C.E., deVlaming, L.A., Major, D.W., and Dworatzek, S.M. (2015). "Field Scale Bio-cementation Tests to Improve Sands", *Ground Improvement*, 168(3), 206-216.

**Gomez, M.G.**, Anderson, C. M., DeJong, J. T., Nelson, D. C., and Lau, X. (2014). "Stimulating in-situ soil bacteria for bio-cementation of sands." Geo-Congress 2014 Technical Papers, ASCE, Reston, VA. 1674−1682.

DeJong, J.T., Proto, C., Kuo, M., and **Gomez, M.G.** (2014). "Bacteria, Bio-films, and Invertebrates… the Next Generation of Geotechnical Engineers?", Geo-Congress 2014 Technical Papers, ASCE, Reston, VA. 3959-3968.

**Gomez, M.G.**, DeJong, J.T., Martinez, B.C., Hunt, C.E., deVlaming, L.A., Major, D.W., and Dworatzek, S.M. (2013). "Bio-mediated Soil Improvement Field Study to Stabilize Mine Sands", Géo-Montréal 2013 Technical Papers, 8 pp.

**Synergistic Activities:**

(i) Education and Leadership Activities

UC Davis College of Engineering SOP Safety Task Force Member (2016 to 2017). Collaborated with engineering faculty, department safety coordinators, and environmental health and safety officials to standardize laboratory operating procedures and provide safety guidance for all college of engineering laboratories.

President of the Student Leadership Council for the NSF Center for Bio-mediated and Bio-inspired Geotechnics (2015 to 2016). Organized first CBBG webinar series, aided in development of biogeotechnics education modules, charted council by-laws, and represented students in meetings with NSF and industrial and scientific advisory boards.

Volunteered for 15+ outreach events and discussion panels to discuss scientific research and personal experiences related to higher education in STEM with K-12 teachers, K-12 students, undergraduate students, and underrepresented groups.

President of Geotechnical Graduate Student Society (GGSS) at UC Davis (2013 to 2014). Organized an annual technical short course on offshore geotechnics, an open house symposium event, and delivered presentations and organized meetings to support GGSS activities.

Professional Affiliations: American Society of Civil Engineers (ASCE), United States Society on Dams (USSD)

(ii) Honors and Awards

| | |
|---|---|
| CBBG Outstanding Outreach Volunteer Award | 2016 |
| Institution of Civil Engineers Telford Premium Journal Prize - Ground Improvement | 2016 |
| I.M. Idriss Award for Excellence in Geotechnical Engineering | 2014 |
| Fugro West Graduate Fellowship | 2013 |
| USDA Forest Service Certificate of Merit, Deschutes National Forest | 2011 |
| Royal Bank of Scotland (RBS) The First Tee Achiever of the Year Award | 2004 |

**Nasser Hamdan**

**Professional Preparation:**

| | | | |
|---|---|---|---|
| Arizona State University | Tempe, Arizona | Zoology | B.S., 2000 |
| Arizona State University | Tempe, Arizona | Biochemistry | B.A.., 2009 |
| Arizona State University | Tempe, Arizona | Civil Engineering | M.S., 2013 |
| Arizona State University | Tempe, Arizona | Civil Engineering | Ph.D., 2014 |

**Appointments:**

| | |
|---|---|
| 2016-Present | Assistant Research Professor, Center for Bio-mediated & Bio-inspired Geotechnics, Arizona State University, Tempe, AZ |
| 2015-Present | Industry Liaison Officer, Center for Bio-mediated & Bio-inspired Geotechnics, Arizona State University, Tempe, AZ |
| 2015 - 2016 | Civil Engineer, Arcadis U.S. Inc. Design & Consultancy, Phoenix, AZ |
| 2009 - 2014 | Graduate Student Researcher, Civil Engineering, Arizona State University, Tempe, AZ |
| 2003 - 2008 | Business owner-operator, Azurite Service Group, LLC, Phoenix, AZ |
| 2000 - 2003 | Supervisor, Noah's Spark Electric (residential electric), Scottsdale, AZ |

**Products:**

***Five most closely related to the proposed project –***

**Hamdan, N.,** Kavazanjian, E., Rittmann, B.E., and Karatas, I. (2016). "Carbonate Mineral Precipitation for Soil Improvement through Microbial Denitrification." *Geomicrobiology*, DOI: http://dx.doi.org/10.1080/01490451.2016.1154117

O'Donnell, S.T., **Hamdan, N.**, Rittmann, B.E. and Kavazanjian, E. (2016). "A Stoichiometric Model for Soil Improvement via MICP." *Proc. Geo-Chicago, ASCE,* DOI: 10.1061/9780784480120.002

**Hamdan, N.,** Zhao, Z., Kavazanjian, E, and He, X. (2016). "Hydrogel-assisted Enzyme Induced Carbonate Mineral Precipitation." *J. of Materials in Civ. Eng*. DOI: 10.1061/(ASCE) MT.1943-5533.0001604

**Hamdan, N.** and Kavazanjian, E. (2015). "Enzyme Induced Carbonate Mineral Precipitation for Surficial Soil Stabilization." *Geotechnique.* DOI: http://dx.doi.org/10.1680/jgeot.15.P.168

**Hamdan, N.**, Kavazanjian, E. Jr. and O'Donnell, S.T. (2013). "Carbonate Cementation via Plant Derived Urease." *Proc. of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris, France, 2-6 September.*

***Five additional significant products –***

Yang, P., O'Donnell, S., **Hamdan, N.,** Kavazanjian, E., and Neithalath, N. (2016). "3D DEM Simulations of Drained Triaxial Compression of Sand Strengthened using Microbially Induced Carbonate Precipitation." *International Journal of Geomechanics.*

Zhao, Z., **Hamdan, N.,** Shen, Li., Hanqing, N., Abdullah, A., Kavazanjian, E., and He, X. (2016, *in-review*). "Biomimetic hydrogel composites for soil stabilization and contaminant mitigation." *Environmental Science & Technology.*

Kavazanjian, E., O'Donnell, S.T, and **Hamdan, N**. (2015). "Biogeotechnical Mitigation of Earthquake-Induced Soil Liquefaction by Denitrification: A Two-Stage Process." *The 6$^{th}$ International Conference on Earthquake Geotechnical Engineering*, Christchurch, New Zealand, November 1-4, 2015.

DeJong, J.T., Soga, K.S., Kavazanjian, E., Burns, **et al.** (2013). "Biogeochemical Processes and Geotechnical Applications: Progress, Opportunities, and Challenges." *Geotechnique*, 63(4), 287-301.

**Hamdan, N.**, Kavazanjian, E. and Rittmann, B.E. (2011). **"**Sequestration of Radionuclides and Metal Contaminants through Microbially-Induced Carbonate Precipitation." *Proc. 14th Pan American Conf. Soil Mech. Geotech. Engng, Toronto.*

**<u>Synergistic Activities:</u>**

(1) Mentor for graduate student in biogeotechnical engineering at Arizona State University. Currently provide research guidance for work on enzyme and microbially induced carbonate precipitation, the use of biomaterials in geotechnics, and other bio-mediated and bio-inspired processes.
(2) Reviewer for the development of engineering education based on research at the Center for Bio-mediated & Bio-inspired Geotechnics (CBBG). Includes CBBG curriculum, free-standing course module/instructional CD and classroom demonstrations.
(3) Coordinator for CBBG-related research presentations and seminars by outside faculty; for example, organized presentation by Professor Jian Chu from Nanyang Technological University, South Korea.
(4) Presenter at CBBG career development seminar for students and CBBG summer research program participants.
(5) CBBG Representative in public outreach events and education programs geared towards diversity, awareness and inclusion. For example, represented the CBBG and attended lectures at the Annual American Indian/Indigenous Teacher Education Conference in Flagstaff, AZ.
(6) Coordinator for industry education seminars and industry engagement at the CBBG. Organized seminars given by several industries including mining, engineering consulting and public agencies.

## Ximin He

**Professional Preparation:**

Shanghai Jiaotong University Shanghai, China Chemistry, Chemical Engineering B.S., 2003
Tsinghua University Beijing, China Chemistry M.S., 2006
University of Cambridge Cambridge, UK Chemistry Ph.D., 2011

**Appointments:**

2017 – present Assistant Professor
Materials Science and Engineering
University of California, Los Angeles

2014 – 2016 Assistant Professor
Materials Science and Engineering
School of Engineering for Matter, Transport and Energy
The Biodesign Institute, Dept. of Chemistry & Biochemistry
Arizona State University

2010 – 2013 Postdoctoral Fellow, Harvard University
School of Engineering and Applied Science
Wyss Institute of Biologically Inspired Engineering

2006 – 2010 Graduate Research and Teaching Asst., University of Cambridge
Department of Chemistry
Department of Physics, Cavendish Laboratory
Nanoscience Center

**Products:**

- N. Hamdan, Z. Zhao, E. Kavazanjian, Jr., X. He, Hydrogel-assisted Enzyme Induced Carbonate Mineral Precipitation**, *J. Mater. Civ. Eng.*** 2016, DOI: 10.1061/(ASCE)MT.1943-5533.0001604
- Z. Zhao, N. Hamdan, E. Kavazanjian, Jr., X. He, Bio-inspired soil stabilization by synthetic hydrogel and EICP, ***ACS Environmental Science and Technology***, 2016, 50, 12401–12410.
- Z. Zhao, H. Han, M. Sun, X. He*, Simultaneous Topographic and Chemical Patterning via Imprinting Defined Nano-reactors, ***RSC Advances***, 2016, *6*, 96538.
- Z. Zhao, N. Wang, H. Nan, L. Shen, C. Durkan, X. He, A novel paradigm for fabricating highly uniform nanowire arrays using residual stress-induced patterning, ***J. Mater. Chem. C**,* 2016, 2016, 4, 5814.
- Shastri, L. McGregor, Y. Liu, V. Harris, H. Nan, M. Mujica, Y. Vasquez, A. Bhattacharya, Y. Ma, M. Aizenberg, O. Kuksenok, A. Balazs, J. Aizenberg, X. He, Chemo-mechanically Modulated Biomolecule "Catch and Release" with Aptamer-functionalized Reconfigurable Systems, ***Nature Chemistry,*** 2015, *7*, 447.
- X. He, M. Aizenberg, O. Kuksenok, L. Zarzar, A. Shastri, A. Balazs, J. Aizenberg, Synthetic Homeostatic Materials displaying Chemo-mechano-chemical Self-regulation, ***Nature*** 2012, *487*, 214.
- X. He, R. Friedlander, L. Zarzar, J. Aizenberg**,** Chemo-Mechanically Regulated Oscillation of an Enzymatic Reaction, ***Chem. Mater.*** 2013, *25*, 521.
- X. He, F. Gao, G. Tu, D. Hasko, S. Hüttner, U. Steiner, N. C. Greenham, R. Friend, W. Huck, Formation of nanostructured polymer blends in photovoltaic devices, ***Nano Lett.*** 2010, *10*,

1302.

- <u>X. He</u>*, J. Slota*, W. Huck, Controlling nanoscale morphology in polymer optoelectronic devices, ***Nano Today**,* 2010, *5*, 231. (*equal contribution)
- <u>X. He</u>, F. Gao, G. Tu, D. Hasko, S. Hüntner, U. Steiner, N. C. Greenham, R. Friend, W. Huck, Formation of well-ordered heterojunction in polymer photovoltaic devices, ***Adv. Funct. Mater.*** 2011, *21,* 139.
- <u>X. He</u>, C. Li, F. Chen, G. Shi, Polypyrrole microtubule actuators for seizing and transferring microparticles, ***Adv. Funct. Mater.*** 2007, *17*, 291.
- L. Zarzar, Q. Liu, <u>X. He</u>, Y. Hu, Z. Suo, J. Aizenberg, Multifunctional Actuation Systems Responding to Chemical Gradients, ***Soft Matter*** 2012, *8*, 8289.
- Y. Liu, A. Bhattacharya, O. Kuksenok, <u>X. He</u>, M. Aizenberg, J. Aizenberg, A. C. Balazs, Utilizing oscillating fins to "catch and release" targeted nanoparticles in bilayer flows, ***Soft Matter*** 2016, *12*, 1374. (Front cover)
- <u>X. He</u>, J. Winkel, W. Huck, Nanopatterning via pressure induced instabilities in thin polymer films, ***Adv. Mater.*** 2009, *21*, 1.

**<u>Synergistic Activities:</u>**

**(1) Awards and Recognitions:**

- Air Force Young Investigators Research Program (YIP) Award (2016-2019)
- NSF CAREER Award (2016-2021)
- Medtronic Best Presentation Award of the Material Research Society MRS 2016 Spring meeting
- The Best Poster Award of the Material Research Society MRS 2011 Fall meeting
- Government Award for Outstanding Students in UK (2010, nationwide)
- UK Excellent Young Scientist by the W. Wing Yip & Brothers Bursaries (2009, 22 awarded national wide)
- UK Overseas Research Scholarship (2006-2010)
- Gates Cambridge Trust Scholarship (2006-2010, ~20/yr selected worldwide)
- Board Editor for *Annals of Materials Science & Engineering* (a peer-reviewed journal)
- Lead Organizer of Symposium *Bioinspired Dynamic Materials* on the MRS 2016 Spring Meeting
- Board Editor for *International Journal of Polymer Science* (a peer-reviewed journal)
- Member, AIChE (2014-present), Materials Research Society (MRS, 2006-present), and Am. Chem. Soc. (ACS, 2006-present)
- Associate Member of Royal Society of Chemistry (AMRSC, 2006-2012)
- Faculty Member of ASU Women in Science and Engineering (2014-present)

**(2) Patents**

- Materials for Autonomous Tracking, Guiding, Modulating and Harvesting of Energetic Emissions, ***U.S. Patent.*** X. He, X. Qian (filed 04/2017, App 62/484,269)
- Hydrogels Biocement Systems and Method, ***U.S. Patent***, X. He, Z. Zhao, N. Hamdan, E. Kavazanjian (filed 12/2015)
- Self-sustained thermal-regulating homeostatic systems, ***U.S. Patent***, X. He, M. Aizenberg, J. Aizenberg (filed 10/2011, App 61/555965)
- Reconfigurable Structured Surfaces for Enhanced Security Features, ***U.S. Patent***, X. He, T-S Wong, S-H Kang, J. Aizenberg (filed 07/2011)
- Method of forming relief structures, ***U.S., U.K. & European Patent***, X. He, Winkel, W. Huck (filed 12/2008, GB0821790, US Pat. App 12/621,208)

**David L. Hu**

**Professional Preparation:**

Massachusetts Institute of Technology; Boston, MA. B.S.., Mechanical Engineering, 2001
Massachusetts Institute of Technology; Boston, MA. Ph.D.., Mechanical Engineering, 2006
Courant Institute of Mathematical Sciences, New York, NY. Postdoc, Mathematics. 2006-2008

**Appointments:**

| | | |
|---|---|---|
| Associate Professor (3/4 appointment) | Georgia Institute of Technology School of Biology | 9/14-present |
| Associate Professor (1/4 appointment) | Georgia Institute of Technology School of Mechanical Engineering | 9/14-present |
| Adjunct Assistant Professor | Georgia Institute of Technology School of Physics | 12/12 - present |
| Assistant Professor (3/4 appointment) | Georgia Institute of Technology School of Mechanical Engineering | 8/08-present |
| Assistant Professor (1/4 appointment) | Georgia Institute of Technology School of Biology | 8/08-present |

**Publications:**

**i. Publications most closely related to project**

1. Tennenbaum, M., Liu, Z., Hu, D.L. Fernandez-Nieves, A. (2016) Mechanics of fire ant aggregations. *Nature Materials.* **15**, 54–59 doi:10.1038/nmat4450
2. Yang, P.J., Pham, J., Choo, J., Hu, D.L. (2014) Duration of urination does not change with body size. *Proceedings of the National Academy of Sciences, USA.* **111**(33):11932-11937.

Dickerson, A., Shankles, P., Madhaven, N., Hu, D. L. (2012) Mosquitoes survive raindrop collisions by virtue of their low mass. *Proceedings of the National Academy of Sciences, USA.* **109** (25) 9822-9827.

3. Mlot, N., Tovey, C. & Hu, D.L. (2011) Fire ants self-assemble into waterproof rafts to survive floods. *Proceedings of the National Academy of Sciences, USA.* **108**: 7669-7673.
4. Hu., D. L., Nirody, J., Scott, T. & Shelley, M. J. (2009) The mechanics of slithering locomotion. *Proceedings of the National Academy of Sciences, USA.* **106**, 10081–10085.

**ii. Other publications**

5. Phonekeo, S., Dave, T., Kern, M., Franklin, S.V. and Hu, D.L. (2016). Ant aggregations self-heal to compensate for Ringlemann Effect. *Soft Matter*.
6. Amador, G., Mao, W., DeMercurio, P., Montero, C., Clewis, J., Alexeev, A., Hu, D.L. (2015) Eyelashes divert airflow to protect the eye. *Journal of the Royal Society Interface.* 20141294.
7. Hu, D. L. & Bush, J. W. M. (2005) Meniscus-climbing insects. *Nature* **437**, 733–736.
8. Hu, D. L., Chan, B. & Bush, J. W. M. (2003) The hydrodynamics of water strider locomotion. *Nature* **424**, 663–666

Dickerson, A., Mills, Z. & Hu, D. L. (2012) Wet mammals shake at tuned frequencies to dry. In press at *Proceedings of the Royal Society: Interface.*

**<u>Synergistic activities:</u>**

**1. Developed course: Biomechanics Project Laboratory** 2010-present

I am teaching a new biomechanics laboratory class for 18 biology undergraduates. In 2010, students investigate structures built by ants (rafts, walls, bridges) and use structural integrity as a measure of cooperation.

**2. Media coverage** 2003-present

Our work on animal locomotion has highlighted in a number of films, television, radio segments, museum installations, newspaper and magazine articles, including *The Economist* (2003), *The New York Times* (2005,2009), *National Geographic* (2009,2011), *Smithsonian Magazine* (2009), *New Scientist* (2003,2009), *Washington Post* (2003, and front page in 2011), *Highlights for Children* and *Ciência Hoje das Crianças*, a Brazilian magazine for children (2011). We performed lab demonstrations for the television shows: *Discovery Channel*, NSF show *Science Nation*; *YouTube* video on the ant raft has received over one million viewers; *Good Morning America* 5-minute segment on The Wet Dog Shake (2011); *National Public Radio* Science Friday (2010,2010,2011) most popular pick of the week; 6th Ed. *Fundamentals of Fluid Mechanics* with a cover photo and a homework problem dedicated to our water strider work

**3. Mini-Workshop on Complex Surface Structure and Locomotion**

Pohang University of Science and Technology, Pohang, Korea 2011 summer

I organized and taught a 6-hour workshop to 28 faculty and students. Topics covered included: walking on water, snake locomotion and cooperation of ants. Tools taught included: animal experiments (visualization, tracking kinematics), mathematical modeling (differential equations, mechanics), scaling arguments (limits in force, mass, size), biological diversity (mega-charts) and simple robots (satisfying physical constraints).

**4. Undergraduate and high school research recruitment**

Georgia Tech, NYU, MIT 2003-present

I have supervised over twenty undergraduate and high school students (2-3 per year), with more than half of them from underrepresented groups.

**5. Georgia Intern Fellowships for Teachers** 2010 summer

Our lab hosted a tenth-grade high school teacher for a summer and co-developed a learning module entitled “Snakes on a plane.”

