INL/CON-09-15487
PREPRINT

Upscaling of Bio-Mediated Soil Improvement

17th International Conference on Soil Mechanics and Geotechnical Engineering

J. T. DeJong
B. C. Martinez
B. M. Mortensen
D. C. Nelson
J. T. Waller
M. H. Weil
T. R. Ginn
T. Weathers
T. Barkouki
Y. Fujita
G. Redden
C. Hunt
D. Major
B. Tanyu

October 2009

Upscaling of bio-mediated soil improvement

Upscaling d'aménagement de sols bio-négocié

J.T. DeJong, B.C. Martinez, B.M. Mortensen, D.C. Nelson,
J.T. Waller, M.H. Weil, T.R. Ginn, T. Weathers, T. Barkouki
University of California, Davis

Y. Fujita, G. Redden
Idaho National Laboratory

C. Hunt, D. Major, B. Tanyu
Geosyntec Consultants

ABSTRACT

As demand for soil improvement continues to increase, new, sustainable, and innocuous methods are needed to alter the mechanical properties of soils. Recent research has demonstrated the potential of bio-mediated soil improvement for geotechnical applications (DeJong et al. 2006, Whiffin et al. 2007). Upscaling the bio-mediated treatment process for *in situ* implementation presents a number of challenges to be addressed, including soil and pore fluid interactions, bioaugmentation versus biostimulation of microbial communities, controlled distribution of mediated calcite precipitation, and permanence of the cementation. Current studies are utilizing large-scale laboratory experiments, non-destructive geophysical measurements, and modeling, to develop an optimized and predictable bio-mediated treatment method.

RÉSUMÉ

Pendant que la demande de l'aménagement de sols continue à augmenter, les nouvelles, soutenables, et innofensives méthodes sont nécessaires pour changer les propriétés mécaniques des sols. La recherche récente a illustré le potentiel de l'aménagement de sols bio-négocié pour des applications géotechniques (DeJong et autres 2006, Whiffin et autres 2007). Upscaling le procédé bio-négocié de traitement pour l'exécution *in situ* présente un certain nombre de défis à adresser, y compris des interactions de fluide de sol et de pore, le bioaugmentation contre le biostimulation des communautés microbiennes, la distribution commandée de la précipitation négociée de calcite, et la permanence de la cémentation. Les études courantes utilisent des expériences à grande échelle de laboratoire, mesures géophysiques non destructives, et modèlent, pour développer une méthode de traitement bio-négociée optimisée et prévisible..

Keywords : bio-mediated, bio-soil, soil improvement, ground improvement, geotechnical engineering, calcite precipitation, microbes, microbial induced calcite precipitation, upscaling, geophysics

1 INTRODUCTION

Demands for civil infrastructure call for sustainable technologies that meet societal needs in a cost-efficient and low-impact manner. Control and modification of soil properties is important for geotechnical, geoenvironmental, agricultural, and other applications.

Synthetic materials are often injected into the subsurface through methods such as chemical permeation grouting to bind the soil particles together and improve the engineering soil properties (i.e. strength, stiffness, permeability). However, synthetic materials are costly, difficult to distribute uniformly in the subsurface, and can introduce hazardous substances. A more environmentally benign method is needed to improve mechanical soil properties. Geotechnical soil improvement can be accomplished by harnessing natural biological processes.

Bio-mediated soil improvement relies on geochemical processes that are facilitated by biological activity (Figure 1). The bio-geochemical process takes place within the pore fluid of the soil matrix, and associated formation of mineral precipitate alters the soil's chemical and physical properties by cementation. Ureolytically-driven microbial induced calcite precipitation (MICP) is addressed herein. Microbial urea hydrolysis generates carbonate ions *in situ* which then react with calcium to form carbonate mineral precipitate. The microbial metabolic activity influences the timing, rate, and location of calcium carbonate precipitation. The ability to stimulate and control the microbial activity enables controlled manipulation of soil properties.