**Edward Kavazanjian, Jr.**

**Professional Preparation:**

| | | |
|---|---|---|
| Massachusetts Institute of Technology Cambridge, MA | Civil Engineering | SB 1973 |
| Massachusetts Institute of Technology Cambridge, MA | Geotechnical Engineering | SM 1975 |
| University of California, Berkeley Berkeley, CA | Geotechnical Engineering | PhD 1978 |

**Appointments:**

| | |
|---|---|
| 2015-present | Director, Center for Bio-mediated and Bio-inspired Geotechnics |
| 2010-present | Professor; Civil and Environmental Engineering, Arizona State University |
| 2004-2010 | Associate Professor; Civil and Environmental Engineering, Arizona State University |
| 2003-2004 | Research Professor; Civil Engineering, U. of Southern California |
| 1996-2002 | Principal; GeoSyntec Consultants, Huntington Beach, CA |
| 1992-1996 | Associate; GeoSyntec Consultants, Huntington Beach, CA |
| 1990-1992 | Executive Vice President; MAA Engineering Consultants Inc., Los Angeles, CA |
| 1988-1990 | Associate; The Earth Technology Corporation, Long Beach, CA |
| 1987-1988 | Supervising Engineer; Parsons Brinckerhoff, New York, NY |
| 1985-1986 | Lead Engineer; Parsons Brinckerhoff, New York, NY |
| 1978-1985 | Assistant Professor, Civil Engineering, Stanford University |

**Products:**

Five products most closely related to the project

1. O'Donnell, S. T., Kavazanjian, E., Jr. (2017), and Rittmann, B.E. (2017) "Liquefaction Mitigation via Microbial Denitrification as a Two-Stage Process, Stage I: Desaturation," acccepted for publication, Journal of Geotechnical and Geoenvironmental Engineering, ASCE
2. O'Donnell, S. T., Kavazanjian, E., Jr. (2017), and Rittmann, B.E. (2017) "Liquefaction Mitigation via Microbial Denitrification as a Two-Stage Process, Stage II: MICP," accepted for publication, Journal of Geotechnical and Geoenvironmental Engineering, ASCE
3. Zhao, Z., Hamdan, N., Shen, L., Nan, H., Almajed, A., Kavazanjian, E., Jr., and He, X. (2016) "Biomimetic Hydrogel Composites for Soil Stabilization and Contaminant Mitigation," Environmental Science and Technology, No. 50, pp. 12401-12410, DOI: 10.1021/acs.est.6b01285
4. Yang, P., O'Donnell, S.T., Hamdan, N., Kavazanjian, E., Jr., and Neithalath, N. (2016) "3D DEM Simulations of Drained Triaxial Compression of Sand Strengthened using Microbially Induced Carbonate Precipitation," International Journal of Geomechanics, ASCE, DOI: 10.1061/(ASCE)GM.1943-5622.0000848
5. Hamdan, N. and Kavazanjian, E., Jr. (2016) ""Enzyme Induced Carbonate Mineral Precipitation for Fugitive Dust Control," Geotechnique, V. 66, No. 7, pp. 546-555, DOI: http://dx.doi.org/10.1680/jgeot.15.P.168

Five other significant products

6. Khodadadi, T.H.+, Kavazanjian, E., Jr., van Paassen, L. T., and DeJong, J.T. (2017) "Bio-grout Materials: A Review," Proceedings of Grouting 2017, ASCE, doi.10.1061/9780784480793.001
7. Kavazanjian, E., Jr., Almajed, A. and Hamdan, N. (2017) "Bio-Inspired Soil Improvement using EICP Soil Columns and Soil Nails," Proceedings of Grouting 2017, ASCE, doi.10.1061/9780784480793.002
8. Dalal, M., Larson, J., Zapata, C., Savenye, W., Hamdan, N., and Kavazanjian, E., Jr. (2017) "An Interdisciplinary Approach to Developing an Undergraduate Module on Biogeotechnical Engineering," Proceedings, Society for Information Technology & Teacher Education International Conference, Association for the Advancement of Computing in Education (AACE), pp. 2074-2079
9. Hamdan, N., Zhao, Z.., Mujica, M., Kavazanjian, E., Jr., and He, X. (2016) "Hydrogel-assisted Enzyme Induced Carbonate Mineral Precipitation," Journal of Materials in Civil Engineering, ASCE, DOI: 10.1061/(ASCE)MT.1943-5533.0001604
10. O'Donnell, S.T. and Kavazanjian, E., Jr. (2015) "Stiffness and Dilatancy Improvements in Uncemented Sands Treated through MICP," ASCE Journal of the Geotechnical and Geoenvironmental Engineering Division, Vol. 141, No. 11, November, p. 1943; doi 10.1061/(ASCE)GT.1943-5606.0001407, 02815004

**Synergistic Activities:**

- *Geomicrobiological and Bio-Inspired Ground Improvement Techniques for Seismic Hazard Mitigation*, Keynote Address, 2nd International Association of Chinese Geotechnical Engineers International Conference on Geotechnical and Earthquake Engineering, Chengdu, China, 25-27 May 2017
- Application of Enzyme Induced Calcium Carbonate Precipitation for Erosion Control," presentation at the 42nd Southwest Geotechnical Engineering Conference, FHWA, 2 May 2017
- *Carbonate Precipitation for Ground Improvement, and Other Biogeotechnologies*, presentation at the S&ME 16th Annual Technical Conference, Concord, NC, January 2017
- *Opportunities and Challenges for Improvement of Granular Soils by Carbonate Precipitation*, Workshop on Bio-mediated and Bio-inspired Soil Modification and Its Applications, 96$^{th}$ Annual Meeting of the Transportation Research Board, Washington, DC, January 2017
- *Process Monitoring of Carbonate Precipitation using S-wave and P-wave Measurements,* presentation at Session 643: Monitoring of Unsaturated Geomaterials, 96th Annual Meeting of the Transportation Research Board, Washington, DC, 10 January 2017
- *Geo-Alchemy: Biogeotechnical Carbonate Precipitation for Hazard Mitigation and Ground Improvement*, 24$^{th}$ Spencer Buchanan Lecture, Texas A&M University, College Station, TX, 14 October 2016
- *Biogeotechnics: Progress, Opportunities, and Challenges* (with Jason DeJong), NSF Workshop on Geotechnical Fundamentals in the Face of New World Challenges, Arlington, VA, 18 July 2016
- *Biogeotechnical Solutions for Deep Foundations*, 41st Annual Meeting of the Deep Foundations Institute, Oakland, CA, 14 October 2015

**Alissa Kendall**

**Professional Preparation:**

| | | | |
|---|---|---|---|
| Duke University | Durham, North Carolina | Environmental Engineering | B.S., 2000 |
| University of Michigan | Ann Arbor, Michigan | Natural Resource Policy | M.S., 2004 |
| University of Michigan | Ann Arbor, Michigan | Natural Resource Policy and Environmental Engineering | Ph.D., 2007 |

**Appointments:**

| | |
|---|---|
| 2013-Present | Associate Professor, Department of Civil and Environmental Engineering, University of California, Davis, CA |
| 2007-2013 | Assistant Professor, Department of Civil and Environmental Engineering, University of California, Davis, CA |
| 2002-2007 | Graduate Student Researcher, Center for Sustainable Systems, University of Michigan, Ann Arbor, MI |
| 2000-2002 | Product Development Engineer, Ford Motor Co., Dearborn, MI |

**Products:**

***Five most closely related to the proposed project –***

Kendall A., Raymond A.J., Tipton J., DeJong J.T. (2017) Review of Life-Cycle-Based Environmental Assessments of Geotechnical Systems Proceedings of the Institution of Civil Engineering – Engineering Sustainability. doi:10.1680/jensu.16.00073

Wang, T., Lee, I-S., Kendall, A., Harvey, J., Lee, E. B., Kim, C. (2012) "Life Cycle Energy Consumption and GHG Emission from Pavement Rehabilitation with Different Rolling Resistance" Journal of Cleaner Production 33: 86-96. DOI:10.1016/j.jclepro.2012.05.001

Chang, B., Kendall, A. (2011) "Life Cycle Greenhouse Gas Assessment of Infrastructure Construction for California's High Speed Rail System" Transportation Research Part D 16(6): 429-434. DOI:10.1016.j.trd.2011.04.004

Kendall, A., Lepech, M.D., Keoleian, G.A. (2008) "Materials Design for Sustainability through Life Cycle Modeling of Engineered Cementitious Composites" Materials and Structures. 41: 1117-113. DOI:10.1617/s11527-007-9310-5

Kendall, A., Keoleian, G. A., Helfand, G. (2008) "An Integrated Life Cycle Assessment and Life Cycle Cost Analysis Model for Concrete Bridge Deck Applications" Journal of Infrastructure Systems. 14(3): 214-222. DOI: 10.1061/(ASCE)1076-0342(2008)14:3(214)

***Five additional significant products –***

Winans K., Kendall A., Deng H. (2017) The History and Current Applications of the Circular Economy Concept Renewable and Sustainable Energy Reviews 68(1): 825-833. doi:10.1016/j.rser.2016.09.123

Ambrose H., Kendall A. (2016) Effects of battery chemistry and performance on the life cycle greenhouse gas intensity of electric mobility, Transportation Research Part D. 47: 182-194. DOI:10.1016/j.trd.2016.05.009

Kendall, A. (2012) "Time-Adjusted Global Warming Potentials for LCA and Carbon Footprints" International Journal of Life Cycle Assessment 17(3): 1042-1049. DOI:10.1007/s11367-012-0436-5

Kendall, A., Price, L. (2012). "Incorporating Time-Corrected Life Cycle Greenhouse Gas Emissions in Vehicle Regulations" Environmental Science & Technology 46(5): 2557-2563. DOI:10.1021/es203098j

Kendall, A., Chang, B., Sharpe, B. (2009) "Accounting for Time-Dependent Effects in Biofuel Life Cycle Greenhouse Gas Emissions Calculations" Environmental Science & Technology 43(18): 7142–7147. DOI:10.1021/es900529u

**Synergistic Activities:**

(1) Selected for the National Academy of Engineering's *Frontiers in Engineering Education* (2012) for the creation of project-based learning course on green buildings that incorporated sustainability and place-based learning themes to better engage all students, but particularly women and underrepresented minorities (URMs)
(2) Created and ran seminar for URM and first generation college student sophomores in engineering to improve retention in the second year and provide a pipeline for research experiences in my lab (2014).
(3) Associate editor at *Resources Conservation and Recycling* 2015-Present.
(4) Reviewer for the *Intergovernmental Panel on Climate Change's Working Group III Contribution to the Fifth Assessment Report (AR5)*, 2013
(5) Chair of the UC Davis Energy Graduate Group (2016), and instructor of core course for the program Life Cycle Assessment for Sustainable Engineering (2008-present)

**Joel E. Kostka**

**<u>Professional Preparation:</u>**
Western Illinois University, Macomb, USA, Biology (High Honors), B.S., 1985
University of Charleston, South Carolina, USA, Marine Biology, M.S., 1988
University of Delaware, Newark, USA, Marine Science, Ph.D., 1993

**<u>Appointments:</u>**
*Professor*, Georgia Institute of Technology, 2011 - present
*Assistant, Associate, Full Professor*, Florida State University, 1999 - 2011
*Assistant Professor*, Skidaway Institute of Oceanography, 1996 - 1999
*Visiting Scientist*, Max Planck Inst. for Marine Microbiology, Bremen, Germany, 1995 - 1996
*NSF Postdoctoral Fellow in Marine Biotechnology*, University of Wisconsin, 1993 – 1995

**<u>Products:</u> (Selected from 99 peer-reviewed publications)**

1. Esson, K.C., X. Lin, D. Kumaresan, J. P. Chanton, J. C. Murrell, J. E. Kostka. 2016. Alpha and Gammaproteobacterial Methanotrophs Co-Dominate the Active Methane Oxidizing Communities in an Acidic Boreal Peat Bog. Applied and Environmental Microbiology 82:2363–2371. doi:10.1128/AEM.03640-15.
2. Cho, H., J.-H. Hyun, O. You, M. Kim, S-H. Kim, D-L. Choi, S. J. Green and J.E. Kostka. 2016. Microbial community structure associated with biogeochemical processes in the sulfate-methane transition zone (SMTZ) of gas hydrate-bearing sediment of the Ulleung Basin, East Sea, Geomicrobiology Journal, DOI:10.1080/01490451.2016.1159767.
3. Hemme, C.L., S. J. Green, L. Rishishwar, O. Prakash, A. Pettenato, R. Chakraborty, A. M. Deutchbauer, J. D. Van Nostrand, L. Wu, Z. He, I. K. Jordan, T. C. Hazen, A. P. Arkin, J. E. Kostka, and J. Zhou. 2016. Lateral Gene Transfer in a Heavy Metal-Contaminated Groundwater Microbial Community. mBio 7(2):e02234-15. doi:10.1128/mBio.02234-15.
4. Lin, X., K. M. Handley, J. A. Gilbert, J. E. Kostka. 2015. Metabolic potential of fatty acid oxidation and anaerobic respiration by abundant members of Thaumarchaeota and Thermoplasmata in deep anoxic peat. ISME Journal, doi: 10.1038/ismej.2015.77.
5. Rodriguez-R, L.M., W.A. Overholt, C. Hagan, M. Huettel, J E Kostka, and K.T.Konstantinidis. 2015. Microbial community successional patterns in beach sands impacted by the Deepwater Horizon oil spill. ISME Journal doi: 10.1038/ismej.2015.5
6. King, G.M., J.E. Kostka, T. Hazen, and P. Sobecky. 2015. Microbial Responses to the Deepwater Horizon Oil Spill: From Coastal Wetlands to the Deep Sea. Annual Review of Marine Science 7: 377-401.
7. Canion, W.A. Overholt, J. E. Kostka, M. Huettel, G. Lavik and Marcel M.M. Kuypers. 2014. Temperature response of denitrification and anaerobic ammonium oxidation rates and microbial community structure in Arctic fjord sediments. Environmental Microbiology 16: 3331-3344.
8. Kostka, J.E., A.P.Teske, S. B. Joye and Ian M. Head. 2014. The metabolic pathways and environmental controls of hydrocarbon biodegradation in marine ecosystems. Frontiers in Microbiology 5: 471. doi: 10.3389/fmicb.2014.00471
9. P. Jasrotia, S. J. Green, A. Canion, W. A. Overholt, O. Prakash, D. Wafula, D. Hubbard, D. B. Watson, C. W. Schadt, S. C. Brooks and J. E. Kostka. 2014. Watershed scale fungal community characterization along a pH gradient in a subsurface environment co-contaminated with uranium and nitrate. Applied and Environmental Microbiology 80: 1810-1820.

10. Kostka, J.E., O. Prakash, W. A. Overholt, S. Green, G. Freyer, A. Canion, J. Delgardio, N. Norton, T. C. Hazen, and M. Huettel. 2011. Hydrocarbon-degrading bacteria and the bacterial community response in Gulf of Mexico beach sands impacted by the Deepwater Horizon oil spill. Applied and Environmental Microbiology 77: 7962-7974.

**Synergistic Activities:**

- College of Sciences Mentor Award, Georgia Tech (2014)
- Georgia Power Professor of Excellence (2013)
- Chair for Division N, Microbial Ecology, American Society of Microbiology(2009-2013)
- Editor, Applied and Environmental Microbiology (2011-2016); Editorial Board Member for Applied and Environmental Microbiology (2001-2011)
- Panel member: U.S. Dept. of Energy Office of Science Graduate Student Research (SCGSR) Program (2015, 2016); U.S. National Science Foundation, Directorate for Biological Sciences, Div. of Integrated Organismal Systems (2015); AAAS/ King Abdulaziz City for Science and Technology (KACST; 2015, 2016), Gulf Research Program (2016); Environmental Pollution Program (2011); U.S. Environmental Protection Agency, Environmental Impact and Mitigation of Oil Spills Program (2011); U.S. Department of Energy, Genome Science Program (2010)

## Rosa Krajmalnik-Brown

**Professional Preparation:**

| | | | |
|---|---|---|---|
| UAMI, Mexico City, Mexico | Industrial Biochemical Engineering | B.S. | 1996 |
| Georgia Institute of Technology, Atlanta, Georgia | Environmental Engineering | M.S. | 2000 |
| Georgia Institute of Technology, Atlanta, Georgia | Environmental Engineering | Ph.D. | 2005 |

**Appointments:**

| | |
|---|---|
| 2013-present | Associate Professor, Civil Environmental and Sustainable Engineering, Biodesign Swette Ctr. for Environmental Biotechnology, ASU, Tempe, AZ |
| 2007-2013 | Assistant Professor, Civil Environmental and Sustainable Engineering, Center for Environmental Biotechnology, Biodesign Institute, ASU |
| 2005–2007 | Postdoctoral Scholar, Ctr. for Environmental Biotechnology, Biodesign Institute, ASU |
| 2004-2005 | Teaching Assistant, Georgia Institute of technology |
| 1997-2004 | Graduate Research Assistant, Georgia Institute of technology |
| 1996-1997 | Process Engineer, IBtech, Inc., Mexico City, Mexico |

**Products:** Selected Publications (out of >75)

Five Products Most Closely Related to the Project

1. Sofia Esquivel-Elizondo, Anca G. Delgado, and **Rosa Krajmalnik-Brown***. 2017 "Evolution of microbial communities growing with carbon monoxide, hydrogen and carbon dioxide". FEMS Microbiology Ecology, 93 (6). doi: 10.1093/femsec/fix076
2. Anca G. Delgado, Devyn-Fajardo-Williams, Kylie L. Kegerreis, Prathap Parameswaran, Rosa Krajmalnik-Brown, 2016 "Impact of high ammonia on microbial populations within trichloroethene reductively-dechlorinating communities", mSphere
3. A.G. Delgado, D. Fajardo-Williams, S.C. Popat, C.I. Torres, **R. Krajmalnik-Brown**. Production of *Dehalococcoides* in a continuous flow stirred-tank reactor coupling high-cell densities to fast rates of trichloroethene dechlorination. *Applied Microbiology and Biotechnology*, 98, 6: 2729-2737 (2014). DOI 10.1007/s00253-013-5263-5
4. A. Ontiveros-Valencia Y. Tang Y., **R. Krajmalnik-Brown**, B.E. Rittmann. Managing the interactions between sulfate- and perchlorate-reducing bacteria when treating highly perchlorate-contaminated groundwater with hydrogen-fed biofilms. *Water Research*. 55: 215-224 (2014).
5. A.G. Delgado, P. Parameswaran, D. Fajardo-Williams R. Halden, **R. Krajmalnik-Brown.** Role of bicarbonate as a pH buffer and electron sink in microbial dechlorination of chloroethenes. *Microbial Cell Factories*, 13;11(1):128 (2012).

Five Other Significant Products

1. Aura Ontiveros-Valencia, Ryan Penton, Rosa Krajmalnik-Brown, Bruce E. Rittman. 2016 "Hydrogen-fed biofilm reactors reducing selenate and sulfate: community structure and location of elemental selenium within the biofilm" Biotechnology and Bioengineering. *In press*
2. H.P. Zhao, Z.E. Ilhan, A. Ontiveros-Valencia, Y. Tang B. Rittmann, **R. Krajmalnik-Brown**. Effects of multiple electron acceptors on microbial interactions in a hydrogen-based biofilm. *Environmental Science and Technology* 47(13), 7396–7403 (2013)
3. A. Ontiveros-Valencia, Z. E. Ilhan, D.-W. Kang, B. Rittmann, **R. Krajmalnik-Brown.** Phylogenetic analysis of nitrate and sulfate reducing bacteria in a hydrogen-fed membrane biofilm reactor**.** *FEMS Microbiology Ecology*. 85(1):158-167 (2013).
4. E. I. Garcia-Pena, P. Parameswaran, D. W. Kang, M. Canul-Chan, **R. Krajmalnik-Brown**. Anaerobic digestion and co-digestion process of vegetable and fruit residues": Process and microbial ecology**.** *Bioresource Technology* 102:9447–9455 (2011).
5. H.Zhang, J.E. Banaszak, P. Parameswaran, J. Alder, **R. Krajmalnik-Brown,** B. E. Rittmann. Focused-Pulsed sludge pre-treatment increases the bacterial diversity and relative abundance of acetoclastic methanogens in a full-scale anaerobic digester. *Water Research* 43: 4517–4526 (2009).

**Synergistic Activities:**

1. Thrust Leader Environmental Protection and Restoration Thrust, CBBG (Center for Bio-mediated and Bio-inspired Geotechnics)
2. Several on-going projects to analyze the microbial ecology in systems dedicated to reduction of chlorinated solvents and conversion to H2, CH4, or electricity.
3. Teaching courses in environmental engineering and microbiology.
4. Reviewer for: 1) *Environmental Science & Technology*, 2) *Ground Water Monitoring & Remediation*, and 3) *Biotechnology and Bioengineering*
5. Associate Editor for the journal *mSphere and* PLOSone
6. Funder and advisor of AGCE (Association of Graduate Civil Engineers), a civil engineering graduate student organization

## Jean S. Larson

**Professional Preparation:**

| | | | |
|---|---|---|---|
| University of Redlands | Redlands, CA | Education | B.A., 1993 |
| Northern Arizona University | Flagstaff, AZ | Elementary Education | M.Ed., 1999 |
| Arizona State University | Tempe, AZ | Educational | Ph.D., 2014 |

**Appointments:**

| | |
|---|---|
| 2015 – present | Education Coordinator, *Center for Bio-mediated and Bio-inspired Geotechnics* |
| 2014 – 2015 | Faculty Associate, *Arizona State University* |
| 2014 – 2015 | Senior Instructional Designer, *Stratus Learning Group* |
| 2011 – 2012 | Instructional Designer, *Arizona Public Service* |
| 2011 – 2012 | Instructional Designer, *Aspen Research* |
| 2008 – 2010 | Consultant, *Adaptive Curriculum* |
| 2006 – present | Math Tutor, *Private* |
| 2006 – 2007 | Instructional Designer, *TBD Consulting* |
| 2005 – 2006 | Teaching Assistant/Research Assistant, *Arizona State University* |
| 2000 – 2004 | Project Coordinator, *Aspen Research* |
| 2001 – 2003 | Program Coordinator, *PT3, Arizona State University* |
| 2001 – 2002 | Teacher Consultant, *Best Practices (AZTEC, PT3, Arizona K-12 Center)* |
| 1997 Summer | Teacher, *Blagardeskolen (Denmark)* |
| 1998 Summer | Teacher, *Tado Ivanausko Mokykla* (Lithuania) |
| 1996 – 2001 | Teacher, *Madison Meadows Middle School* |
| 1995 – 1996 | Teacher, *Harpenden Preparatory School (England)* |
| 1994 – 1995 | Math Tutor, *Crafton Hills College* |
| 1994 – 1995 | Substitute Teacher, *Orange Unified School District* |

**Products:**

Larson, J., Dalal, M., Savenye, W., Zapata, C., Hamdan, N., & Kavazanjian, E. (2017). *Implementation of an Introductory Module on Biogeotechnics in a Freshman Engineering Course.* Proceedings of the ASEE Annual Conference & Exposition, Columbus, OH, June 25 -28, 2017.

Dalal, M., Larson, J., Savenye, W., Zapata, C. Hamdan, N., & Kavazanjian, E. (2017). *Supporting Engineering Education with Instructional Design: The Case of an Introductory Module on Biogeotechnical Engineering.* Proceedings of the ASEE-PSW Annual Conference, Tempe, AZ, April 20-22, 2017.

Dalal, M., Larson, J., Zapata, C., Savenye, W., Hamdan, N. & Kavazanjian, E. (2017). An Interdisciplinary Approach to Developing an Undergraduate Module on Biogeotechnical Engineering. In *Proceedings of Society for Information Technology & Teacher Education International Conference 2017* (pp. 2074-2079). Chesapeake, VA: Association for the Advancement of Computing in Education (AACE).

Elwood, K., Savenye, W., Larson, J., Jordan, M. E., & Zapata, C. (2017, November). Wicked instructional problems: Exploring how STEM teachers use design thinking. Paper session accepted for presentation at the meeting of the Association for Educational Communications & Technology, Jacksonville, FL.

Elwood, K., Savenye, W., Jordan, M. E., Larson, J., Zapata, C. (2016). Design thinking: A new construct for educators. Proceedings of the Association for Educational Communications & Technology, Las Vegas, NV, Vol. 1, 43-52.

Savenye, W., Larson, J., Zapata, C., Kavazanjian, E., Elwood, K., Reed, A., Mitchell, M., Brown, S., Bronner, C., Saenz, D., Newstetter, W., Benton-Johnson, F., Dalal, M., Gomez, M., & Delgado. (2016). The ultimate higher education start-up: Building education / outreach /

diversity for an NSF Engineering Research Center. Paper accepted for presentation at the annual meeting of the Associate for Educational Communications and Technology, to be held in Las Vegas, NV, October 17-21, 2016

Archambault, L. & Larson, J. (2015). Pioneering the digital age of instruction: Learning from and about K-12 online teachers. *Journal of Online Learning Research,* 1(1), 49-83. Association for the Advancement of Computing in Education (AACE).

Larson, J., & Archambault, L. (2015). The Ever-Evolving Educator: Examining K-12 Online Teachers in the United States. In T. Heafner, R. Hartshorne, & T. Petty (Eds.) *Exploring the Effectiveness of Online Education in K-12 Environments* (pp. 169-190). Hershey, PA: Information Science Reference. doi:10.4018/978-1-4666-6383-1.ch009

Larson, J. (2014, November). *Preparing Teachers for Success in K-12 Online and Blended Contexts: Research From the Field*. Presenter on expert panel session for the iNACOL Blended and Online Learning Symposium, Palm Springs, CA.

Larson, J. S. (2014). *Demographics and preparation levels of K-12 online teachers* (Order No. 3619287). Available from ProQuest Dissertations & Theses Global. (1536437169). Retrieved from http://login.ezproxy1.lib.asu.edu/login?url=http://search.proquest.com/docview/1536437169?accountid=4485

Sutton, J. (2004, June). LectureMaker: *Effective and efficient knowledge transfer via online multimedia delivery*. One-hour workshop for the International Literacy and Education Research Network Conference on Learning, Havana, Cuba.

Sutton, J. & Glazewski, K. (2004, March). *LectureMaker: Promoting efficient and effective online learning via video delivery*. Poster/Demo at the Annual Society for Information Technology and Teacher Education Conference (SITE), Atlanta, GA.

Glazewski, K., Sutton, J., Ozogul G., Igoe, A., & Rutowski, K. (2003, October). *The impact of integrated field- based technology courses on preservice teachers' beliefs, competence, and practice*. Paper presented at the Annual Association for Educational Communications and Technology (AECT), Anaheim, CA.

Brush, T., Glazewski, K., Rutowski, K., Berg, K., Stromfors, C., Van-Nest, M. H., Stock, L., Sutton, J. A. (2003). Integrating technology in a field-based teacher training program: The PT3@ASU Project. *Educational Technology Research and Development*, 51(1), 57-72.

Glazewski, K., Rutowski, K., Berg, K., Brush, T., Igoe, A., Krumwiede, L., Mansfield, J., Smith, P., Stromfors, C., Sutton, J. A. (2003, March). *The impact of integrated field-based technology courses on preservice teachers' beliefs, competence, and practice*. Paper presented at the Fourteenth Annual Society for Information Technology and Teacher Education Conference (SITE), Albuquerque, NM.

**Synergistic Activities:**

- Online continuing legal education courses for patent attorneys (Patent Resources Group)
- Web-based and Instructor-led training modules (Banner Health, Arizona Public Services, American Express, Clear Channel Outdoor, USA Gymnastics, Arizona State University)
- Procedure documentation and mapping (KBI Construction)
- Teacher guides and student activity sheets for interactive online math modules (Adaptive Curriculum)
- Technology-rich curricula, model lessons, and instructor guides for pre-service teachers (Arizona State University)

**Alejandro Martinez**

**Professional Preparation:**

| | | | |
|---|---|---|---|
| The University of Texas at Austin | Civil Engineering | B.S.C.E. | 2010 |
| Georgia Institute of Technology, Atlanta Georgia | Geotechnical Engineering | M.S.C.E. | 2012 |
| Georgia Institute of Technology, Atlanta Georgia | Geotechnical Engineering | Ph.D. | 2016 |

**Appointments:**

| | |
|---|---|
| 2016 – present | Assistant Professor of Civil Engineering, University of California at Davis |
| 2016 | Postdoctoral Fellow, Georgia Institute of Technology |

**Products:**

1. Martinez A., Frost, J.D., and Hebeler, G. L. (2015). "Experimental study of shear zones formed at sand/steel interfaces in axial and torsional axisymmetric tests." *ASTM Geotech. Test. J.*, 38(4), 409-426. DOI: 10.1520/GTJ20140266.
2. Martinez, A. and Frost, J.D. (2016). "Particle-scale effects on global axial and torsional interface shear behavior." *Int. J. Num. Anal. Geomech*. 41(3), 400-421. DOI: 0.1002/nag.2564.
3. Martinez, A., and Frost, J.D. (2017). "The influence of surface roughness form on the strength of sand-structure interfaces." *Geotechnique Letters*, 7(1), 104-111. DOI: http://dx.doi.org/10.1680/jgele.16.00169.
4. Frost, J.D., Jackson, K., Leonard, L, Martinez, A., Roozbahani, M., and Yamamoto, K. (2017). "Biologically-inspired insights into soil arching and tunnel stability from topology of ant nests." In press for *19th Int. Conf. Soil Mech. Geotech. Eng.*, Seoul, South Korea.
5. Frost, J.D., Martinez, A., Mallet, S., Roozbahani, M., and DeJong, J.T. (2017). "The intersections of modern soil mechanics with ants and roots." *ASCE Geotech. Frontiers 2017*, Orlando, FL, 900-909.
6. Frost, J.D., Hebeler, G.L., and Martinez, A. (2012). "Cyclic multi-piezo-friction sleeve penetrometer testing for liquefaction assessment." *Proc. 4th Int. Conf. Geotech. Geoph. Site Charact. (ISC'4)*, Pernambuco, Brazil, 629-636.
7. Hebeler, G.L., Martinez, A. and Frost, J.D. (2015). "Shear zone evolution of granular soils in contact with conventional and textured CPT sleeves." *KSCE Civ. Eng. J.*, 20(4), 1267-1282. DOI:10.1007/s12205-015-0767-6.
8. Martinez, A., Frost, J.D., and Su, J. (2015). "The importance of interfaces in geotechnical foundation systems." *Proc. ASCE IFCEE 2015 Conf.*, San Antonio, USA, 817-826.
9. Martinez, A. and Frost, J.D. (2016). "Numerical assessment of shear-induced particle interactions under different loading conditions by means of axial and torsional interface shear tests." *Proc. 6th Int. Symp. on Def. Charact. of Geom*., Buenos Aires, Argentina, 1129-1136.
10. Frost, J.D., Martinez, A., Su, J. and Xu, T. (2016). "Discrete element modeling of the interactions between soils and in-situ testing devices." *Proc. 5th Int. Conf. Geotech. Geoph. Site Charact. (ISC'5)*, Queensland, Australia.

**Synergistic Activities:**

1. *Service Activities in Geotechnical Engineering*. I serve in leadership roles for various scientific and engineering societies. I am an active member of the ASCE Geo-Institute

International Activities Council, corresponding member of the Young Member Presidential Group of the International Society of Soil Mechanics and Geotechnical Engineering, and member of the Geotechnical Extreme Events Reconnaissance (GEER) Association team funded by NSF that reported on the effects of the 2015 floods in South Carolina USA. Additionally, I serve as reviewer for several journals, including the Journal of Geotechnical and Geoenvironmental Engineering, Geotechnique Letters, International Journal of Analytical and Numerical Methods in Geomechanics, Engineering Geology, Ocean Engineering, and the Journal of Engineering Mechanics.

2. *Inclusion of Diversity in Biogeotechnical Engineering:* I serve as the faculty diversity lead for UC Davis as part of the Center for Biomediated and Bioinspired Geotechnics (CBBG) Engineering Research Center. My efforts in this role focus on increasing the participation as well as raising awareness of the importance of inclusion of underrepresented groups, such as women, persons with disabilities, Hispanics, and African Americans, in biogeotechnical engineering. This has been achieved through diversity-focused recruitment of students, as well as through open discussions among CBBG students, staff, and faculty, and seminars delivered by professionals in the field of inclusion in STEM higher education.
3. *Promotion of Inclusion and Diversity in Engineering Education.* As a Goizueta Fellow at Georgia Institute of Technology (Georgia Tech), I led and participated in activities that promoted higher education among the underrepresented Hispanic communities in Georgia. These efforts included delivering recruiting presentations at middle and elementary schools, leading campus tours to high and middle school students, and providing guidance and advice in the process of applications for admission and financial aid.
4. *Mentorship of Undergraduate Students in Engineering Projects.* I have mentored a total of eight undergraduate research assistants. I mentored three of these students through the NSF Research Experience of Undergraduates (REU) program as part of the CBBG, and I mentored the other five students as part of internal research programs. To date, the research of five of these students has been published in journal or conference papers, and three of these students are currently coursing graduate school.
5. *Innovation in Teaching.* I developed a series of demonstration activities and formative assessments for the "Introduction to Geotechnical Engineering" class at Georgia Tech. These demonstration activities served as visual aids for facilitation of student understanding of concepts such as effective stresses, elevation, pressure and total heads, seepage, liquefaction, and consolidation. The formative assessments were compiled in a portfolio that was made available to student-instructors for future use in this class.

## Martha Mitchell

**Professional Preparation:**

| | | | |
|---|---|---|---|
| University of Wisconsin-Madison | Madison, Wisconsin | Chemical Engineering | B.S. 1989 |
| University of Minnesota-Minneapolis | Minneapolis, Minnesota | Chemical Engineering | Ph.D. 1996 |

**Appointments:**

| | |
|---|---|
| 1996 – Present | Asst. Prof., Assoc. Prof and Professor, Chemical Engineering, New Mexico State University, Las Cruces, NM |
| 2012 – 2015 | Associate Dean for Research, College of Engineering, New Mexico State University, Las Cruces, NM |
| 2004 – 2012 | Academic Department Head, Chemical Engineering, New Mexico State University, Las Cruces, NM |

**Products:**

1. LY Flores, RL Navarro, HS Lee, DA Addae, R Gonzalez, LL Luna, RB Jacquez, S Cooper, and MC Mitchell. Academic Satisfaction Among Latino/a and White Men and Women Engineering Students. *Journal of Counseling Psychology*. doi: 10.1037/a0034577 (2014).
2. VKK Upadhyayula, S Deng, GB Smith, and MC Mitchell, Adsorption of Bacillus subtilis on Carbon Nanotube Aggregates, Activated Carbon and NanoCeram. *Water Research* 43:148-156 (2009).
3. VKK Upadhyayula, S Ghoshroy, VK Nair, GB Smith, MC Mitchell, and S Deng. Single–Walled Carbon Nanotubes as Fluorescence Biosensors for Pathogen Recognition in Water Systems *Res. Lett. Nanotechnology* 2008 Article ID 156358, 5 pages, doi:10.1155 (2008).
4. MC Mitchell, M Gallo, and TM Nenoff. Molecular Dynamics Simulations of Binary Mixtures of Methane and Hydrogen in Titanosilicates, *Journal of Chemical Physics* 121:1910-1916 (2004).
5. LJD Frink, and MC Mitchell. Studying ion permeation through ion channel proteins with density functional theories for inhomogeneous fluids. Biophysical Journal 82:340A (2002).
6. VKK Upadhyayula, S Deng, MC Mitchell, VK Nair, GB Smith, and S Ghoshroy. Adsorption kinetics of Escherichia coli and Staphylococcus aureus on single-walled carbon nanotube aggregates. *Water Science & Technology* 58(1): 179-184 (2008).
7. MC Mitchell, RW Rakoff, TO Jobe, DL Sanchez, and DB Wilson. Thermodynamic Analysis of Equations of State for the Monopropellant Hydrazine. *Journal of Thermophysics and Heat Transfer* 21: 243-247.
8. MC Mitchell, JD Autry, and TM Nenoff. Molecular Dynamics Simulations of Binary Mixtures of Methane and Hydrogen in Zeolite A and a Novel Zinc Phosphate. *Molecular Physics* 99:1831-1837 (2001).
9. MC Mitchell, AV McCormick, and HT Davis. Prediction of Adsorption of Xenon in Zeolite NaA with Molecular Density Functional Theory. *Zeitschrift für Physik B* 97: 353-360 (1995).
10. MC Mitchell, AV McCormick, and HT Davis. Predicting Adsorption in One-Dimensional Zeolite Pores with the Exact Theory of One-Dimensional Hard Rods. *Molecular Physics* 83:429-437 (1994).

**Synergistic Activities:**

1. Broader Impacts Summit. Participated in NSF-sponsored Broader Impacts Summit in 2014. Member of the planning committee for the Network for Broader Impacts Summit in 2015. Summit will included discussions of best practices on development and assessment of broader impacts activities for faculty and for program developers.
2. Workshop on Key Challenges in the Implementation of Convergence. Participant in the National Academies-sponsored workshop on implementation of convergence, 2013.Participated in discussion of the convergence of science, engineering and medicine in health research. Discussed the need for convergent teams: teams that come together from the different disciplines to shape the research questions. Discussed barriers to convergence research.
3. Principal Investigator for ADVANCE Partnerships for Adaptation, Implementation and Dissemination Award: Alliance for Faculty Diversity in STEM (PAID). Organized department head training, training for senior and junior faculty, diversity activities, and best practices dissemination at NMSU, New Mexico Tech, the University of New Mexico and Los Alamos National Laboratories (2010-2011).
4. NMSU one-on-one faculty mentor and chair of Advancing Leaders Program committee. Mentored mid-career faculty through the NMSU Advancing Leaders program. Mentored untenured female faculty in the NMSU College of Engineering through the NMSU-ADVANCE grant. Chairs committee that plans activities for leadership program called Advancing Leaders at NMSU.
5. Society of Women in Engineering advisor. Advisor (one of three) for the NMSU student section of the Society for Women in Engineering. Included organizing Women in Engineering conferences for undergraduate students, graduate students and female faculty in 2010 and 2011.

## Narayanan Neithalath

**Professional Preparation:**

| | | |
|---|---|---|
| University of Calicut, India | Civil Engineering | B.Tech (Hons.), 1996 |
| Indian Institute of Technology (IIT) Madras, India | Civil Engineering | M.S, 1999 |
| Purdue University, West Lafayette, IN | Civil Engineering | PhD, 2004 |

**Appointments:**

1. Professor, School of Sustainable Engineering and Built Environment, Arizona State University, Tempe, AZ (07/2016 onwards)
2. Associate Professor, School of Sustainable Engineering and Built Environment, Arizona State University, Tempe, AZ (04/2011-06/2016)
3. Associate Professor, Assistant Professor, Department of Civil and Environmental Engineering, Clarkson University, Potsdam, NY. (08/2005 – 04/2011)
4. Assistant Professor, College of Basic and Applied Sciences, Middle Tennessee State University, Murfreesboro, TN. (08/2004 – 08/2005)
5. Visiting Lecturer, Department of Civil Engineering, Purdue University, West Lafayette, IN. (05/2004-08/2004)
6. Group Leader, Concrete Admixtures, Specialty Products and Repairs Division, Cera-Chem Limited, Chennai, India. (05/2000 – 08/2001)
7. Technical Co-ordinator, Cements Division, Grasim Industries Limited, Chennai, India. (06/1999 – 04/2000)

**Products:**

**(i) Five Products Most Closely Related to This Proposal:**

1. Yang, P., Kavazanjian, E., and Neithalath, N., "Particle-scale mechanisms in undrained triaxial compression of bio-cemented sands examined using 3D DEM with flexible boundaries", under review with the International Journal of Geomechanics
2. Dakhane, A., Das, S., O'Donnell, S., Hansen, H., Hanoon, F., Rushton, A., Perla, C., and Neithalath, N., Crack Healing in Cementitious Mortars using Enzyme Induced Carbonate Precipitation (EICP): Quantification Based on Fracture Response, under review with ASCE Journal of Materials in Civil Engineering
3. Yang, P., Sant, G., and Neithalath, N., (2017). "A refined, self-consistent Poisson-Nernst-Planck (PNP) model for electrically induced transport of multiple ionic species through concrete", Cement and Concrete Composites, Vol. 82, pp. 80-94
4. Yang, P., O'Donnell, S., Hamdan, N., Kavazanjian, E., and Neithalath, N., (2016). "3D DEM simulations of triaxial compression in sands strengthened using microbial carbonate precipitation", International Journal of Geomechanics, ASCE, DOI: 10.1061/(ASCE)GM.1943-5622.0000848
5. Das, S., Maroli, A., Singh, S., Stannard, T., Xiao, S., Chawla, N., and Neithalath, N., (2016). "A microstructure-guided constitutive modeling approach for random heterogeneous materials: Application to structural binders", Computational Materials Science, Vol. 119, pp. 52-64.