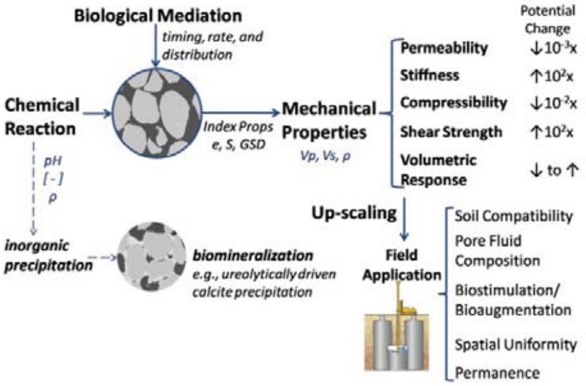

Figure 1. Overview of bio-mediated soil improvement systems. (*[-]* = chemical concentration, *ρ* = resistivity, *Vp* = compression wave velocity, *Vs* = shear wave velocity). (Modified from DeJong et al 2008)

Improvement in mechanical soil properties has been observed in laboratory studies (Ferris et al. 1996, DeJong et al. 2006, Whiffin et al. 2007, and Martinez & DeJong 2009). Results demonstrate that bio-mediated soil improvement has potential to improve soil properties *in situ* for a variety of applications and subsurface conditions. Addressing challenges associated with upscaling from laboratory experiments to field application is necessary and the focus of this paper (Figure 1).

2 ENVISIONED APPLICATIONS

Bio-mediated soil improvement has unique characteristics with potential advantages over conventional soil improvement

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-2300

techniques. The advantages stem from bio-geochemical processes that effectively induce precipitation. The materials required to activate mineral precipitation are generally inexpensive and less hazardous, with reduced impact to the environment. The degree of soil cementation as well as the treatment duration can potentially be tuned to achieve an optimal cementation level.

The advantages of the bio-geochemical process provide a broad range of applications. For civil infrastructure these include liquefaction prevention and damage mitigation, building settlement reduction, piping prevention for dams and levees, soil stabilization prior to tunneling construction, and slope stabilization. Other applications include groundwater protection from contaminants, impermeable/reactive barriers in remediation, emergency immobilization of hazardous contaminants for security applications, and subsurface facilities for energy and carbon sequestration (DeJong et al. 2007).

3 UPSCALING PRINCIPLES

Upscaling bio-mediated soil improvement from the laboratory to the field-scale requires an understanding of geotechnical, hydrological, biological, and chemical principles.

3.1 *Soil Compatibility*

The natural variability and heterogeneity of soil, such as particle size and mineralogy, can affect how bio-chemical amendments and the reactions they stimulate are distributed. The hydraulic boundary conditions and pore space geometry affect the transport of microbes and nutrients, and the fluid, solute, and suspension (e.g. microbes) properties affect the diffusive mixing of the reactants. In addition, an increase in shear strength occurs with cementation at the particle-particle contacts. Therefore, a balance of pore throats large enough to allow microbial transport and a relatively large number of particle-particle contacts is required for bio-mediated soil improvement to be effective (see DeJong et al. 2008).

The soil mineralogy may affect calcium carbonate precipitation. Different minerals may provide more favorable nucleation sites for calcite precipitation because the mineralogy of the particles can directly affect the thermodynamics of the precipitation/dissolution reaction in the system. For instance, calcium carbonate rich soil particles provide ideal surfaces for the growth of additional calcite.

Soil column experiments indicate that MICP can occur in sands rich in silica, calcite, and iron oxide. Calcite precipitation was observed in all soil samples marked by an increase in shear wave velocity (Figure 2). The results suggest that MICP can occur within a variety of soil minerals. Site specific investigations can verify that MICP is a viable option prior to field implementation.

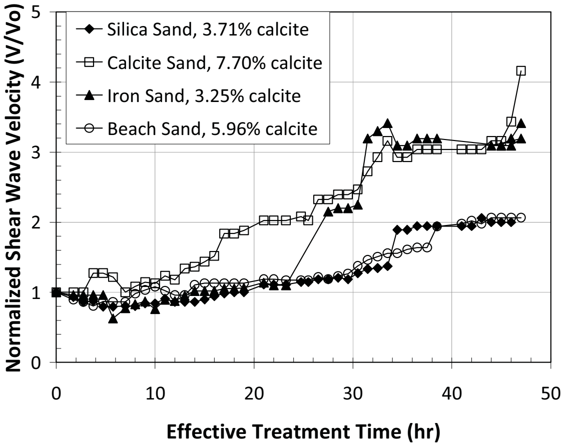

Figure 2. Normalized shear wave velocity for bio-mediated treatment with various soil mineral composition. Average initial shear wave velocity (Vo) is 174 m/s. Beach sand consists of a mixture of silica and iron sands. Final percent calcite determined from oven-dried masses.