**(ii) Five Other Significant Products:**

1. Arora, A., Sant, G., and Neithalath, N., (2017). "Numerical Simulations to Quantify the Influence of Phase Change Materials (PCMs) on the Early- and Later-Age Thermal Response of Concrete Pavements", Cement and Concrete Composites, 81, 11-24

2. Dakhane, A., Madavarapu, S., Marzke, R., and Neithalath, N., (2017). "Spectroscopic studies on the time and temperature dependence of alkali activation of slag", Applied Spectroscopy, DOI: 10.1177/0003702817704588, pp. 13
3. Egan, G., Kumar, A., Neithalath, N., and Sant, G., (2017). "Re-examining the influence of inclusion characteristics on the drying shrinkage of cementitious composites", Construction and Building Materials, 146, 713-722
4. Das, S., Kizilkanat, A., Chowdhury, S., Stone, D., and Neithalath, N., (2016). "Temperature-induced Phase and Microstructural Transformations in a Synthesized Iron Carbonate (Siderite) Complex", Materials and Design, Vol. 92, pp. 189-199
5. Arora, A., Sant, G., and Neithalath, N., (2016). "Ternary blends containing slag and interground/blended limestone: Hydration, strength, and pore structure", Construction and Building Materials, Vol. 102 Part I, 113-124

**Synergistic Activities:**

1. Section Editor – ASCE Journal of Materials in Civil Engineering (managing ~600 submissions a year); Member of the Editorial Board – Cement and Concrete Composites;
2. Reviewer for ACI Materials Journal, ACI Structural Journal, ASCE Journal of Materials in Civil Engineering, Cement and Concrete Research, Cement and Concrete Composites, Materials and Structures, Transport in Porous Media, and many other international journals, and several conference proceedings papers;
3. Member of American Concrete Institute (ACI) Committees 123, 232, 236, and 522; Chair of Committee 522; Chair of the Task group to bring out Version 2 of the ACI 522 document on Pervious Concrete (08/2005 – 04/2007); Chair of the Task Group on Properties and Performance of ACI 522; Member of ASTM C 09.49, and sub-committees on porosity and permeability testing;
4. Advises undergraduate student researchers and REU students on cement-based materials. So far, has advised 34 undergraduate researchers over the summers and during the semesters, including 15 female students. Several journal and conference publications have resulted from undergraduate-graduate collaborative work.

**Douglas C. Nelson**

**Professional Preparation:**

| | | | | |
|---|---|---|---|---|
| Harvey Mudd College | Claremont, CA | Chemistry/ Biology | B.S. | 1970 |
| University of Oregon | Eugene, OR | Biology/Microbiology | Ph.D. | 1979 |

**Appointments:**

| | |
|---|---|
| 1997-present | Professor of Microbiology, University of California, Davis |
| 1999-2003 & 2006 to 2011 | Chairperson, Department of Microbiology, University of California, Davis |
| 1985-1997 | Assistant and Associate Professor, University of California, Davis |
| 1984 | Postdoctoral Investigator, Aarhus University, Denmark (Marine Microbiology with B. B. Jorgensen) |
| 1981-1985 | Postdoctoral Investigator, Woods Hole Oceanographic Institution (Marine Microbiology with H. W. Jannasch) |
| 1980 | Visiting Assistant Professor, Oregon State University, OR |

**Products:**


*1.* Graddy, CMR, Gomez, MG, Kline, L, Morrill, S, DeJong, JT, and Nelson, DC (submitted) "Phylogenetic and Functional Diversity of Isolates from Large-scale Bio-stimulated Microbially Induced Calcite Precipitation" *Environmental Science & Technology*

2. Gomez, MG, Graddy, CRM, DeJong, JT, Nelson, DC, Tsesarsky, M (2017). "Stimulation of Native Microorganisms for Bio-cementation at Field Scale Treatment Depths." *Journal of Geotech. and Geoenviron. Eng.,* Submitted in Review.

3. Gomez, MG, Anderson, CM, DeJong, JT, Nelson, DC, Graddy, CMR, and Ginn, TR (2017). "Large-scale Comparison of Bioaugmentation and Biostimulation Approaches for Bio-cementation of Sands." *Journal of Geotech. and Geoenviron. Eng.* 143(5):

4. Proto, CJ., DeJong, JD, Nelson, DC, and Sturm, AP (2014) "Bio-Mediated Permeability Reduction of Saturated Sands" *ASCE J. Geotechnical and Geoenvironmental Engineering* 142(12):

5. DeJong, JT, KS Soga, E Kavazanjian, S Burns, L Van Paassen, A Al Qabany, A Aydilek, SS Bang, M Burbank, L Caslake, CY Chen, X Cheng, J Chu, S Ciurli, S Fauriel, AE Filet, N Hamdan, T Hata, Y Inagaki, S Jefferis, M Kuo, L Laloui, J Larrahondo, DAC Manning, B Martinez, BM Montoya, DC Nelson, A Palomino, P Renforth, JC Santamarina, EA Seagren, B Tanyu, M Tsesarsky and T Weaver (2013) "Biogeochemical processes and geotechnical applications: progress, opportunities and challenges" *Géotechnique* 63: 287-301

6. Mortensen, BM, MJ Haber, JT DeJong LF Caslake and DC Nelson (2011) "Effects of environmental factors on microbial induced calcium carbonate precipitation" *J. Appl. Microbiol.* 111: 338-349.

7. DeJong, JT, BM Mortensen, BC Martinez and DC Nelson (2010) *"Bio-mediated soil improvement"* Ecological Engineering 36(2): 197-210.

8. DeJong, JT, K Soga, SA Banwart, WR Whalley, TR Ginn, DC Nelson, BM Mortensen, BC Martinez and T Barkouki (2011) "Soil engineering in vivo: harnessing natural

biogeochemical systems for sustainable, multifunctional engineering solutions" *Journal of the Royal Society Interface* 8: 1-15.

9. Fleming, EJ, EE Mack, PG Green and DC Nelson (2006) "Mercury methylation from unexpected sources: molybdate-inhibited freshwater sediments and an iron-reducing bacterium" *Applied and Environmental Microbiology* 72(1):457-464.
10. Kalanetra, KM and DC Nelson (2010) "Vacuolate attached filaments: highly productive epibionts of *Ridgeia piscesae* at the Juan de Fuca hydrothermal vents" *Marine Biology* 157(4): 791-800.

**Synergistic Activities**:

1. Chair, Site Visit Team, NSF Science and Technology Center (C-MORE);
2. Member, RIDGE 2000 (NSF) Relevancy Review Panel;
3. Ad hoc reviewer numerous NSF proposals;
4. Provided *pro bono* technical advice to Delta Tributaries Mercury Council of Sacramento River Watershed Program, a non-profit group composed of diverse stakeholders (regulators, scientists, landowners, resource managers and users) interested in reducing mercury burden in delta fish and wildlife.

**Wendy C. Newstetter**

**Professional Preparation:**

| | | | |
|---|---|---|---|
| Colby College | Waterville, ME. | Asian Studies | BA 1971 |
| Lancaster University | England | Linguistics for Language Teaching | MA 1981 |
| Lancaster University | England | Linguistics | Ph.D. 1995 |

**Appointments:**

Georgia Institute of Technology, College of Engineering, Assistant Dean of Educational Research and Innovation, 2012-present

Georgia Institute of Technology, Department of Biomedical Engineering, Director of Learning Sciences Research, 2000-2012

Georgia Institute of Technology, College of Computing, School of Interactive Computing, Adjunct Faculty, 2000-Present

Georgia Institute of Technology, College of Computing, Research Scientist, 1996-2000

Georgia Institute of Technology, College of Computing, EduTech Institute, Post-Doctoral Fellow, 1994-1996

**Publications:**

Aurigemma, J., Chandrasekharan, S., Nersessian, N. J., & Newstetter, W. (2013). Turning Experiments into Objects: The Cognitive Processes Involved in the Design of a Lab-on-a-Chip Device. *Journal of Engineering Education*, *102*(1), 117-140.

Barrett, Thomas, Matthew Pizzico, Bryan D. Levy, Robert L. Nagel, Julie S. Linsey, Kimberly G. Talley, Craig R. Forest, and Wendy C. Newstetter. "A Review of University Maker Spaces." (2015).

Ferri, B., Newstetter, W., & Majerich, D. (2015, October). Instructor and graduate teaching assistant development and training for a blended linear circuits and electronics course. In *Frontiers in Education Conference (FIE), 2015. 32614 2015. IEEE* (pp. 1-4). IEEE.

Forest, C. R., Moore, R. A., Jariwala, A. S., Fasse, B. B., Linsey, J., Newstetter, W., Ngo, Peter & Quintero, C. (2014). The Invention Studio: A University Maker Space and Culture. *Advances In Engineering Education*, *4*(2).

Morocz, R., Levy, B. D., Forest, C. R., Nagel, R. L., Newstetter, W. C., Talley, K. G., & Linsey, J. S. (2015). University Maker Spaces: Discovery, Optimization and Measurement of Impacts.

Newstetter, W. C. and Svinicki, M. (2014) Learning theories for engineering education practice and research. Aditya Johri and Barbara Olds (Eds.) *Cambridge Handbook of Engineering Education Research.* Cambridge University Press.

Newstetter, W. C., Behravesh, E., Nersessian, N.J., & Fasse, B. B. (2010). Design Principles for Problem-Driven Learning Laboratories in Biomedical Engineering Education. *Annals of Biomedical Engineering, 38*(10), 3257-3267.

Newstetter, W. (2006) Fostering Integrative Problem Solving in Biomedical Engineering: The PBL Approach. *Annals of Biomedical Engineering.* 34/2 (217-225).

Newstetter, W. C., Behravesh, E., Nersessian, N.J., & Fasse, B. B. (2010). Design Principles for Problem-Driven Learning Laboratories in Biomedical Engineering Education. *Annals of Biomedical Engineering, 38*(10), 3257-3267.

Newstetter, W. (2005) Creating cognitive apprenticeships in biomedical engineering. *Journal of Engineering Education.* 94:2.

**Synergistic Activities:**

1. **Research on cognition and learning in-the-wild.**
   My research seeks to understand cognition and learning in-the-wild so as to develop new educational models that better approximate authentic practice. With my collaborator, Nancy Nersessian, we have been awarded two NSF ROLE grants and one REESE grant to study two biomedical engineering labs and one bio-robotics labs. Recently we are completing a three-year REESE-funded study of the emerging field of integrated systems biology. We use our findings from studying the research labs to design classrooms that promote interdisciplinary cognitive practices at the undergraduate and graduate level. In another REESE-funded project, we are trying to understand the challenges of learning to problem solve like an engineer with a particular focus on model-driven reasoning.

2. **Service to the STEM (Science, Technology, Engineering and Math) education community**
   I was a senior associate editor and special issues editor for the Journal of Engineering Education for four years. I have also served on their advisory board. I serve as an advisory board member for the Departments of Engineering Education at both Purdue University and at Virginia Tech. I review for the Annals of Biomedical Engineering and Journal of Women & Minorities in Science & Engineering. I have reviewed submissions for the Frontiers in Education, BMES conference and the International Conference of Learning Sciences and AERA. Spring 2013, I sat on a AAAS Science Policy Forum panel on MOOCs. More recently I was the plenary speaker for the Education and Research Methods SIG at the ASEE (American Society of Engineering Educators) conference.

3. **Learning Spaces Collaboratory**
   I work with Jeanne Narum on the development of a community devoted to understanding how space affects learning and creativity http://www.pkallsc.org/. We currently have two grants to support this work from NSF and from the Sloan Foundation. We have a recent publication titled: *Learning Spaces Collaboratory Guide: Planning for Assessing 21st Century Spaces for 21st Century Learners*.

4. **Development of interdisciplinary research and education opportunities**
   I participate in the following interdisciplinary centers and programs: NSF CCLI Georgia Tech Center for Biologically Inspired Design; NSF IGERT Stem Cell Biomanufacturing;

   NSF IGERT-CIF21: Computation-Enabled Design and Manufacturing of High Performance Materials and NIH BEST program at Georgia Tech and Emory.

## Craig M. Newtson

**Professional Preparation:**

| | | | |
|---|---|---|---|
| University of Wyoming | Civil Engineering | BSCE | 1989 |
| University of Wyoming | Civil Engineering | MSCE | 1992 |
| University of Washington | Civil Engineering | Ph.D. | 1997 |

**Appointments:**

| | |
|---|---|
| 2015 – Present | Professor, Dept. of Civil Engineering, New Mexico State University |
| 2015 – Present | Structures Chair, Dept. of Civil Engineering, New Mexico State University |
| 2005 – 2015 | Associate Professor, Dept. of Civil and Geological Engineering, New Mexico State University |
| 2001 – 2005 | Assistant Professor, Dept. of Civil and Geological Engineering, New Mexico State University |
| 1997 – 2001 | Assistant Professor, Dept. of Civil Engineering, University of Hawaii at Manoa |
| 1993 – 1997 | Graduate Research Assistant, Dept. of Civil Engineering, University of Washington |
| 1992 – 1993 | Graduate Teaching Assistant, Dept. of Civil Engineering, University of Washington |
| 1990 – 1992 | Graduate Research Assistant, Dept. of Civil Engineering, University of Wyoming |

**Products:**

1. Manning, M. P., Weldon, B. D., McGinnis, M. J., Jauregui, D. V., and Newtson, C. M., (2016). "Behavior Comparison of Prestressed Channel Girders from High Performance Concrete and Locally Developed Ultra-High Performance Concrete," *Transportation Research Record Journal of the Transportation Research Board*, Transportation Research Board, No. 2577, p. 60.
2. Pakravan, A., Kang, J. W., and Newtson, C. M., (2016). "A Gauss-Newton full-waveform inversion for material profile reconstruction in viscoelastic semi-infinite solid media," *Inverse Problems in Science and Engineering*, Vol. 24, No. 3, p. 393.
3. Aguilar, C. V., Jauregui, D. V., Weldon, B. D., and Newtson, C. M., (2017). "Load Rating of Prestressed Concrete Adjacent Beam Bridges without Plans in New Mexico," *American Concrete Institute (ACI) Special Publication on Evaluation of Concrete Bridge Behavior through Load Testing – International Perspectives*, Accepted.
4. Aguilar, C. V., Jauregui, D. V., Newtson, C. M., Weldon, B. D., and Cortez, T. M., (2015). "Load Rating a Prestressed Concrete Double T-Beam Bridge without Plans by Field Testing," *Transportation Research Record Journal of the Transportation Research Board*, No. 2522, p. 90.
5. Allena, S., and Newtson, C. M., (2015). "Materials Specification Needs for Future Development of Ultra High Performance Concrete," *Advances in Civil Engineering Materials*, ASTM, Vol. 4, No. 2, p. 17.
6. Allena, S., and Newtson, C. (2011). "Ultra High Strength Concrete Mixtures Using Local Materials," *Journal of Civil Engineering and Architecture*, Vol. 5, No. 4, pp 1-9, April 2011.
7. Allena, S., and Newtson, C. (2012). "Shrinkage of Fiber Reinforced Ultra High Strength Concrete," ASCE *Journal of Materials in Civil Engineering*, Vol. 24, No. 5, p. 612.
8. Bola, M. M. B., and Newtson, C. M. (2005). "Field Evaluation of Marine Structures Containing

Calcium Nitrite," American Society of Civil Engineers, *Journal of Performance of Constructed Facilities*, Vol. 19, No. 1, p. 28.

9. Xiang, H., Newtson, C. M., and Woodward, C. (2008). "Optimization of NLUT Results to Determine Dynamic Properties of Concrete," ASCE *Journal of Materials*, Vol. 20, No. 11, p. 700.
10. Newtson, C. M., Johnson, G. P., and Enomoto, B. T. (2006). "Fundamental Frequency Testing of Reinforced Concrete Beams," ASCE *Journal of Performance of Constructed Facilities*, Vol. 20, No. 2, p. 196.

**Synergistic Activities:**

1. Faculty advisor to the American Society of Civil Engineers Student Chapters from 1998-2001 at the University of Hawaii and from 2002-2010 at New Mexico State University.
2. Officer in the New Mexico Section of the American Society of Civil Engineers (ASCE) from 2003-2012. Offices held included:
   Director, New Mexico Section, 2003-2004
   Vice-President, New Mexico Section, 2004-2005
   President Elect, New Mexico Section, 2005-2006
   President, New Mexico Section, 2006-2007
   Past President, New Mexico Section, 2007-2008
   Governor, Region 6 (New Mexico, Oklahoma, Texas), 2009-2012
3. Board of Directors: New Mexico Ready Mixed Concrete and Aggregates Association (Dec. 2008-Present)
4. Senior Personnel (Researcher) and member of the Curriculum Committee of the Engineering Research Center for Bio-mediated and Bio-inspired Geotechnics (Aug. 2015-Present).
5. Professional Short Course Organization/Instruction:
   Quality Concrete School – Chair (Dec. 2006-Present)
   Quality Concrete School – Instructor (Dec. 2002-Present)
   Bridge Inspection Training School – Instructor (May 2002-Present)

## Megan O'Donnell

**Professional Preparation:**

| | | | |
|---|---|---|---|
| Elon University | Elon, NC | Psychology | B.A., 2000 |
| UNC Charlotte | Charlotte, NC | Counseling | M.A. 2004 |
| Arizona State University | Tempe, AZ | Human Development | Ph.D., 2014 |

**Appointments:**

| | |
|---|---|
| Research Professional, Arizona State University (ASU) | 2014-Present |
| Research Professional, Maricopa Community College | 2012-2012 |
| Graduate Research Assistant, ASU | 2007-2012 |
| Project Coordinator, UNC-Charlotte (UNCC) | 2004-2007 |

**Products:**

**O'Donnell, M**., Barnard, W., Carlson, D.L., and Cruz, J. (December 2015). Final Evaluation Report: The Mexico Teacher Professional Development Program. Submitted to Comexus (in collaboration with Global Launch, ASU).

**O'Donnell, M**. & Barnard, W. (February 2016). Palestinian Next Generation Leaders: Short Term Outcomes. Submitted to Next Generation Leaders (NGL) Program.

**O'Donnell, M**. & Barnard, W. (January 2016). India Support for Teacher Education Progrom (in-STEP). Mid-term Report. Submitted to USAID.

**O'Donnell, M**. & Barnard, W. (November 2016). Year One Evaluation: CBBG-ERC Education Program. Submitted to NSF.

**Synergistic Activities:**

Evaluation Grants Funded in STEM and Higher Education:

- *Center for Bio-inspired Bio-mediated Geotechnics (CBBG).* The evaluation focuses on the CBBG education component (students and teachers' knowledge, skills, attitudes, and engagement levels).

- *Nanotechnology Collaborative Infrastructure Southwest (NCI-SW).* Evaluation efforts include program implementation as well as the impact of the center's education efforts.

- *Adaptive Learning Evaluation.* This evaluation examined learning trajectories of student success in adaptive learning courses compared with traditionally taught courses.

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**Charalambos Papelis**

**Professional Preparation:**

| | | | |
|---|---|---|---|
| National Technical University | Athens, Greece | Civil Engineering, Water Resource | Diploma 1980 |
| Stanford University | Stanford, California | Environmental Engineering and Science | M.S. 1981 |
| Stanford University | Stanford, California | Environmental Engineering and Science | Ph.D. 1992 |

**Appointments:**

| | |
|---|---|
| 2010 – Present | Associate Professor of Civil Engineering, New Mexico State University |
| 2001 – 2009 | Associate Research Professor, Desert Research Institute |
| 2002 – 2008 | Director of Water Resources Management Graduate Program, University of Nevada, Las Vegas |
| 2005 – Present | Graduate Faculty of Geoscience Department, University of Nevada, Las Vegas |
| 1994 – 2001 | Assistant Research Professor, Desert Research Institute |
| 1994 – Present | Graduate Faculty of Hydrologic Sciences Program, University of Nevada, Reno |
| 1995 – 1998 | Associate Graduate Faculty of Chemistry, University of Nevada, Las Vegas |
| 1999 – 2002 | Associate Graduate Faculty of Civil and Environmental Engineering, University of Nevada, Las Vegas |
| 1994 – 2005 | Associate Graduate Faculty of Geoscience, University of Nevada, Las Vegas |
| 2002 – 2007 | Visiting Professor of Chemistry, Nevada State College |
| 1993 – 1994 | Visiting Assistant Professor of Civil and Environmental Engineering, University of Michigan |
| 1992 – 1993 | Research Fellow of Civil and Environmental Engineering, University of Michigan |
| 1990 – 1992 | Research Assistant of Civil Engineering, Stanford University |
| 1981 – 1988 | Research Assistant of Civil Engineering, Stanford University |
| 1982 – 1985 | Teaching Assistant of Civil Engineering, Stanford University |

**Products:**

1. Normile, H., C. Papelis, and T. Kibbey (2017). "Remobilization dynamics of caffeine, ciprofloxacin and propranolol following evaporation-induced immobilization in porous media." *Environmental Science and Technology*, 51, 6082-6089.
2. Que, S., C. Papelis, A.T. Hanson, L. Wang, and E. Livingston (2016). "Modeling the efficiency of the iron coprecipitation-filtration process for the removal of arsenate at low initial concentrations." *Journal of Environmental Engineering, ASCE*, 142, 10, 04016047.
3. Xu, X., L. Lin, C. Papelis, M. Myint, T. Cath, and P. Xu (2015). "Use of drinking water treatment solids for arsenic removal from desalination concentrate." *Journal of Colloid and Interface Science*, 445, 252-261.
4. Lin, L., X. Xu, C. Papelis, and P. Xu (2017). "Innovative use of drinking water treatment solids for heavy metal removal from reverse osmosis concentrate: synergistic effect of salts and natural organic matter." *Chemical Engineering Research and Design, 120,* 231-239.
5. Que, S., C. Papelis, and A.T. Hanson (2013). "Predicting arsenate adsorption on iron coated sand based on a surface complexation model." *Journal of Environmental* Engineering, 139 (3), 368-374.
6. Lin, L, X. Xu, C. Papelis, T. Cath, and P. Xu (2014). "Sorption of metals and metalloids from reverse osmosis concentrate on drinking water treatment solids." *Separation and Purification*

*Technology*, *134,* 37-45.
7. Zhang, Y., J. Qian, C. Papelis, P. Sun, and Z. Yu (2014). "Improved understanding of bimolecular reactions in deceptively simple homogeneous media: From laboratory experiments to Lagrangian quantification" *Water Resources research*, 50, 1704-1715.
8. Zhang, Y. and C. Papelis (2011). "Particle-tracking simulation of fractional diffusion-reaction processes." *Physical Review E*, 84, 066704.
9. Um, W. and C. Papelis (2004). "Metal ion sorption and desorption on zeolitized tuffs from the Nevada Test Site." *Environ. Sci. Technol.*, *38*, 496-502.
10. Um, W. and C. Papelis (2003). "Sorption mechanisms of Sr and Pb on zeolitized tuffs from the Nevada test site as a function of pH and ionic strength." *American Mineralogist*, *88*, 2028-2039.
11. Um, W. and C. Papelis (2002). "Geochemical effects on colloid-facilitated metal transport through zeolitized tuffs from the Nevada Test Site." *Environmental Geology, 43*, 209-218.
12. Papelis, C., K.F. Hayes, and J.O. Leckie (1988). "HYDRAQL: A program for the computation of chemical equilibrium composition of aqueous batch systems including surface complexation modeling of ion adsorption at the oxide/solution interface", Technical Report No. 306, Department of Civil Engineering, Stanford University, Stanford, CA.
13. Zhang, Y., J. Qian, C. Papelis, P. Sun, and Z. Yu (2014). "Improved understanding of bimolecular reactions in deceptively simple homogeneous media: From laboratory experiments to Lagrangian quantification" *Water Resources research, 50,* 1704-1715.
14. Zhang, Y., C. Papelis, P. Sun, and Z. Yu (2013). "Evaluation and linking of effective parameters in particle-based models and continuum models for bimolecular reactions." *Water Resources Research, 49,* 4845-4865.
15. Diallo, M.S., S. Christie, P. Swaminathan , L. Balogh, X. Shi, W. Um, C. Papelis, W.A. Goddard III, and J.H. Johnson, Jr. (2004). "Dendritic chelating agents: 1. Cu(II) binding to ethylene diamine core poly(amidoamine) dendrimers in aqueous solutions." *Langmuir*, *20*, 2640-2651.
16. Papelis, C. and K.F. Hayes (1996). "Distinguishing between interlayer and external sorption sites of clay minerals using x-ray absorption spectroscopy," *Colloids & Surfaces A, 107*, 89-96.
17. Hayes, K.F., C. Papelis, and J.O. Leckie (1988). "Modeling ionic strength effects on anion adsorption at hydrous oxide/solution interfaces", *J. Colloid Interface Sci.*, *125*, 717-726.

**<u>Synergistic Activities:</u>**

1. <u>P</u>articipant: Interdisciplinary Graduate Program of Hydrologic Sciences at University of Nevada, Reno.
2. <u>D</u>irector: Interdisciplinary Graduate Program of Water Resources Management at University of Nevada, Las Vegas. 2002-2008.
3. <u>Numerous presentations:</u> including to the Nevada System of Higher Education's Board or Regents, non-profit organizations, and high school students, as well as numerous other outreach activities.
4. <u>Appearances:</u> at local, national, at international media, including PBS's *Nightly Business Report* and the *Economist*.

## Rebecca Ehrlich Parales

**Professional Preparation:**

| | | | |
|---|---|---|---|
| University of Connecticut, Storrs, CT | Chemistry | B.S. | 1981 |
| Cornell University, Ithaca, NY | Microbiology | Ph.D. | 1993 |
| The University of Iowa, Iowa City, IA | Microbiology | Postdoctoral Fellow | 1993 |

**Appointments:**

| | |
|---|---|
| 2010- | Professor, Department of Microbiology and Molecular Genetics, UC Davis |
| 2006-2010 | Associate Professor, Department of Microbiology, UC Davis |
| 2003-2006 | Assistant Professor, Section of Microbiology, UC Davis |
| 1998-2003 | Associate Research Scientist, Dept. of Microbiology, The University of Iowa |
| 1994-1998 | Assistant Research Scientist, Dept. of Microbiology, The University of Iowa |
| 1993-1994 | Research Scientist, Biotreatment Systems, Celgene Corporation, Warren, NJ |
| 1982-1986 | Research Assistant II, Dept. of Biology, Yale University, New Haven, CT |
| 1981-1982 | Research Assistant I, Dept. of Human Genetics, Yale University, New Haven, CT |

**Publications:** (past 3 years; #graduate, *undergraduate, ** high school student author)

R.A. Luu#, J. Kootstra*, C. Brunton*, V. Nesteryuk*, J.V. Parales, J.L. Ditty and **R.E. Parales**. 2015. Integration of chemotaxis, transport, and catabolism in *Pseudomonas putida* and identification of the aromatic acid chemoreceptor PcaY. Mol. Microbiol. **96:**134-147.

K.M. Mahan#, J.T. Penrod, R. Truong*, W.A. Tan#, N. Al Kass#, J.V. Parales, K.-S. Ju#, and **R.E. Parales**. 2015. Selection for growth of 2-nitrotoluene degrading *Acidovorax* sp. strain JS42 on 3-nitrotoluene identifies nitroarene dioxygenases with altered specificities. Appl. Environ. Microbiol. **81:**309-319.

C.M. Timm, A.G. Campbell, S.M. Utturkar, S.R. Jun, **R.E. Parales**, W.A. Tan#, M.S. Robeson, T.-Y.S. Lu, S. Jawdy, S.D. Brown, D.W. Ussery, C.W. Schadt, G.A. Tuskan, M.J. Doktycz, D.J. Weston and D.A. Pelletier. 2015. Metabolic functions of *Pseudomonas fluorescens* from *Populus deltoids* depend on rhizosphere or endosphere isolation compartment. Front. Microbiol. **6:**1118.

**R.E. Parales**, R.A. Luu#, J.G. Hughes#, and J.L. Ditty. 2015. Chemotaxis to xenobiotic chemicals and naturally-occurring analogs. Curr. Opin. Biotechnol. **33:**318-326.

I. Sampedro#, **R.E. Parales**, T. Krell, and J. Hill. 2015. *Pseudomonas* Chemotaxis. FEMS Microbiol. Rev. **39:**17-46.

H. Jabeen#, S. Iqbal, S. Anwar, and **R.E. Parales**. 2015. Optimization of profenofos

degradation by a novel bacterial consortium PBAC using response surface methodology. Int. Biodeter. Biodeg. **100:**89-97.

W.A. Tan[#] and **R.E. Parales**. 2016. Application of Aromatic Hydrocarbon Dioxygenases. In: Green Biocatalysis. R. Patel, Ed., John Wiley & Sons, Ch. 17, pp. 457-469.

S.G. Pati[#], H.-P. E. Kohler, A. Pabis, P. Paneth, and **R.E. Parales**, T.B. Hofstetter. 2016. Substrate and enzyme specificity of the kinetic isotope effects associated with the dioxygenation of nitroaromatic contaminants. Environ. Sci. Technol. **50:**6708-6716.

Z. Huang[#], B. Ni[#], C.-Y. Jiang, Y.-F. Wu, Y.-Z. He, **R.E. Parales**, and S.-J. Liu. 2016. Direct sensing and signal transduction during bacterial chemotaxis towards aromatic compounds in *Comamonas testosteroni* Mol. Microbiol. **101:**224-237.

J.L. Ditty, N.N. Nichols and **R.E. Parales**. 2017. Protocols for the measurement of hydrocarbon transport in bacteria. pp. 55-67. In: *Hydrocarbon and Lipid Microbiology Protocols.* T.J. McGenity, K.N. Timmis, and B. Nogales, Eds. Springer-Verlag, Berlin.

J.L. Ditty and **R.E. Parales**. 2017. Protocols for the measurement of hydrocarbon chemotaxis in bacteria. pp. 7-42. In: *Hydrocarbon and Lipid Microbiology Protocols.* T.J. McGenity, K.N. Timmis, and B. Nogales, Eds. Springer-Verlag, Berlin.

W.A. Tan[#] and **R.E. Parales**. 2017. Environmental and clinical *Acidovorax* strains. In: Plant Pathogenic *Acidovorax* species. S. Burdman and R. Walcott, Eds. American Phytopathological Society Press (In press).

C.A. Rabinovitch[#], J.L. Ditty and **R.E. Parales**. 2017. Motility and Chemotaxis of *Acidovorax*. In: Plant Pathogenic *Acidovorax* species. S. Burdman and R. Walcott, Eds. American Phytopathological Society Press (Invited review in press).

**Synergistic Activities:**

1. Co-organizer of the Annual Meeting of the West Coast Bacterial Physiologists (2010-present). This meeting provides a venue for undergraduate, graduate and postdoctoral students to present their research in all areas of microbial physiology.
2. Editor for Applied and Environmental Microbiology (2011-2021); Editor for Microbiology (2012-2017).
3. Served on review panels for NSF (2006; 2007; 2009; 2012); Strategic Environmental Research and Development Program (U.S. DoD, 2006; 2007); and the Department of Energy (1997, 1999, 2002, and 2004). Each year since 1997, I also completed invited reviews for NSF.
4. Developed a biodegradation laboratory module for the isolation and characterization of naphthalene-degrading bacteria from pristine and contaminated environments for students in COSMOS, the California State Summer School for Mathematics and Science at UC Davis. This program brings California high school students to UC Davis for summer research experience.
5. Judge for 2015 West Campus Science Fair, West Campus High School Sacramento, CA.

**Bruce E. Rittmann**

**Professional Preparation:**

| | | |
|---|---|---|
| Washington University in St. Louis, St. Louis, MO | Civil Engineering | B.S. 1974 |
| Washington University in St. Louis, St. Louis, MO | Environmental Engineering | M.S. 1974 |
| Stanford University, Stanford CA | Environmental Engineering | Ph.D. 1979 |
| Stanford University, Stanford, CA | Environmental Engineering | P.D. 1979 |

**Appointments:**

2009-present Regents' Professor, School of Sustainable Engineering and the Built Environment, Arizona State University

2005-present Professor of Environmental Engineering in the School of Sustainable Engineering and the Built Environment, with affiliate appointments in the School of Life Science, Chemical Engineering Program, Biological Design PhD Program, Environmental Life Sciences Program, Microbiology Program, and School of Sustainability, Arizona State University

2005-present Director of the Biodesign Swette Center for Environmental Biotechnology, Biodesign Institute, Arizona State University

1992-2004 John Evans Professor of Environmental Engineering, with affiliate appointments in Chemical Engineering, Northwestern University

1980-1992 Full, Assoc., and Asst. Professor, Dept. of Civil Engineering, University of Illinois at Urbana-Champaign

**Products:**

Dr. Rittmann has published more than 650 papers, chapters, and books. Here is a selection of recent ones:

Torres, C. I., A. K. Marcus & B. E. Rittmann (2008). Proton transport inside the biofilm limits electrical current generation by anode-respiring bacteria. Biotechnol. Bioengr. 100: 872-881.

Torres, C. I., A. K. Marcus, P. Parameswaran, & B. E. Rittmann (2008). Kinetic experiments for evaluating the Nernst-Monod model for anode-respiring bacteria (ARB) in a biofilm anode. Environ. Sci. Technol. 42(17): 6593-6597.

Parameswaran, P., H. Zhang, C. I. Torres, B. E. Rittmann, and R. Krajmalnik-Brown (2010). Microbial community structure in a biofilm anode fed with a fermentable substrate: the significance of hydrogen scavengers. Biotechnol. Bioengr. 105: 69-78.

Torres, C. I., Andrew K. Marcus, H.-S. Lee, P. Parameswaran, R. Krajmalnik-Brown, and B. E. Rittmann (2010). A kinetic perspective on extracellular electron transfer by anode-respiring bacteria. FEMS Microb. Rev. 34: 3 – 17.

Marcus, A. K., C. I. Torres, and B. E. Rittmann (2011). Analysis of a microbial electrochemical cell using the proton condition in biofilm (PCBIOFILM) model. Bioresources Technol. 102: 253 – 262.

Zhao, H.-P; Z. E. Ilhan, A. Ontiveros-Valencia, A.; Y. Tang, B. E. Rittmann, Bruce, and R Krajmalnik-Brown (2013) Effects of multiple electron acceptors on microbial interactions in a hydrogen-based biofilm. Environ. Sci. Technol. 47: 7396 – 7403.

Lai, C.-Y., X. Yang, Y. Tang, B. E. Rittmann, and H.-P. Zhao (2014). Nitrate shaped the selenate-reducing microbial community in a hydrogen-based biofilm reactor. Environ. Sci. Technol. 48: 3395-3402.

Luo, Y.-H., R. Chen, L.-L. Wen, F. Meng, Y. Zhang, C.-Y. Lai, B. E. Rittmann, H.-P. Zhao, and P. Zheng (2015). Complete perchlorate reduction using methane as the sole electron donor and carbon source. Environ. Sci. Technol. 49: 2341-2349.

Li, W.-W., H.-Q. Yu, and B. E. Rittmann (2015). Reuse water pollutants. Nature 528: 29 – 31.
Lai, Y.-J., P. Parameswaran, A. Li, A. Aguinaga, and B. E. Rittmann (2016). Selective fermentation of carbohydrate and protein fractions of *Scenedesmus*, and biohydrogenation of its lipid fraction for enhanced recovery of saturated fatty acids. Biotechnol. Bioengr.113: 320 – 329.

**Synergistic Activities:**

Dr. Rittmann and colleagues formed a spin-out company, ARBsource, to commercialize technology the area of microbial electrochemical cells (MXCs). ARBsource is now called Admiral Instruments.

Dr. Rittmann has nine patents on the membrane biofilm reactor (MBfR), which is licensed and commercialized by APTwater.

Dr. Rittmann has seven other patents on microbial electrochemical cells, managing the human intestinal microbiome, intimately coupled photobiocatalysis, and other technologies.

Dr. Rittmann has been honored with many prestigious awards: e.g., Fellow of the Association of Environmental Engineering and Science Professors (AEESP) (2017), Fellow of the National Academy of Inventors (NAI) (2017); Daniel Jankowski Legacy Award, Ira A. Fulton Schools of Engineering, Arizona State Univerity (2017); Perry L. McCarty/AEESP Founders Award (2016); Gordon Maskew Fair Award (AAEES) (2016); Alumni Achievement Award, Washington University in St. Louis (2015); Joan Hodges Queneau Palladium Medal, American Association of Engineering Societies (AAES) (2014); Honorary Doctorate, University of Waterloo (2014); Honorary Member, American Academy of Environmental Engineers and Scientists (AAEES) (2013); Fellow, Water Environment Federation (WEF) (2013); Distinguished Member, American Society of Civil Engineers (ASCE) (2012); Fellow, International Water Association (IWA) (2012); Excellence in Environmental Engineering Award, AAEE (2011 and 2014); Research Excellence Award, Arizona BioIndustry Association (2009); Simon W. Freese Environmental Engineering Award and Lecture, ASCE (2009); Member, National Academy of Engineering (NAE) (2004); Distinguished Lecturer, Association of Environmental Engineering and Science Professors (AEESP) (2004); Fellow, American Association for the Advancement of Sciences (AAAS) (1996); A.R.I. Clarke Prize, National Water Research Institute (NWRI) (1994); Walter Huber Research Prize, ASCE (1990); Best thesis or dissertation awards, AEESP (1980, 1989, 1992, 1992, 1993, 1995, 1995); Academic Achievement Award, AWWA (1990); Presidential Young Investigator Award, NSF (1984).

Dr. Rittmann has provided distinguished professional service: e.g., Board of Directors, Foundation of AEESP (2009-2012); Core Management Committee, Leading Edge Technology Conferences (IWA) (2007-present); Organizing Committee, National Academy Keck Frontiers Initiative (NAKFI) Symposium (2011-2013); Chairman, Panel on Intrinsic Remediation, National Research Council (NRC) (1997-2000); Chairman, Panel on *In Situ* Bioremediation, NRC (1992-1993); Water Science and Technology Board, NRC, NAS, (1991-1997), Vice Chairman (1994-1997); Board of Directors, AEESP (1988-1992), President (1990-1991), Past-President (1991-1992); Chairman and Organizer, IWA Specialists Conference on Microbial Ecology of Biofilms (1996-1998); Editorial Advisory Board, *Environmental Science & Technology* (2003-present); Editorial Board, *Environmental Microbiology* (1998-present); Editorial Board of Review, *Water Environment Research* (1999-2003); Editor-in-Chief, *Biodegradation* (1996-2004); Environmental Protection Agency Science Advisory Board (2001-2003).

**Delia S Saenz**

**Professional Preparation:**

Texas Southmost College, Brownsville, TX, Psychology, AA, *Magna cum laude*, 1979
Pan American University, Brownsville, TX, Psychology, BA, *Magna cum laude*, 1981
Princeton University, Princeton, NJ, Psychology, MA, 1985
Princeton University, Princeton, NJ, Social Psychology, Ph.D., 1987

**Appointments:**

| | |
|---|---|
| 07/95-present | Associate Professor, Department of Psychology & Associate Research Professor, Hispanic Research Center, Arizona State University |
| 9/07-6/13 | Vice Provost (International Education & Institutional Inclusion; Undergraduate Education), Arizona State University |
| 7/04-9/07 | Director, Intergroup Relations Center, Office of the Provost, Arizona State Univ. |
| 7/96-6/97 | Interim Associate Dean, Graduate College, Arizona State University |
| 8/89-6/95 | Assistant Professor, Department of Psychology & Assistant Research Professor, Hispanic Research Center, Arizona State University |
| 6/87-5/89 | Assistant Professor, Department of Psychology, University of Notre Dame |
| 8/86-5/87 | Instructor, Department of Psychology, University of Notre Dame |

**Products:**

Cookston, J. T., Olide, A., Parke, R. D., Fabricius, W. V., Saenz, D., & Braver, S. L. (2015). He said what? Guided cognitive reframing about the co-resident father/stepfather-adolescent relationship. Journal of Research on Adolescence, 25, 263-278, doi: 10.1111/jora.121220.

Neiri, T., Grindal, M., Adams, M. A., Cookston, J. T., Fabricius, W. V., Parke, R. D., & Saenz, D. S. (2014). Reconsidering the "acculturation gap" narrative through an analysis of parent-adolescent acculturation differences in Mexican American families. Journal of Family Issues, 41,1-26, doi: 10.1177/0192513X14551175.

Finlay, A. K., Cookston, J. T., Saenz, D. S., Baham, M. E., Parke, R. D., Fabricius, W. V., & Braver, S. L. (2014). Attributions of fathering behaviors among adolescents: The role of gender, ethnicity, family structure, and depressive symptoms. Journal of Family Issues, 35(4), 501-525.

Perez-Brena, N. J., Cookston, J. T., Fabricius, W. V., & Saenz, D. S. (2012). Patterns of father self-evaluations among Mexican and European American men and links to adolescent adjustment. Fathering: A Journal of Theory, Research, and Practice about Men as Fathers, 10, 213-235.

Diaz, P., Saenz, D. S., & Kwan, V. (2011). Economic dynamics and changes in attitudes toward undocumented Mexican American immigrants in Arizona. Analyses of Social Issues and Public Policy, 11, 300-313.

**Other relevant publications**

Campesino, M., Saenz, D. S., Choi, M., & Krause, R. S. (2012). Perceived discrimination and ethnic identity among breast cancer survivors. Oncology Nursing Forum, 39, 91-100.

Roosa, M., W., Zeiders, K. H., Knight, G. P., Gonzales, N. A., Tein, J., Saenz, D., O'Donnell, M., & Berkel, C. (2011). A test of the Social Development Model during the transition to junior high with Mexican American adolescents. Developmental Psychology, 47, 527-537.

Saenz, D. S. (1997). Token status and problem-solving deficits: Detrimental effects of distinctiveness and performance monitoring. In L. A. Peplau & S. E. Taylor (Eds.), Sociocultural perspectives in social psychology (pp. 100-112). Upper River Saddle, NJ: Prentice-Hall, Inc.