3.2 *Pore Fluid Composition*

The chemical composition of the pore fluid can assist or hinder the bio-treatment reaction network. Groundwater with high calcium concentration acts as a calcium reserve for calcite precipitation, while groundwater conditions high in organics may inhibit calcite precipitation (Lebron & Suarez 1996). Understanding the aqueous chemistry of the groundwater and injection solutions is essential prior to field implementation.

Groundwater in coastal areas may be influence by salt water intrusion, resulting in an increase in pore fluid salinity. Soil column experiments indicate a more rapid increase in shear wave velocity with increased pore fluid saltwater concentration (Figure 3). This is attributed to the larger concentrations of cations available to precipitate with microbe-generated carbonate in the higher salinity samples.

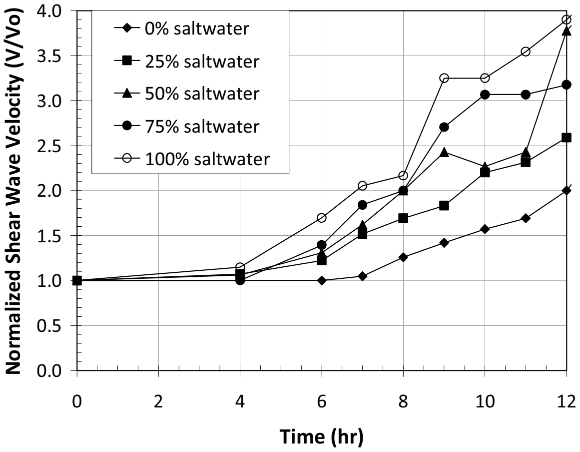

Figure 3. Normalized shear wave velocity for bio-mediated treatment in various saltwater concentrations. Silica sand with a D_{50} of 0.22 mm was used. Saltwater was prepared using Instant Ocean mix. Average initial shear wave velocity (Vo) is 204 m/s.

3.3 *Bio-stimulation verses Bio-augmentation*

Microbial densities, the fraction of attached microbes, or the microbial activity level may need to be enhanced to efficiently promote calcite precipitation. This can be accomplished by stimulating the growth of the native microbes (Fujita et al. 2008) or by augmenting the subsurface by injecting ureolytic microbes. The approach selected will depend on the anticipated ureolytic activity within the particular soil. The ability to hydrolyze urea is common among subsurface microorganisms, but its presence should be confirmed. This can be done using a variety of methods (Fujita et al. 2000). If ureolytic organisms are present, increasing their numbers and activity may be possible by providing suitable nutrients (Fujita et al. 2008). Stimulating indigenous populations has advantages with respect to the “fitness” of the microbes (introduced, non-native species may not be well adapted to the environment and hence survival may be low) and also avoids the engineering challenge of controlling transport of cells in the subsurface. It may also face fewer logistics with respect to regulatory acceptance. However, in cases where the treated soil volume is relatively small, and amenable to hydrodynamic mixing (e.g., accessible, uniform gradation), bioaugmentation may be very effective.

3.4 *Uniformity*

Creating uniform cementation is essential for bio-mediated soil improvement to be used for civil infrastructure applications. When microbes are injected into the subsurface, the microbial cells are filtered by the soil matrix. Filtration of cells generally results in a log-linear reduction of microbe concentration along the injection path (Ginn et al. 2002). The gradient in microbial concentration generally corresponds to a gradient in reaction rates and therefore in cementation rate; larger concentrations of microbes induce a greater rate of precipitation. The degree of cementation corresponds directly to the stiffness of the soil; therefore, a cementation gradient results in a stiffness gradient.

Creating a uniform stiffness throughout the soil is necessary, and therefore the stiffness gradient is an important challenge to overcome if *in situ* bio-treatment is to be successful. Laboratory results indicate that a push-pull injection process (e.g. Boving et al. 2008) may effectively counteract the gradient of microbial concentration, resulting in more uniform cementation. Using a grid of injection/extraction wells, the microbes and nutrients are injected through the soil by inducing an artificial hydraulic gradient. Subsequently nutrients are injected using a reversed artificial hydraulic gradient. The reversal of injection direction provides more nutrients for consumption by the smaller microbe concentration, and less nutrients for the large microbe concentration near the initial injection source. This process improves spatial distribution of the treatment, and therefore cementation uniformity across the treated zone.

Chemical optimization of the treatment media also contributes to uniform calcite precipitation. Calcite precipitation is triggered by an increase in pH and carbonate production. Microbial metabolic activity increases the pore fluid pH. Calcite typically precipitates when the pore fluid increases to a pH of 8.5 to 9.0 (Stocks-Fisher et al. 1999). Adjusting the chemical concentrations in the treatment media enable control of the microbially-induced rate of pH change. Research is currently ongoing on the optimization of the timing and rate of pH-triggered calcite precipitation.

3.5 *Permanence*

The stability of the MICP is an important aspect of the treatment process. For some applications the induced cementation must endure for time horizons equal to any realistic design life. For this reason, the compatibility of the precipitated calcite with the long-term environment is critical. This treatment process is most favorable for environments where calcite is already stable, that is, supersaturated aqueous phases; then, when engineering treatments cease and pre-treatment geochemical conditions return, the bulk of the newly precipitated calcite should be maintained. In cases where calcite stability is not as assured, continuous monitoring during the service life of the treated soil may be needed (the tools for which are discussed below in "*Monitoring of Processes with Geophysics*").

4 UPSCALING TOWARDS FIELD IMPLEMENTATION

Useful and practical implementation of bio-mediated soil improvement in the field requires upscaling of the system developed at the element laboratory scale (~ cm scale). This upscaling challenge is being addressed using bench-scale laboratory experiments, real-time geophysical monitoring, and numerical modeling.

4.1 *Bench-scale Laboratory Experiments*

Bench-scale laboratory experiments (~ m scale) can be used as an intermediate step between small soil experiments (~ cm scale) and field implementation *in situ*. These systems enable optimization of treatment formulation and injection procedure before the treatment is implemented *in situ*.

Soil column experiments (Whiffin et al. 2007) and model shallow foundation tests (Martinez & DeJong 2009) have evaluated the potential for MICP for soil improvement and addressed upscaling challenges. The results indicate that cementation is induced within relatively large soil volumes (~m scale) with a corresponding increase in soil shear strength. The 5-m soil column resulted in cementation throughout the entire length of the sample (Whiffin et al. 2007). The shallow foundation load test resulted in a 5-fold settlement reduction comparing treated soil to untreated soil (Figure 4, Martinez & DeJong 2009).

In addition, a reduction of cementation was observed with increased distance from the injection source in both bench-scale experiments with an associated decrease in shear strength (Whiffin et al 2007). Differential settlement of the shallow foundation occurred during the load test and was correlated to the variability of the cementation (Martinez & DeJong, 2009).

4.2 *Monitoring Processes with Geophysics*

Uniformity and permanence respectively relate to the "certainty of execution" during treatment and "health monitoring" throughout the service life of the treated soil. Nondestructive geophysical monitoring is a promising approach for real-time assessment of the cementation levels throughout the system's design life. Geophysical properties used to monitor the treatment process are seismic waves and electrical potential (both real and imaginary components). Within these properties, shear wave velocity (V_s), compression wave velocity (V_p), and the real component of resistivity (ρ) have been investigated to monitor the change in soil matrix during the cementation process.