Saenz, D. S., & Lord, C. G. (1989). Reversing Roles: A cognitive strategy for undoing memory deficits associated with tokenism. Journal of Personality and Social Psychology, 56, 698-708.

Lord, C. G., & Saenz, D. S. (1985). Memory deficits and memory surfeits: The differential cognitive consequences of tokenism for tokens and observers. Journal of Personality and Social Psychology, 49, 918-926.

**Synergistic Activities:**

1. Dr. Saenz has taken research outcomes from her scientific work and developed a training curriculum on "Creating optimal learning environments for diverse classrooms." The training provides instructors with an understanding of classroom dynamics that emerge for numerically distinctive individuals (e.g., women in STEM, minorities in K12 and higher education), and focuses on pedagogies that promote inclusion and increase participation of historically underrepresented groups. Workshops have been delivered to K-12 teachers, graduate students, university faculty, and science/engineering firm employees (e.g., Intel).
2. Dr. Saenz has won multiple awards for excellence in teaching and mentoring at the institutional, disciplinary, and national levels and has been recognized for contributions to mentoring of students of color (e.g., *Outstanding Mentor Faculty Mentor Award,* ASU Faculty Women's Association, 2016; *Excellence in Education Award*, Ronald McDonald Charities National Scholarship Program, 2005; *Kenneth & Mamie Clark Award for Outstanding Contribution to the Professional Development of Ethnic Minority Graduate Students*, American Psychological Association of Graduate Students, 1995).
3. Dr. Saenz has been PI and/or co-PI on multiple grants that focus on broadening participation. VOCTEC focuses on training policy makers, engineering faculty, and technicians in developing countries on clean energy and the importance of gender inclusion therein. She has conducted research on experiences of women of color faculty in research intensive doctoral universities via a Ford Foundation funded grant, "Diversification of the Academy Post-Grutter."
4. Dr. Saenz is experienced in grant review panels focused on women. She served on the *National Science Foundation ADVANCE PAID grant review panel*, March, 2009 & on the *National Science Foundation Committee of Visitors for the Social Psychology division*, Behavioral and Cognitive Sciences Directorate, March, 2006.
5. Dr. Saenz has served on editorial board of *Small Group Research* & *The Business Journal of Hispanic Research*, and has been funded by NSF, NIH, NIMH, US Agency on International Development, & the Ford & Spencer Foundations.

## Zohrab A. Samani

**Professional Preparation:**

| | | | | |
|---|---|---|---|---|
| Utah State University | Logan, Utah | Agricultural & Irrigation Engineering | Ph.D. | 1983 |
| Utah State University | Logan, Utah | Agricultural & Irrigation Engineering | M.S. | 1980 |
| University of Tehran | Amir Abad, Iran | Water Resources Engineering | B.S. | 1974 |

**Appointments:**

| | |
|---|---|
| 2000 – Present | Professor, Civil Engineering Department, New Mexico State University |
| 1993 – 2000 | Associate Professor, Civil Engineering Department, New Mexico State University |
| 1987 – 2000 | Assistant Professor, Civil Engineering Department, New Mexico State University |
| 1984 – 1987 | Research Associate Professor, International Irrigation Center, Utah State University |
| 1983 – 1984 | Post Doctorate Research Professor, University of Arizona |

**Products:**

1. Mostafazadeh-Fard, S., Samani, Z., and Bandini, P. 2017. Production of liquid organic fertilizer through anaerobic digestion of grass clippings. *Waste and Biomass Valorization* (Technical paper, accepted).
2. Samani Z., Jacquez R., Suraj, K., and Hernandez, C. 1994. Remediation of contaminated surface and groundwater with straw filter. Invited paper, *U.S. Mexico Foundation for Science Conference*, Oct. 1994.
3. Samani Z., Suraj, K., and Jacquez R. 1995. Removal of heavy metals from contaminated water using an organic filter. Water Resources Engineering, *Proceedings of the First International Conference of the American Society of Civil Engineers*, San Antonio, Texas, Aug. 1995, 1738-1743.
4. Hanson, A., Samani, Z., Dwyer, B., and Jacquez, R. 1992. Heap leaching as a solvent extraction technique for remediation of metals contaminated soils. Book Chapter in *Transport and Remediation of Subsurface Contaminants*, American Chemical Society, Edited by Sabatini and Knox, 1992.
5. Samani Z., 1999. Water conservation and planning. *Acuiferos Costeros Conference*, Empalme, Mexico, May 1999.
6. Samani, Z. A., and Willardson, L. S. 1981. Soil hydraulic stability in a subsurface drainage system, *Trans. of ASAE*, 24(3).
7. Samani, Z. A., Cheraghi, A., and Willardson, L. 1989. Water movement in horizontally layered soils, *Journal of Irrigation and Drainage Engineering*, 115(3), 1989.
8. Hanson, A., Dwyer, B., Samani, Z., and York, D. 1993. Remediation of chromium contaminated soils by heap leaching: Column study, *Journal of Environmental Engineering*, 119(5).
9. Heil, D., Samani Z., and Hanson, A. 1995. Soil and chemical factors which control the efficiency of remediation of lead-polluted soils by chelation extraction, Chapter 11 in *Waste Management from Risk to Remediation*, EMC Press, EMC Inc.

10. Macias, M., Samani, Z., Hanson, A. T., DelaVega, R., and Funk, P. 2005. Producing energy and soil amendment from dairy manure and cotton gin waste, *Trans. of ASAE*, 48(4), 1521-1526.

**Synergistic Activities:**

1. Developed and taught short courses on Water Resource Engineering for national and international audiences in Mexico, Afghanistan, Tajikstan, Uzbakistan, India, China, Egypt and the U.S. during 2002-2017.
2. Supervised water infrastructure reconstruction projects in Afghanistan during 2010.
3. Developed a Manual for Soil and Water Conservation (2013).
4. Developed a Manual for flow measurement (2016).
5. Entrepreneurship and commercialization activities:
   - Received $50,000 NSF Innovation Corps (I-Corps) grant to participate in mentorship and training for commercialization of Liquid Organic Fertilizer (LOF), with graduate student Saman Mostafazadeh-Fard (2017)
   - Received $2,000 NMSU Aggie I-Corps stipend to participate in mentorship and training for commercialization of Liquid Organic Fertilizer (LOF), with graduate student Saman Mostafazadeh-Fard (summer 2017)
   - Participated in NMSU Arrowhead Center's LAUNCH entrepreneurship training program (semester-long program). The team was a 2017 LAUNCH finalist this spring. http://arrowheadcenter.nmsu.edu/launch/
   - Filed an invention disclosure (by Z. Samani, P. Bandini, and S. Mostafazadeh-Fard) in August 22, 2016 (NMSU Arrowhead Center Case Number INV-00044) for the production technology and application of a liquid organic anti-icer. A provisional patent application is in progress through NMSU Arrowhead Center.
   - Patent # US 7771504 B1: Producing liquid organic fertilizer from organic substrates, 2017 (Z. Samani and NMSU Arrowhead Center, Inc.)

**Regina D. Sanborn**

**Professional Preparation:**

| | | | |
|---|---|---|---|
| City University of New York | New York, New York | Psychology/Education | B.A., 1974 |
| Arizona State University | Tempe, Arizona | Liberal Studies | M.A., 2007 |

**Appointments:**

Arizona State University (1998-present):

Administrative Director, Center for Bio-mediated and Bio-inspired Geotechnics Engineering Research Center (2015-present); Administrative Director, Quantum Energy and Sustainable Solar Technologies Engineering Research Center (2013-2015); Assistant Director, Center for Nanotechnology in Society (2011-2013); Program Manager, Center for Nanotechnology in Society (2007-2011); Director, Member Services, ASU Alumni Association (2006-2007); Director, Research and Partnerships, ASU Alumni Association (2004-2006); Director, Marketing and Membership, ASU Alumni Association (2000-2004); Marketing Specialist, ASU Alumni Association (1998-2000)

Foundation for Physical Therapy (1995-1997)

Vice President, Administration (1997); Director of Operations (1997); Advancement Associate (1996-1997); Office Manager (1995-1996)

American Medical Women's Association (1988-1995)

Director, Membership and Services

American Society of Mechanical Engineers (1978-1988)

Director, Member Services (1987-1988); Associate Director, Member Services (1984-1987); Manager, Field Services (1981-1984); Sections Administrator (1979-1981); Administrative Assistant (1978-1979)

Gimbel Brothers (1970-1978)

Assistant to Divisional Merchandise Manager (1974-1978); Sales Associate (1970-1974)

**Related Publications:**

N/A

**Other Significant Publications**:

N/A

**Synergistic Activities:**

1. Developed and executed strategic plans, marketing plans, communications plans, and fund-raising plans.
2. Cultivated strategic business partnerships; recognized and capitalized on market trends utilizing strategic planning, market research, and forecasting.
3. Managed membership development activities and services, fund development, projects, information systems, and people.
4. Written and submitted grant proposals, and administered grants, including development of budgets, budget justifications, interim, annual and final reports, technical reports, and supplemental funding requests.
5. Managed all major aspects of meeting and event management, including site selection, marketing/promotional materials, registration processes and databases, on-site management, preparation and management of program budgets, negotiation of complex service contracts, and management of meeting vendors, including venues, transportation, hotels, caterers, security, speakers, and more.

**Wilhelmina C. Savenye**

**Professional Preparations:**

| | | | | |
|---|---|---|---|---|
| Bellevue Community College | Bellevue, WA | Media Technology | A.A. | 1976 |
| University of Washington | Seattle, WA | Anthropology | B.A. | 1979 |
| Arizona State University | Tempe, AZ | Educational Technology | M.Ed. | 1982 |
| Arizona State University | Tempe, AZ | Educational Technology | Ph.D. | 1985 |

**Appointments:**

2015 – present Education Director, Center for Bio-mediated and Bio-inspired Geotechnics

2007 - present Professor, Educational Technology, Div. of Educational Leadership & Innovation, Arizona State University (2008-present - PhD Program Leader - Educational Technology 2008-2016 - Master's Program Leader - Educational Technology)

2010 – present Editor – Journal of Applied Instructional Development

2012 – 2016 Associate Editor - Encyclopedia of Educational Technology (Sage)

2002 – 2014 Visiting Professor – Teaching with Technology Summer Faculty Institutes – Texas State University – San Marcos

1992 – 2007 Associate Professor, Educational Technology, Arizona State University

Summer, 1999 Adjunct Faculty, Instructional Technology and Distance Education, ITDE Program, Nova Southeastern University

1991 – 1992 Assistant Professor, Learning and Instructional Technology, Arizona State University

1985 – 1990 Assistant Professor, Instructional Technology, Department of Curriculum and Instruction, The University of Texas at Austin

1987 – 1988 Assistant Professor, Department of Educational Technology, San Diego State University (while on leave from UT-Austin)

**Products:**

1. Larson, J. S., Dalal, M. D., **Savenye, W. C.,** Zapata, C. E, Hamdan, N., Kavazanjian, E. Implementation of an Introductory Module on Biogeotechnics in a Freshman Engineering Course. *Proceedings of the American Society for Engineering Education*. Columbus, OH, June 25-28, 2017.

**2. Savenye**, W., Larson, J., Zapata, C., Kavazanjian, E., Elwood, K., Reed, A., Mitchell, M., Brown, S., Bronner, C., Saenz, D., Newstetter, W., Benton-Johnson, F., Dalal, M., Gomez, M., & Delgado, N. *The Ultimate Higher Education Start-Up: Building Education, Outreach and Diversity for an NSF Engineering Research Center*. Paper presented at the annual meeting of the Association for Educational Technology & Communications (AECT), Las Vegas, NV, October 17-21, 2016.

3. **Savenye, W. C.** (2016). Willi's voice: The academic road – thorns and roses. In *Women's voices in the field of educational technology: Our journeys*. J. A. Donaldson, Ed. Switzerland: Springer International, pp. 121-130.

4. Elwood, K., **Savenye**, W., Jordan, M., Larson, J., & Zapata, C. *Design Thinking: A New Construct for Educators*. Paper presented at the annual meeting of the Association for Educational Technology & Communications (AECT), Las Vegas, NV, October 17-21, 2016.

annual meeting of the Association for Educational Technology & Communications (AECT), Las Vegas, NV, October 17-21, 2016.

5. Ornelas, A., **Savenye, W**., Sadauskas, J. D., Houston, S., Zapata, C., & Ramirez, E. (2013). An engineering and educational technology team approach to introducing new unsaturated soils mechanics material into introductory undergraduate geotechnical engineering courses: Cross-curricular coordination and working outside of your comfort zone. *Proceedings of the 120th ASEE Annual Conference and Exposition,* held in Atlanta, GA, June 23 - 26, 2013.
6. **Savenye, W**. (2013). Perspectives on assessment of educational technologies for informal learning: A review of issues, perspectives, strategies and possibilities. In J. M. Spector, M. D. Merrill, J. Elen, & M. J. Bishop, Eds. *Handbook of research on educational communications and technology*. (4th ed.). New York: Springer, 257-267.
7. **Savenye, W**., Robinson, R., Niemczyk, M., Atkinson, R. (2008). Data collection and analysis: Measuring individual learning. In J. M. Spector, M. D. Merrill, J. J. G. vanMerrienboer, & M. Driscoll, (Eds.), *Handbook of research on educational communications and technology. 3rd Ed.* New York, Routledge.
8. **Savenye, W**., & Robinson, R. (2004). Qualitative research issues and methods: An introduction for instructional technologists. In D. Jonassen, (Ed.), *Handbook of research on educational communications and technology*. 2nd Ed. Mahwah, NJ: Lawrence Erlbaum, 1045-1071.
9. **Savenye, W**. (2007). Interaction: The power and promise of active learning. In M. Spector, Ed. *Finding your online voice: Stories told by experienced online educators*. Lawrence Erlbaum Publishers, 141-162.
10. **Savenye, W. C**. (2004). Evaluating web-based learning systems and software. In N. Seel, & Z. Dijkstra (Eds.) *Curriculum, plans, and processes in instructional design: International perspectives*. Mahwah, NJ: Lawrence Erlbaum, 309-330.

**Synergistic Activities:**

1. *Evaluation/Assessment, Instructional Design, Interactive Multimedia & Online Learning Technologies for the following*: Advancement Of Unsaturated Soils Theory Into The Undergraduate Civil Engineering Curriculum (PI: Houston, S. Co-PIs: Zapata & Savenye, NSF, TUES. (inst.design,evaluation); Embodied STEM Learning Across Technology-Based Learning Environments (PI: Birchfield, D., Co-PIs: Glenberg & Glenberg-Johnson) NSF, DRK-12. (sr. researcher); Comprehensive School Reform in Rural K-8 Schools in the Southeast: Integrative Technologies for Quality Initiatives. Learning Systems Institute, Florida State University, (evaluation); Arts, Media & Engineering Collaborations – NSF IGERT Co-PI, earlier IGERT online Engineering Education Proj. (interactive design, evaluation/assessment) and JACMET continuing engineering education group (instructional design); Museums including the Desert Botanical Garden, The Phoenix Zoo, Tempe Historical Museum and Rancho Santa Ana Botanic Garden (evaluation, instructional design); United States Air Force Academy - Colorado Springs (tools for software evaluation)**;** K-12 Schools - Tempe Unified High School, and Murphy Elementary, School Districts; Texas Assoc. of School Boards (instructional design , assessment, evaluation, online learning, faculty development)
2. *Editor*: *Journal of Applied Instructional Design* and *Encyclopedia of Educational Technology*
3. *Editorial board member, consulting editor & reviewer*: Ed. Board for 2 journals: *Educational Technology Research & Development* and *Quarterly Review of Distance Education*; consulting editor and reviewer for other journals and research societies.
4. *Teaching Fellow*: Member of the 12-member inaugural "class" of the Provost's Teaching Fellows (2015-present). Responsible for developing new faculty training for ASU, and for mentoring three new faculty members.

**Everett L. Shock**

**Professional Preparation:**

| | | | |
|---|---|---|---|
| UC Santa Cruz | Santa Cruz, CA | Earth Sciences | B.S. 1978 |
| UC Berkeley | Berkeley, CA | Geology | Ph.D. 1987 |

**Appointments:**

Co-director, Environmental Life Sciences Graduate Program, Arizona State University (2013-2017).

Professor, School of Earth & Space Exploration and School of Molecular Sciences, Arizona State University (2002-present).

Director, W.M. Keck Foundation Laboratory for Environmental Biogeochemistry, Arizona State University (since 2002-present).

Director, Environmental Studies Program, Washington University, St. Louis, MO, USA (1993-2001).

Professor, Associate Professor, and Assistant Professor, Department of Earth and Planetary Sciences, Washington University, St. Louis, MO, USA: (1987-2002).

Research Assistant, U.C. Berkeley: theoretical research in high-pressure/temperature inorganic and organic aqueous solution chemistry, chemical interaction of minerals and organic compounds with aqueous solutions in geochemical processes (six years).

**Products:**

*Five Products Most Closely Related*

Amenabar MJ, **Shock EL**, Roden EE, Peters JW, Boyd ES (2017) Microbial substrate preference dictated by energy demand rather than supply. *Nature Geoscience* doi:10. 1038/ngeo2978.

Canovas PC III, **Shock EL** (2016) Geobiochemistry of metabolism: Standard state thermodynamic properties of the citric acid cycle. *Geochim. Cosmochim. Acta* **195**, 293-322.

Colman DR, Poudel S, Hamilton TL, Havig JR, Selensky MJ, **Shock EL**, Boyd ES (2017) Oxygen and the evolution of thermoacidophiles. *ISME Journal* (in press).

Colman DR, Feyhl-Buska J, Robinson KJ, Fecteau KM, Xu H, **Shock EL**, Boyd ES (2016) Ecological differentiation in planktonic and sediment-associated chemotrophic microbial populations in Yellowstone hot springs. *FEMS Microbiology Ecology* **92**, doi: 10.1093/femsec/fiw137.

**Shock EL**, Boyd ES (2015) Principles of geobiochemistry. *Elements* **11**, 395-401. doi:10.2113/gselements.11.6.395.

*Five Additional Products*

Boyd ES, Fecteau K, Havig JR, **Shock EL** Peters JW (2012) Modeling the habitat range of phototrophic microorganisms in Yellowstone National Park: Toward the development of a comprehensive fitness landscape. *Frontiers in Microbiological Chemistry* **3**, 221. doi:10.3389/fmicb.2012.00221.

Cox A, **Shock E,** Havig J (2011) The transition to microbial photosynthesis in hot spring ecosystems. *Chemical Geology* 280, 344-351. doi:10.1016/j.chemgeo.2010.11.022

Dick JM, **Shock EL** (2013) A metastable equilibrium model for the relative abundances of microbial phyla in a hot spring. *PLoS ONE* **8**, e72395. doi:10.1371/journal.pone. 0072395.

Schubotz F, Hays L, Meyer-Dombard DR, Gillespie A, **Shock EL**, Summons, R.E. (2015) Stable isotope labeling confirms heterotrophy is a major metabolic pathway in streamer biofilm communities from alkaline hot springs. *Frontiers in Microbiology* **6**, 42.

doi:10.3389/fmicb.2015.00042.

Swingley WD, Meyer-Dombard DR, Alsop EB, Falenski HD, Havig JR, **Shock EL,** Raymond J (2012) Coordinating environmental genomics and geochemistry reveals metabolic transitions in a hot spring ecosystem. *PLoS ONE* **7**, e38108. doi:10.1371/journal.pone.0038108.

**Synergistic Activities:**

- Development of thermodynamic databases for aqueous organic and inorganic species that are freely distributed over the internet, and used around the world.
- Application of High-Resolution Inductively-Coupled Plasma Mass Spectrometry to trace element studies of natural and human-impacted water resources, hydrothermal fluids, petroleum, and soils.
- Renewal of hydrothermal experimentation at ASU.
- Field research on hydrothermal ecosystems at Yellowstone National Park 1999, 2000, 2001, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017. Involving >150 scientists from Arizona State University, Washington University, University of New Mexico, Yale, Stanford, MIT, University of Colorado, Carleton College, University of Waikato, McMaster University, Lawrence Livermore National Lab, Woods Hole Oceanographic Institution, University of North Carolina, University of Nevada-Las Vegas, NASA-Ames, University of Illinois-Chicago, Montana State University, University of Oslo, Universidad Nacional Autónoma de México, China University of Geosciences – Wuhan, University of the Philippines, ETH-Zurich, Northwestern University, Montana Tech, UCLA, University of Wyoming, and Johns Hopkins.
- Member of NASA's Europa Clipper Mission via MASPEX-Europa since 2015.