Shear wave velocity of the soil is affected by the soil particle matrix and is a measure of the shear stiffness of the soil. Cementation occurring at the particle-particle contacts will increase the shear stiffness of the soil and the shear wave velocity (Figure 5). Compression wave velocity of the soil is affected by the bulk stiffness of both the pore fluid and particle matrix, as well as the saturation level of the soil. Monitoring the soil sample during treatment will result in measuring the compression wave velocity of the pore fluid (approximately

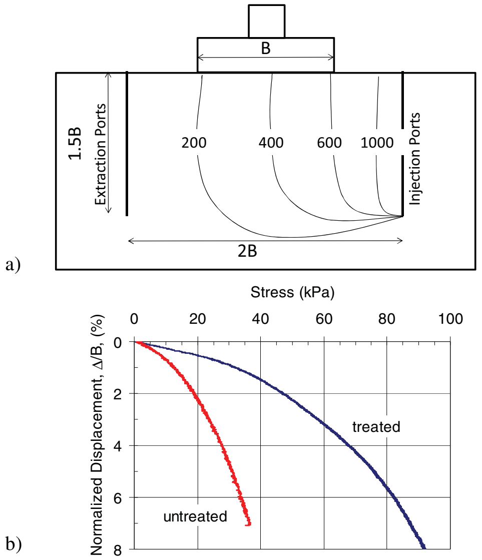

Figure 4. a) Approximate V_s (m/s) contours across treated area, initial V_s approximately 160 m/s. Column width B = 4 inches. b) quantitative results, displacement at center of footing (modified from Martinez & DeJong 2005)

1500 m/s, Fang 1991) until sufficient cementation has occurred and the soil skeleton becomes more incompressible than water. When this occurs, the velocity increases above ~1500 m/s (Figure 5).

Electrical resistivity of the soil is affected by the pore fluid composition, the bulk solid, and properties of the electrical double layer at the solid-solution interface. Monitoring resistivity during the treatment process does not detect structural changes within the soil matrix because the bio-geochemical process is constantly changing the ionic concentration of the pore fluid (Figure 5). However, electrical geophysical methods might be used to monitor the progress and spatial distribution of chemical processes (Revil & Linde 2006).

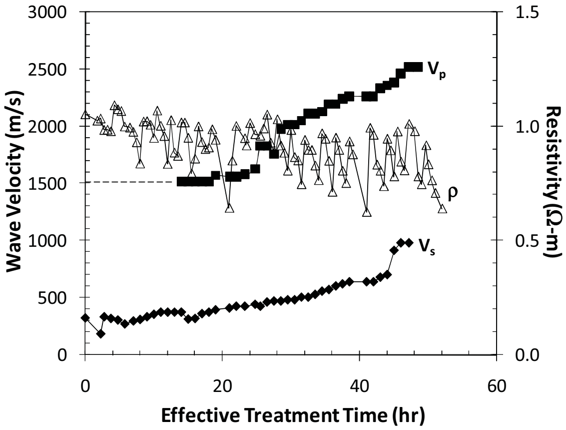

Figure 5. Geophysical trends during bio-treatment. (Vs = shear wave velocity, Vp = compression wave velocity, and ρ = resistivity).

4.3 *Modeling*

The ability to model the *in situ* precipitation process is required for successful field implementation. The modeling should address the hydrological, chemical, biological, and geotechnical properties of the treatment system and allow for *in situ* treatment optimization. In particular, the flow field of injected and groundwater solutions must be accurately simulated in order to provide the velocity field governing the advective, dispersive, and diffusive transport of injected solutions and their mixing with initially present groundwater. This requires characterization of the initial hydraulic boundary conditions and the hydrologic properties of the subsurface, namely the porosity and the hydraulic conductivity. The velocities obtained by solving the flow problem are then used in the mathematical model of transport, mixing, and reactions of the reactant species. This entails appropriately controlled (e.g., kinetically or equilibrium) representation of: multi-domain diffusion, microbial transport with attachment/detachment, ureolysis, ammonium inhibition, carbonate production, pH changes, and precipitation/dissolution of calcite. When volumes of precipitated calcite comprise even a small though significant fraction of the pore space, then knowledge of how porosity and hydraulic conductivity reduce with increasing precipitate is required for updating these hydraulic parameters in an iterative solution scheme that updates the flow field solution as well as the reactive transport solution. Generally the modeling technology required is developed, but the constitutive basis for the kinetically controlled reactions, the microbial attachment/detachment, and the reduction in hydraulic conductivity, are in continued development. Monitoring of the treatment process will allow conditional validation of the bio-treatment model.