**César I. Torres**

**Professional Preparation:**

| | | | |
|---|---|---|---|
| University of Puerto Rico | Mayagüez, PR | Chemical Engineering | B.S., 2002 |
| Northwestern University | Evanston, IL | Civil and Environmental Engineering | M.S., 2005 |
| Arizona State University | Tempe, AZ | Civil and Environmental Engineering | Ph.D., 2009 |

**Appointments:**

2016-Present Associate Professor, Chemical Engineering, School of Engineering for Matter, Transport, and Energy, Arizona State University, Tempe, AZ

2010-2016 Assistant Professor, Chemical Engineering, School of Engineering for Matter, Transport, and Energy, Arizona State University, Tempe, AZ

2009-2010 Postdoctoral Researcher, Center for Environmental Biotechnology, Arizona State University; Tempe AZ

2000-2001 Engineer, Co-op, Merck Sharp & Dohme; Barceloneta, PR

**Products:**

Ki D, Popat SC, Rittmann BE, Torres CI. 2017. $H_2O_2$ production in microbial electrochemical cells fed with primary sludge. *Environmental Science & Technology 51*, 6139-6145.

Popat SC, Torres CI. 2016. Critical transport rates that limit the performance of microbial electrochemistry technologies. *Bioresource Technology* 215: 265–273.

Ki D, Popat SC, Torres CI. 2016. Reduced overpotentials in microbial electrolysis cells through improved design, operation, and electrochemical characterization. *Chemical Engineering Journal* 287: 181-188.

Lusk BG, Khan QF, Parameswaran P, Hameed A, Ali N, Rittmann BE, Torres CI. 2015. Characterization of electrical current-generation capabilities from thermophilic bacterium *Thermoanaerobacter pseudethanolicus* using xylose, glucose, cellobiose, or acetate with fixed anode potentials. *Environmental Science & Technology* 49 (24): 14725-14731.

Yoho RA, Popat SC, Rago L., Guisasola A, Torres CI. 2015. Anode biofilms of *Geoalkalibacter ferrihydriticus* exhibit electrochemical signatures of multiple electron transport pathways. *Langmuir 31*: 12552-12559.

Yoho RA, Popat SC, Torres CI. 2014. Dynamic potential-dependent electron transport pathway shifts in anode biofilms of *Geobacter sulfurreducens*. *ChemSusChem 7:* 3413-3419.

Popat SC, Ki D, Young MN, Rittmann BE, Torres CI. 2014. Buffer pKa and transport govern concentration overpotential in electrochemical oxygen reduction at neutral pH. *ChemElectroChem*, 1*,* 1909-1915.

D Ki, P Parameswaran, SC Popat, BE Rittmann, CI Torres. 2013. Effects of pre-fermentation and pulsed-electric-field treatment of primary sludge in microbial electrochemical cells. *Bioresource technology* 195, 83-88

Badalamenti JP, Krajmalnik-Brown R, Torres CI. 2013. Generation of High Current Densities by Pure Cultures of Anode-Respiring *Geoalkalibacter* spp. under Alkaline and Saline Conditions in Microbial Electrochemical Cells. *mBio* 4(3): e00144-13.

Parameswaran P, Bry T, Popat SC, Lusk B, Rittmann BE, Torres CI. 2013. Kinetic, electrochemical and microscopic characterization of the thermophilic anode respiring bacterium, *Thermincola ferriacetica*. *Environmental Science & Technology* 47(9): 4934–4940.

**Synergistic Activities:**

Member of editorial board for Applied and Environmental Microbiology. Technical reviewer for over 15 peer-reviewed journals, including: ACS Catalysis, Bioresource Technology, Biotechnology and Bioengineering, Chemical Engineering Journal, Energy and Environmental Science, Environmental Science & Technology, Nature Communications, Science, and Water Research.

Chair of the Membership Committee, co-founder, and conference organizer (2015) of the International Society for Microbial Electrochemical Technologies (ISMET).

Session organizer for the "Microbial Fuel Cell" session at the Association for Environmental Engineer and Science Professors (AEESP) Conference (2012) and scientific committee member for the 4$^{rd}$ International Microbial Fuel Cell Conference (2013).

Scientific Advisor to Arbsource LCC., an ASU-Venture Catalyst startup company focused on microbial electrochemical technologies (http://arbsource.us/)

Advisor to AIChE's Chem-E-Car team, 1st place winners of the regional West Division AIChE competition (2012).

## Leon A. van Paassen

**Professional Preparation:**

| | | |
|---|---|---|
| Delft University of Technology | Delft, Netherlands, Applied Earth Sciences | MSc 2002 |
| Delft University of Technology | Delft, Netherlands, Applied Sciences | PhD 2009 |

**Appointments:**

Center for Bio-mediated and Bio-inspired Geotechnics, Arizona State University
Senior Investigator, January 2017 - present

Department of Civil and Environmental Engineering, Arizona State University
Associate Professor, January 2017 - present

Department of Civil Engineering and GeoSciences, Delft University of Technology, The Netherlands, Assistant Professor, September 2009 – December 2016

Deltares, Delft, The Netherlands, Consultant Geo-Engineering, Researcher SmartSoils, January 2008 - September 2009.

GeoDelft, Delft, The Netherlands, Geotechnical Consultant, Department of Foundations and Underground Constructions. September 2002 – December 2007

IFCO Foundation Expertise BV, Waddinxveen, The Netherlands, Junior Geotechnical Engineer, January 2000 – April 2002

**Publications:**

### Most Closely Related Publications

Pham, VP, Nakano A, Van der Star WRL, Heimovaara TJ, & Van Paassen LA (2017) Applying MICP by denitrification in soils: a process analysis, Environmental Geotechnics, Published Online: November 03, 2016, http://dx.doi.org/10.1680/jenge.15.00078

van Wijngaarden, W.K., van Paassen, L.A., Vermolen, F.J., van Meurs, G.A.M., Vuik, C. (2016) Simulation of Front Instabilities in Density-Driven Flow, Using a Reactive Transport Model for Biogrout Combined with a Randomly Distributed Permeability Field, Transport in Porous Media, 112 (2), pp. 333-359.

van Wijngaarden, W.K., van Paassen, L.A., Vermolen, F.J., van Meurs, G.A.M., Vuik, C. (2016) A Reactive Transport Model for Biogrout Compared to Experimental Data, Transport in 8)

Van Paassen, LA, Ghose, R, Van der Linden, TJM, Van der Star, WRL and Van Loosdrecht, MCM, 2010. "Quantifying bio-mediated ground improvement by ureolysis: a large scale biogrout experiment", ASCE Journal of Geotechnical and Geoenvironmental Engineering, 136(12): 1721–1728

Van Paassen, L.A., Daza, C.M., Staal, M., Sorokin, D.Y., Van der Zon, W. and Van Loosdrecht, M.C.M. 2010. Potential soil reinforcement by microbial denitrification, Ecological Engineering 36(2): 168-175.

Van Paassen, LA, (2011). Bio-mediated ground improvement: From laboratory experiment to pilot applications, Geofrontiers, 2011, Advances in Geotechnical Engineering, Eds Jie Han Geotechnical Special Publication, (211 GSP), pp. 4099-4108.

Van der Star, WRL, van Wijngaarden-van Rossum, WK, van Paassen, LA, van Baalen, LR, van Zwieten, G, (2011), Stabilization of gravel deposits using microorganisms, Proceedings of the 15th European Conference on Soil Mechanics and Geotechnical Engineering, A. Anagnostopoulos et al. (Eds.), 12-17 Sep 2011, Athens, Greece, pp 85-90.

Harkes, M.P., Van Paassen L.A., Booster J.L., Whiffin, V.S. and Van Loosdrecht, M.C.M. 2010. Fixation and distribution of bacterial activity in sand to induce carbonate precipitation for ground reinforcement, Ecological Engineering 36(2):112-117.
Whiffin, VS, Van Paassen, LA, Harkes, MP 2007. Microbial Carbonate Precipitation as a Soil Improvement Technique. Geomicrobiology Journal. 24 (5): 417-423.Porous Media, 111 (3), pp. 627-648.

**Other Signification Publications:**

Tollenaar, R.N., van Paassen, L.A., Jommi, C. (2017) Experimental evaluation of the effects of pull rate on the tensile behavior of a clay, Applied Clay Science, 144, pp. 131-140.
Van Paassen LA & Kulshreshta, Y (2017) Biopolymers: Cement Replacement, in Cultivated Building Materials, Industrialized Natural Resources for Architecture and Construction, Eds Hebel, DE & Heisel F.
Van Paassen, LA, Vardon, PJ, Mulder, A, Van de Weg, G & Jeffrey, P (2013) 'Investigating the susceptibility of iron ore to liquefaction' Proceedings of the 5th Biot conference on poromechanics, 10-12 June 2013, Vienna
Van Paassen, LA, Harkes, MP, Van Zwieten, GA, Van der Zon, WH, Van der Star, WRL & Van Loosdrecht, MCM, 2009, Scale up of BioGrout: a biological ground reinforcement method, Proceedings of the 17th international conference on soil mechanics and geotechnical engineering, 5-9 october 2009, Alexandria, Egypt
Van Paassen, LA, Pieron, M, Mulder, A, Van der Linden TJM, Van Loosdrecht, MCM & Ngan-Tillard, DJM, 2009, Strength and deformation of biologically cemented sandstone, Proceedings of the ISRM Regional conference EUROCK 2009 – Rock engineering in difficult ground conditions – Soft rocks and karst, 29-31 October 2009, Dubrovnik, Croatia
Van der Star, W.R.L., Taher, E., Harkes, M.P., Van Loosdrecht, M.C.M. & Van Paassen, L.A. (2009). Use of waste streams and microbes for in situ transformation of sand into sandstone. International Symposium on Ground Improvement Technologies and Case Histories (ISGI2009), Singapore.
Van Paassen, L.A. 2009. Microbes turning sand into sandstone, using waste as cement. Presented at 4th International Young Geotechnical Engineering Conference Alexandria, Egypt.

**Michelle R. Walker**

## Professional Preparation:

| | | | |
|---|---|---|---|
| Arizona State University | Tempe, Arizona | Graphic Information Technology | B.S. expected 2018 |

## Appointments:

Arizona State University (2000-present):

Project Coordinator, Center for Bio-mediated and Bio-inspired Geotechnics Engineering Research Center (2016-present); Business Operations Specialist, Quantum Energy and Sustainable Solar Technologies Engineering Research Center (2014-2016); Program Coordinator, Center for Nanotechnology in Society (2011-2014); Administrative Associate, Center for Nanotechnology in Society (2007-2011); Administrative Assistant, ASU Alumni Association (2006-2007); Office Specialist, ASU Alumni Association (2000-2006)

## Related Publications:

N/A

## Other Significant Publications:

N/A

## Synergistic Activities:

1. Developed and executed fiscal and records management plans, including managing budgets, projects, events, information systems, and personnel.
2. Developed and managed databases, web site, social media, and spreadsheets; produced interim, annual, and final reports for sponsors.
3. Designed and disseminated fliers, brochures, newsletters, collateral materials, etc.
4. Planned and executed successful meeting and events, managing everything from site selection to on-site management of activities.
5. Provided outstanding service to all clients and customers, including faculty, students, members, vendors, etc.

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**Brad D. Weldon**

**Professional Preparation:**

| | | | |
|---|---|---|---|
| New Mexico State University | Civil Engineering | Bachelor of Science | 2001 |
| University of Notre Dame | Civil Engineering | Master of Science | 2006 |
| University of Notre Dame | Civil Engineering | Doctor of Philosophy | 2010 |

**Appointments:**

| | |
|---|---|
| 2016 – present | Associate Professor of Civil Engineering, New Mexico State University |
| 2008 – 2016 | Assistant Professor of Civil Engineering, New Mexico State University |

**Products:**

1. McGinnis, M. J., Davis, M. De La Rosa, A., Weldon, B., Kurama, Y. C. (2017). "Quantified Sustainability of Recycled Concrete Aggregates," *Magazine of Concrete Research* – DOI 10.1680/jmacr.16.00338.
2. McGinnis, M. J., Davis, M., de la Rosa, A., Weldon, B. D., Kurama, Y.C. (2017). "Strength and Stiffness of Recycled Concrete Aggregate Concrete," *Building and Construction Materials*, 154, pp. 258-269.
3. Manglekar, H.C., Visage, E.T., Ray, T., Weldon, B.D., "Experimental and Analytical Investigations of a Locally Developed Ultrahigh-Performance Fiber-Reinforced Concrete." Journal of Materials in Civil Engineering. (accepted)
4. Giesler, A.J., Applegate, S., Weldon, B. D., "Implementing a non-proprietary ultra high performance concrete into a precast plant." Precast/Prestressed Concrete Institute Journal. Nov.-Dec. 2016.
5. Manning, M., Weldon, B. D., McGinnis, M., Jauregui, D. V., Newtson, C. M. (2016). Behavior Comparison of Prestressed Channel Girders from High Performance Concrete and Locally Developed Ultra-High Performance Concrete. Transportation Research Record/TRB, 2577, 60-68. http://trrjournalonline.trb.org/doi/pdf/10.3141/2577-08. **Best Paper Award Concrete Materials Section, 2016**
6. Marquez, J., Jauregui, D.V., Weldon, B.D., Newtson, C.M., "A simplified procedure to obtain LRFD preliminary design charts for simple-span prestressed concrete bridge girders." Practice Periodical on Structural Design and Construction, American Society of Civil Engineers. Vol. 21, No. 1, 2016, p. 1-6: 06015003.
7. Aguilar, C. V., Jauregui, D. V., Newtson, C. M., Weldon, B. D., Cortez, T. M. Load Rating a Prestressed Concrete Double-Tee Beam Bridge without Plans by Proof Testing. Transportation Research Record: Journal of the Transportation Research Board, No. 2522, 2015, pp. 90-99. (DOI 10.3141/2522-09)
8. Wosick, E., Gerbremariam, T., Al-Aqtash, U., Weldon, B., and Bandini, B. "Strength characteristics of typical adobe material in southwestern United States. *9th International Masonry Conference*, Guimaraes, Portugal, July 7-9, 2014.
9. McGinnis, M., Gangone, M., and Weldon, B. Lateral load behavior of clay masonry façade with advanced wood framing. *9th International Masonry Conference*, Guimaraes, Portugal, July 7-9, 2014.
10. Muro-Villanueva J., Newtson, C., Weldon, B., Jauregui, D., and Allena, S., Freezing and thawing durability of ultra high strength concrete. *Journal of Civil Engineering and Architecture*, David Publishing Company, Vol. 7, No. 8 (Serial No. 69), August 2013, pp. 907-915.
11. Weldon, B. and Kurama, Y., Analytical modeling and design validation of post-tensioned

precast concrete beams for seismic regions. *Journal of Structural Engineering,* American Society of Civil Engineers, Vol. 138, No. 2, February 2012.

12. Weldon, B. and Kurama, Y., Experimental evaluation of post-tensioned precast concrete coupling beams. *Journal of Structural Engineering,* American Society of Civil Engineers, Vol. 136, No. 9, September 2010, pp. 1066-1077.
13. Weldon, B. and Kurama, Y., Nonlinear behavior of precast concrete coupling beams under lateral loads. *Journal of Structural Engineering,* American Society of Civil Engineers, Vol. 133, No. 11, November 2007, pp. 1571-1581.
14. Taylor, C.W., Weldon, B.D., Jauregui, D.V., and Newtson, C.M., Case studies using ultrahigh-performance concrete for prestressed bridge design. *Practice Periodical on Structural Design and Construction*, American Society of Civil Engineers, Vol. 18, No. 4, November 2013, pp. 261-267.

**Synergistic Activities:**

1. Undergraduate Research Students Advised: *New Mexico Alliance for Minority Participation:* Pascual Camacho (2016 – 2017); Lorenzo Martinez (2015-2016); Adam Sanchez (2012-2016); Jessica Salazar (2013-2014); Daniel Delgado (2013); Lucas Guaderrama (2011-2013); Theresa Aragon (2010-2012) – *Other Undergraduate Students advised:* Jordan Daniels (2017 – present); Tyus Bowman (2017 – present); Joshua Flores (2016 – 2017); Jeffrey Kellner (2014 – 2016) Daniel Diaz (2014-2016); Rafael Garcia (2013-2016); Heather Pedersen (2014-2015); Casey McElroy (2013-2014); Vyacheslav Prakhov (2013-2014); Erin Wosick (2012-2014); Mark Manning (2013); Wry Hurt (2013); Bo Simpson (2012-2013); Andrew Giesler (2011-2012).

2. Professional Outreach: Bridge Inspection Training (lecturer); Quality Concrete School (lecturer); NM Section of the American Society of Civil Engineers – Chair Structures and Engineering Mechanics; Southern Branch of NM Section of ASCE – Secretary/Treasurer.

3. Recruitment of Students: NM Pre-Freshman Engineering Program, "Seismic Design Challenge: Bio-Inspired Adobe Walls"; Ambassador Liaison for the Department of Civil Engineering (recruiting program); Developed Departmental Facebook Page; Presented "What is Civil Engineering?" for DreamMakers Summer Program through the Indian Resource Development Program.

4. Faculty Advisor: Earthquake Engineering Research Institute at New Mexico State University (EERI@NMSU) (2012-present); Chi Epsilon Honor Society (2012-present); Civil Engineering Graduate Student Organization (2011-present); Daniel B. Jett Student Chapter of the American Society of Civil Engineering (2010-2013).

**Daniel Wayne Wilson**

**Professional Preparation:**

| | | | |
|---|---|---|---|
| University of California, Davis | Davis, California | Civil Engineering | B.S., 1992 |
| University of California, Davis | Davis, California | Geotechnical Engineering | M.S., 1994 |
| University of California, Davis | Davis, California | Geotechnical Engineering | Ph.D., 1998 |

**Appointments:**

2010-present Associate Director, Center for Geotechnical Modeling, & Academic Administrator, Department of Civil and Environmental Engineering, University of California, Davis

1997-2010 Manager, Center for Geotechnical Modeling, & Associate Project Scientist, Assistant Research Engineer/Academic Coordinator, Department of Civil and Environmental Engineering, University of California, Davis

1992-1997 Post-Graduate Research Engineer, Civil and Environmental Engineering, University of California, Davis

**Products:**

***Five publications most closely related to the proposed project –***

Khosravi, M., Boulanger, R.W., **Wilson, D.W.**, Olgun, C.G., Tamura, S., and Wang, Y. (2017). Dynamic centrifuge tests of structures with shallow foundations on soft clay reinforced by soil-cement grids. Soils and Foundations, https://doi.org/10.1016/j.sandf.2017.06.002.

Dashti S, Bray J, Pestana J, Riemer M, **Wilson D**. (2010). Centrifuge Testing to Evaluate and Mitigate Liquefaction-Induced Building Settlement Mechanisms. Journal of Geotechnical and Geoenvironmental Engineering, 136(7): 918-929.

Montoya B, Gerhard R, DeJong J, Weil M, Martinez B, **Wilson D**, Pedersen L. (2012). Fabrication, Operation, and Health Monitoring of Bender Elements for Aggressive Environments. ASTM Geotechnical Testing Journal, 35(5): Paper ID GTJ103300.

**Wilson DW**, Allmond JD. (2014). Advancing geotechnical earthquake engineering knowledge through centrifuge modeling. Physical Modelling in Geotechnics, pp. 125-137.

Stringer ME, Allmond JD, Proto CJ, **Wilson DW**, Kutter BL. (2014). Evaluating the response of new pore pressure transducers for use in dynamic centrifuge tests. Physical Modelling in Geotechnics, pp. 345-351.

***Five additional significant publications –***

**Wilson DW**, Boulanger RW, Kutter BL. (2000). Seismic lateral resistance of liquefying sand. Journal of Geotechnical and Geoenvironmental Engineering, 126(10): 898-906.

Elgamal A, Yang Z, Lai T, Kutter BL, **Wilson DW**. (2005). Dynamic Response of Saturated Dense Sand in Laminated Centrifuge Container. Journal of Geotechnical and Geoenvironmental Engineering, 131(5): 598-609.

Bian Y, Hutchinson TC, **Wilson D**, Laefer D, Brandenberg S. (2008). Experimental Investigation of Grouted Helical Piers for Use in Foundation Rehabilitation. Journal of Geotechnical and Geoenvironmental Engineering, 134(9): 1280-1289.

Brandenberg S, **Wilson D**, Rashid M. (2010). A Weighted Residual Numerical Differentiation Algorithm Applied to Experimental Bending Moment Data. Journal of Geotechnical and Geoenvironmental Engineering, 136(6): 854-863.