5 CONCLUSION

A natural and sustainable soil improvement method is needed for continued infrastructure growth and mitigation. Utilizing biological activity to induce calcite precipitation has broad potential for ground improvement applications – particularly for civil infrastructure applications – and advantages over current industry techniques. However, continued research must still address several challenges associated with upscaling the process for *in situ* treatment and the permanence of the induced cementation. Ongoing research is currently using bench-scale laboratory experiments, non-destructive geophysical monitoring, and modeling to address these challenges.

ACKNOWLEDGEMENTS

Funding provided by the National Science Foundation (CMMI#0727463), UC Discovery Program in collaboration with Geosyntec Consultants, and U.S. Department of Energy.

REFERENCES

Boving, T.B., Blanford, W.J., McCray, J.E., Divine, C.E., & Brusseau, M.L. 2008. Comparison of Line-Drive and Push-Pull Flushing Schemes. *Ground Water Monitoring & Remediation*, 28(1), 75-86.

DeJong, J.T., Mortensen, B.M., Martinez, B.C., & Nelson, D.C. 2009. Bio-mediated soil improvement. *Ecological Engineering, Special Issue from 1st International Conference on Bio-Geo-Civil Engineering* (in press).

DeJong, J., Mortensen, B., & Martinez, B. 2007. *Bio-Soils Interdisciplinary Science and Engineering Initiative*, NSF Final Report for Grant #CMS-0628782, 85 pp., http://www.sil.ucdavis.edu/biosoil-outcomes.htm.

DeJong, J.T., Fritzges, M.B., & Nüsslein, K. 2006. Microbial Induced Cementation to Control Sand Response to Undrained Shear. *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 132 (11): 1381-1392.

Fang, H.Y., ed. 1991. *Foundation Engineering Handbook*. New York, NY: Van Nostrand Reinhold. 923pp.

Ferris, F.G., Stehmeier, L.G., Kantzas, A., & Mourits, F.M. 1996. Bacteriogenic Mineral Plugging, *The Journal of Canadian Petroleum Technology*, 35(8), 56-61.

Fujita, Y., Taylor, J.L., Gresham, T.L.T., Delwiche, M.E., Colwell, F.S., McLing, T.L., Petzke, L.M., & Smith, R.W. 2008. Stimulation of Microbial Urea Hydrolysis in Groundwater to Enhance Calcite Precipitation. *ES&T*, Vol. 42 (8): 3025-3032.

Fujita, Y., Ferris, F. G., Lawson, R. D., Colwell, F. S. & Smith, R.W. 2000. Calcium Carbonate Precipitation by Ureolytic Subsurface Bacteria. *Geomicrobiology Journal*, 17, 305-318.

Ginn, T., Wood, B.D., Nelson, K.E., Scheibe, T.D., Murphy, E.M., & Clement, T.P. 2002. Processes in microbial transport in the natural subsurface, *Advances Water Resource*, Vol. 25: 1017-1042.

Kramer, S.L. 1996. *Geotechnical Earthquake Engineering*. Upper Saddle River, NJ: Prentice Hall. 653pp.

Lebron, I. & D. L. Suarez (1996). Calcite nucleation and precipitation kinetics as affected by dissolved organic matter at 25 degrees C and pH>7.5. *Geochimica Et Cosmochimica Acta* 60(15): 2765-2776.

Martinez, B.C. & DeJong, J.T. 2009. Bio-Mediated Soil Improvement: Load Transfer Mechanisms at the Micro- and Macro- Scales, *US – China Workshop on Ground Improvement Technologies, ASCE GSP*, 10 pp. (in press).

Mitchell, J.K., & Santamarina, J.C. 2005. Biological Considerations in Geotechnical Engineering. *Journal of Geotechnical and Geoenvironmental Engineering*, 131(10), 1222-1233.

Revil, A. & Linde, N. 2006. Chemico-electromechanical coupling in microporous media. *Journal of Colloid and Interface Science*, 302, 682-694.

Stocks-Fisher, S., Galinat, J. K., & Bang, S. S. 1999. Microbiological precipitation of CaCO3. *Soil Biology and Biochemistry*, 31(11), 1563–1571.

Whiffin, V.S., van Paassen, L.A., & Harkes, M.P. 2007. Microbial Carbonate Precipitation as a Soil Improvement Technique. *Geomicrobiology Journal*, Vol. 24: 417-423.