Brandenberg SJ, Zhao M, Boulanger RW, **Wilson DW**. (2013). p-y Plasticity Model for Nonlinear Dynamic Analysis of Piles in Liquefiable Soil. Journal of Geotechnical and Geoenvironmental Engineering, 139(8): 1262-1274.

**Synergistic Activities:**

- Member - American Society of Civil Engineers (ASCE), International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE), United States Universities Council on Geotechnical Education and Research (USUCGER), United States Society on Dams (USSD)
- U.S. Member of ISSMGE Technical Committee 104 – Physical Modeling in Geotechnics (2010-present)
- The Center for Geotechnical Modeling at UC Davis operates geotechnical centrifuges for the NSF Natural Hazards Engineering Research Infrastructure project. This facility is a national resource that has been shared by faculty from Arizona State University, Drexel University; University of Texas, Austin; Oregon State; Virginia Tech; UC Berkeley; UC Irvine; UCLA; UCSD; University of Oklahoma, Tokyo Institute of Technology; and others.
- The Center for Geotechnical Modeling maintains a web-based archive of more than 20 years of model test data that has been accessed by many researchers from around the world. The archives include complete sets of data and metadata to enable researchers to use results of model tests at UC Davis. This data is freely available online to interested users.

**Jeannette Yen**

## Professional Preparation:

| Institution | Degree | Major/Area | Year |
|---|---|---|---|
| Bryn Mawr College | B.A. | Biology | 1975 |
| University of Washington | M.S. | Oceanography | 1977 |
| University of Washington | Ph.D. | Oceanography | 1982 |

## Appointments:

| | |
|---|---|
| 2005-present | Director, Center for Biologically Inspired Design |
| 2002-present | Professor, School of Biology, Georgia Institute of Technology |
| 2000-2002 | Associate Professor, School of Biology, Georgia Tech |
| 1994-2000 | Associate Professor, Marine Sciences Research Center, SUNY-Stony Brook |
| 1989-1994 | Assistant Professor, Marine Sciences Research Center, SUNY-Stony Brook |
| 1983-1989 | Research scientist, Hawaii Inst. of Geophysics, Hawaii Inst. of Marine Biology |

## Products:

*5 relevant to this proposal*

1. Goel, AK, G. Zhang, B. Wiltgen, Y. Zhang, S. Vattam, and J. Yen. 2015. On the benefits of digital libraries of case studies of analogical design: Documentation, access, analysis, and learning. Artificial Intelligence for Engineering Design, Analysis and Manufacturing 29: 1–13.
2. Sharif, Shani, T. Russell Gentry, Jeannette Yen and Joseph N. Goodman. 2013. Transformative Solar Panels: A Multidisciplinary Approach. International Journal of Architectural Computing 11:227-245.
3. Yen, Jeannette, Michael Helms, Ashok Goel, Craig Tovey, and Marc Weissburg. 2013. Adaptive Evolution of Teaching Practices in Biologically Inspired Design. Ch. 7. In: *Biologically Inspired Design: Computational Methods and Tools*. Editors: Ashok Goel, Dan McAdams & Robert Stone. Springer.
4. Yen, J., M. Weissburg, M. Helms, A. Goel. 2011. Biologically Inspired Design: A tool for interdisciplinary education. **Ch. 10**, In: *Biomimetics. Nature Based Innovation*, edited by Y. Bar-Cohen, Taylor and Francis.
5. Yen, J., M. Helms, S. Vattam, A. Goel. 2010. Evaluating biological systems for their potential in engineering design. The 3rd International Conference of Bionic Engineering. Advances in Natural Science Vol. 3, No. 2, 2010, pp. 1-14.

*Additional relevant products*

1. Weissburg, M., C. Tovey, J. Yen. 2010. Enhancing Innovation through Biologically Inspired Design. The 3rd International Conference of Bionic Engineering. Advances in Natural Science Vol. 3, No. 2, 2010

2. Yen, J. 2010. Marine Dynamics. **Ch. 1.** In: *Bulletproof feathers. How science uses nature's secrets to design cutting-edge technology*. Robert Allen, editor. The University of Chicago Press.
3. Wilson, Jamal O., David Rosen, Brent A. Nelson, Jeannette Yen. 2010. The effects of biological examples in idea generation. *Design Studies* 31(2): 169-186.
4. Nelson, B., J. Yen, J.O. Wilson, and D. Rosen. 2009. Refined metrics for measuring ideation effectiveness. Design Studies 30: 737-743.
5. Yen, J. & M.J. Weissburg. 2007. Perspectives on biologically inspired design: introduction to the collected contributions. Bioinsp. Biomim. 2: DOI 10.1088/1748-3190/2/4/E01

**Synergistic Activities:**

**1. Interdisciplinary research**

*A novel apparatus for simulating oceanic turbulence*, NSF: Ocean Technology and Interdisciplinary Coordination program, 2002.

*Fluid mechanical and chemical cues in Thin Layers: Role in organizing zooplankton aggregations*. Office of Naval Research. 2003

*Dynamic similarity or size proportionality? Adaptations of a polar copepod*. NSF, Polar Programs. 2003

*Collaborative Research. Biologically-Generated Flow by Plankton: Numerical Simulations and Experiments*, NSF: Division of Chemical, Bioengineering, Environmental, and Transport Systems Program: Fluid Dynamics and Hydraulics, 2006.

**2. Interdisciplinary research and education in biologically inspired design**

*Workshop for Biologically Inspired Design*, NSF: Division of Civil, Mechanical, and Manufacturing Innovation, Program: Engineering Design, 2006.

*Biologically Inspired Design: A tool for enhancing engineering education*. Post-doctoral Engineering Education Researcher (AGEP PEER). Center for the Advancement of Scholarship on Engineering Education, National Academy of Engineering. 2006.

*Center for Biologically Inspired Design*, FOCUSED RESEARCH PROGRAM-Georgia Institute of Technology. May 2005/2006.

*Biologically !nspired Design: A novel interdisciplinary biology-engineering curriculum*. NSF, Div. Undergrad. Edu, Yen, Rosen, Weissburg Goel, Newstetter. Course Curriculum and Laboratory Improvement. Phase I: 2008. Phase 2: 2010.

**3. Participation in interdisciplinary education and organizational efforts:**

Director, *Center for Biologically Inspired Design*, Georgia Institute of Technology, 2005, started w/ internal seed money in 2005.

Joined Faculty, *School of Physics*, Georgia Tech, 2004.

Chaired session at July 2003 conference: *The Next Generation of in situ Biological and Chemical Sensors in the Ocean*. Woods Hole Institute of Oceanography, MA.

**4. Participation in education and service:**

Co-editor of special issue of *Bioinspiration & Biomimetics*. 2007.

Selected as one of Atlanta's most innovative minds, *Creative Loafing*, spring 2008.

Co-editor *Bioinspiration & Biomimetics*. Appointed: 2009.

## Claudia E. Zapata

**Professional Preparation:**

| | | |
|---|---|---|
| Universidad Nacional, Manizales, Colombia | Civil Engineering | B.Sc.E, 1988 |
| Arizona State University, Tempe, AZ | Geotechnical Engineering | M.S.E., 1996 |
| Arizona State University, Tempe, AZ | Geo-Environmental Engineering | Ph.D, 1999 |

**Appointments:**

| | |
|---|---|
| 2015-present | Deputy Director, Center for Bio-mediated and Bio-inspired Geotechnics, ASU |
| 2014-present | Associate Professor, Honors Disciplinary Faculty, School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ |
| 2006-2014 | Assistant Professor, Geotechnical Eng., Dept. of Civil & Env. Eng., ASU |
| 1999-2006 | Faculty Research Associate, Arizona State University |
| 1996-1999 | Research and Teaching Assistant, Arizona State University |
| 1994-1995 | Consultant Engineer, Tomas Shuk Engineers, Inc., Bogotá, Colombia |
| 1990-1992 | Research Assistant, Arizona State University |
| 1988-1989 | Consultant Engineer, Aquaterra, Engineering Consultants, Ltd., Manizales, Colombia |
| 1987-1988 | Engineering Assistant, Caldas Hydroelectric Power Station, Manizales, Colombia |
| 1986-1988 | Engineering Assistant, Colombian Geological Survey, Manizales, Colombia |

**Publications Most Closely Related to Proposed Project:**

Larson, J., Savenye, W., Zapata, C.E. and Kavazanjian, E. (2017). Implementation of an Introductory Module on Biogeotechnics in a Freshman Engineering Course. In Proceedings of the 2017 American Society of Engineering Education Annual Conf. and Exposition, Columbus, OH, June 25-28, 2017

Dalal, M., Larson, J., Zapata, C. Savenye, W., Hamdan, N. and Kavazanjian, E. (2017). An Interdisciplinary Approach to Developing an Undergraduate Module on Biogeotechnical Engineering. In Proc. of Soc. for Information Tech. & Teacher Education. Int. Conf. 2017. Chesapeake, VA: Association for the Advancement of Computing in Education (AACE). pp. 2074-2079.

Elwood, K.*, Savenye, W., Jordan, M.E., Larson, J., and Zapata, C.E. (2016). Design Thinking: A New Construct for Educators. Proc. of the Assoc. for Educational Communications and Tech., Las Vegas, NV, Vol. 1, 43-52.

Ornelas, A., Houston, S., Savenye, W., Zapata, C.E., Ramirez, E. and Corral, A. (2015). Disciplinary Diversity in the Development of Geotechnical Engineering Undergraduate Education Materials. 2015 International Foundations Congress and Equipment Expo (IFCEE), pp. 2161-2168.

Ornelas, A., Sadauskas, J., Houston, S., Savenye, W.C., Ramirez, E. and Zapata, C.E. (2013). An Engineering and Educational Technology Team Approach to Introducing New Unsaturated Soils Mechanics Material into Introductory Undergraduate Geotechnical Engineering Courses. Proceedings of the 120th American Society for Engineering Education (ASEE) annual conference. June 2013, Atlanta, GA. pp. 1-24.

**Other Significant Publications:**

Rosenbalm, D. and Zapata, C.E. (2016). Effect of Wetting and Drying Cycles on the Behavior of Expansive Soils". Journal of Materials in Civil Engineering, ASCE. Vol. 29, No. 1, pp. 1-9.

Cary, C. and Zapata, C.E. (2016). Pore Water Pressure Response of a Soil Subjected to Dynamic Loading under Saturated and Unsaturated Conditions. International Journal of Geomechanics, 10.1061/(ASCE)GM.1943-5622.0000642, D4016004, pp. 1-9.

Cary, C.E. and Zapata, C.E. (2014). Unsaturated Soil Modeling for Airfield Pavement Design. Journal of Transportation Engineering, ASCE. Vol. 140 (1), pp. 50-60.

Zapata, C.E. (2010). Research Results Digest 347: A National Catalog of Subgrade Soil-Water Characteristic Curves and Selected Soil Properties for Use with the MEPDG. National Cooperative Highway Research Program, Transportation Research Board, of the National Academies. ISSN 0077-5614. ISBN: 978-0-309-09929-5. Library of Congress Control Number 2008924251. pp. 62.

Miller, G.A., Zapata, C.E., Houston, S.L. & Fredlund, D.G. (eds). (2006). *Unsaturated Soils. Geotechnical Special Publication No. 147*. The Geo-Institute of the ASCE. Proceedings of the Fourth International Conference on Unsaturated Soils. April 2-6, Carefree, AZ.

**Synergistic Activities:**

a) Outreach and Impact K-12 Education. Dr. Zapata has contributed to broadening the participation of K-12 populations in the learning process, especially for CBBG.

b) Service to the Scientific and Engineering Community. Dr. Zapata has contributed to the improvement of the state of the practice by serving as chair of the TRB Engineering Behavior of Unsaturated Soils Committee; and as an official reviewer for numerous journals. She has participated as a member of several technical committees, is a member of the Editorial Board of the Int. J. of Roads and Airports, and has served as panelist for NSF. She has been an organizer for national /international meetings. She received the "Honors Disciplinary Faculty" title for her outstanding contributions and commitment of time from the ASU Barrett Honors College; and the Office of the Vice-President for Student Affairs at ASU award for "Leader, mentor, and a person who has contributed in a significant way to the success of ASU students." She received the honorific designation as Senior Sustainability Scientist at ASU for her "…achievements in sustainability-related research."

c) Broadening the Participation of Underrepresented Groups in Engineering. Dr. Zapata has participated with CBBG in activities aimed at broadening the participation of Native American students, students with disabilities, and LGBT population in STEM programs. Also, with ASU College of Engineering WISE (Women in Science and Engineering) Program as an instructor of activities designed to introduce minorities to engineering. She has been heavily involved with the Hispanic Research Center by mentoring or undergraduate female students, promoting inter-disciplinary work and attracting minority students into engineering graduate programs.

d) Contributions to the Development and Refinement of Computation Methodologies and Algorithms for Problem Solving. Dr. Zapata has been heavily involved in the generation of algorithms to represent unsaturated constitutive relationships and expansive potential as a function of material properties.

e) Development of Databases to Support Research and Education. Dr. Zapata has generated and published a database of unsaturated soil properties for more than 36,000 soils that has become the bases for several research studies at national and international levels and an important tool for pavement design and slabs-on-grade applications and practice.

**Katerina Ziotopoulou**

**Professional Preparation:**

| | | | | |
|---|---|---|---|---|
| National Tech University of Athens | Athens, Greece | Civil Engineering | B.S. | 2007 |
| University of California, Davis | Davis, CA | Civil Engineering | M.S. | 2010 |
| University of California, Davis | Davis, CA | Civil Engineering | Ph.D. | 2014 |

**Appointments:**

| | |
|---|---|
| 08/16 – present | Assistant Professor, CEE Department, University of California, Davis |
| 08/14 – 07/16 | Assistant Professor, CEE Department, Virginia Tech |
| 09/10 – 08/14 | Graduate Research Assistant, CEE Department, UC, Davis |
| 01/10 – 08/10 | Associate Researcher, National Technical University of Athens, Greece |
| 09/08 – 12/09 | Graduate Research Assistant, CEE Department, UC, Davis |

**Products:**


1. **Ziotopoulou, K.** (2017). "Seismic response of liquefiable sloping ground: Class A and C numerical predictions of centrifuge model responses." Soil Dynamics and Earthquake Engineering, dx.doi.org/10.1016/j.soildyn.2017.01.038
2. Manzari, M. T, El Ghoraiby, M., Kutter, B. L., Zeghal, M., Abdoun, T., Arduino, P., Armstrong, R. J., Beaty, M. H., Carey, T., Chen, Y., Ghofrani, A., Gutierrez, D., Goswami, N., Haigh, S. K., Hung, W-Y, Iai, S., Kokkali, P., Lee, C. J., Madabhushi, S. P. G., Mejia, L., Sharp, M., Tobita, T., Ueda, K., Zhou, Y., **Ziotopoulou, K.** (2016). "Liquefaction Experiment and Analysis Projects (LEAP): Summary of Observations from the Planning Phase." *Special issue of Soil Dynamics and Earthquake Engineering*, *Elsevier Publications* dx.doi.org/10.1016/j.soildyn.2017.05.015
3. **Ziotopoulou, K.**, and Boulanger, R. W. (2016). "Plasticity Modeling of Liquefaction Effects under Sloping Ground and Irregular Cyclic Loading Conditions" Soil Dynamics and Earthquake Engineering, 84, 269-283.
4. **Ziotopoulou, K.**, and Boulanger, R. W. (2013). "Numerical modeling issues in predicting post-liquefaction reconsolidation strains and settlements." Proc. 10th International Conference on Urban Geotechnical Engineering (CUEE), March 1-2, Tokyo, Japan.
5. Boulanger, R. W., and **Ziotopoulou, K.** (2013). "Formulation of a sand plasticity plane-strain model for earthquake engineering applications." Soil Dynamics and Earthquake Engineering, 53, 254-267.
6. **Ziotopoulou, K.**, Maharjan, M., Boulanger, R. W., Beauty, M. H., Armstrong, R. J., and Takahashi, A. (2014). "Constitutive modeling of liquefaction effects in sloping ground." *Proc. 10th U.S. National Conference on Earthquake Engineering*, July 21-25, Anchorage, AK.
7. **Ziotopoulou, K.**, and Boulanger, R. W. (2013). "Calibration and implementation of a sand plasticity plane-strain model for earthquake engineering applications." *Soil Dynamics and Earthquake Engineering*, 53, 268-280.
8. **Ziotopoulou, K.**, and Montgomery, J. (2017). "Numerical modeling of earthquake-induced liquefaction effects on shallow foundations." *Proc. 16th World Conference on Earthquake Engineering* (16WCEE), January 9-13, Santiago, Chile.
9. **Ziotopoulou, K.**, and Boulanger, R. W. (2015). "Validation protocols for constitutive modeling of liquefaction", *Proc. 6th International Conference on Earthquake Geotechnical Engineering*, November 1-4, Christchurch, New Zealand.

10. Ghanat, S., Kaklamanos, J., **Ziotopoulou, K.**, and Selvaraj, S. I. (2016). "A multi-institutional study of pre- and post-course knowledge surveys in undergraduate geotechnical engineering courses." Proc. 123rd Annual Conference and Exposition, June 26-29, New Orleans, LA.

**Synergistic Activities:**

***Research Areas:*** Geotechnical earthquake engineering, Constitutive modeling of soils (liquefiable sands, silts and biocemented materials), Liquefaction and its effects on structures and lifelines, Validation of and Numerical modeling of soil-structure systems, Laboratory testing of soils, Development of numerical tools, Systems engineering.

***Education Related Activities:*** UC Davis Engaged Learning Community Member; Graduate Program Committee Representative, Department of Civil and Environmental Engineering, UC Davis; Invited lecturer – ECI 3 Civil Infrastructure and Society, Undergraduate Curriculum Committee Center for Biomediated and Bioinspired Geotechnics; Translation of book on Soil Mechanics from English to Greek -- currently being used as the official textbook of the two undergraduate Soil Mechanics courses at the National Technical University of Athens, Greece.

***Honors and Awards**:* ASCE 2016 Outstanding Reviewer Recognition, Engaged Learning Community Award (UC Davis), Anonymous Thank You Letter (recognition program Virginia Tech), Teacher of the Week – Virginia Tech CIDER, W(H)YDOC Young Doctors in Geomechanics Fellow, ExCEEd (Excellence in Civil Engineering Education) ASCE Fellow, International Travel Supplemental Grant (ITSG) Award, Virginia Tech, Earthquake Engineering Research Institute Travel Award, Fugro West Graduate Fellowship, Idriss Award for Excellence in Geotechnical Engineering, International Fulbright Science and Technology Award

***Professional Service:*** Active member of AWIS, ASEE, and Young Members Committee (YMC) of the Earthquake Engineering Research Institute (EERI), Member (2014 – present) – ASCE Earthquake Engineering and Soil Dynamics Committee, Corresponding Member (2014 – present) – Technical Committee TC203 on Geotechnical Earthquake Engineering and Associated Problems, ISSMG; Conference Minisymposium Chair and Organizer – "MS 63 Recent Advances in Constitutive Modeling for Geotechnical Engineering", Engineering Mechanics Institute Conference, June 4-7, 2017, Conference Session Chair and Organizer – "Ground failure and liquefaction: Analysis and Effects on Structures and Lifelines", International Conference on Natural Hazards and Infrastructure, June 28-30, 2016. Reviewer for ASCE JGGE, CGJ, TRB, SDEE, Earthquake Spectra, Computers and Geotechnics, Geotechnique Letters, Earthquakes and Structures, Geofluids, Geomatics, Natural Hazards and Risk.

***Development of Innovative Numerical Tools:*** PM4Sand Version 3 is the product of my doctoral research (development, implementation, and calibration), and I continue supporting and utilizing it. It is a dynamic link library constitutive model compatible with the widely used commercial platforms FLAC 7.0 and FLAC 8.0 for performing earthquake engineering nonlinear deformation analyses to evaluate the effects of liquefaction. The software together with its manual and example files are freely available, and is being used by researchers and practitioners nationally and internationally. Most recently it was successfully used in the seismic evaluation of the levees in the deltas of The Netherlands. This tool has given me the opportunity to feed high-end and fundamentally robust research into practice, but also learn from all these industry and research partners from problems they are grappling with and come up with mechanistically sound solutions. Many of the features of PM4Sand have been and continue being implemented based on new projects and research needs.

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CBBG graduate student researcher at NMSU, Diego Garcia-Vera, is focused on creating natural fiber-reinforced earth bricks and foundation-wall connections to improve the performance of earth brick masonry systems.

Photo courtesy of Paola Bandini, Ph.D./for New Mexico State University


CBBG applies observations from nature to
solve infrastructure challenges
biogeotechnics.org