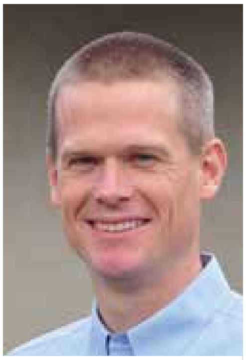
Main image: bio-cemented soil. Inset: Biocementation treatment in 2-m-diameter tanks: Figure 1a. Setup.

// What's New in Geo?

Sustainable Biogeotechnics

Biogeotechnics will likely become part of mainstream geotechnical engineering in the future.

By Jason T. DeJong, PhD, A.M.ASCE

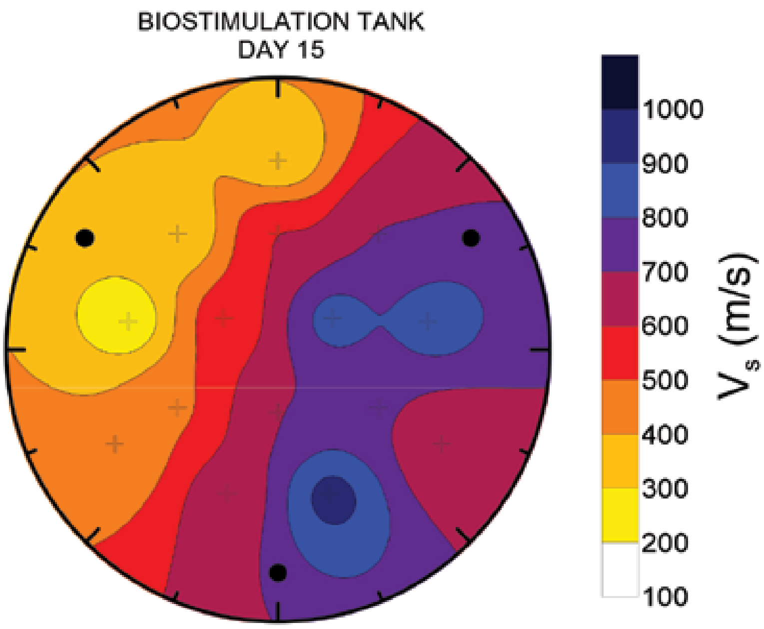


JASON T. DEJONG

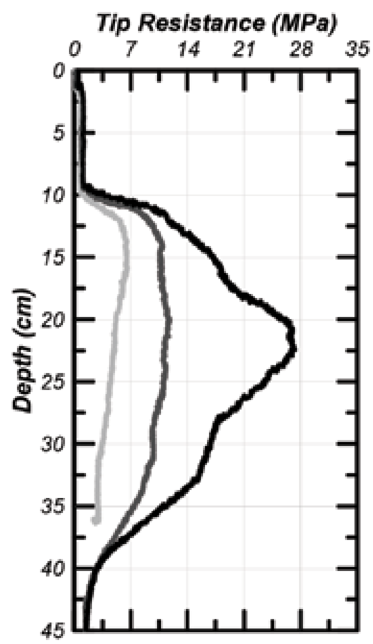
Geotechnical engineering is simultaneously science and art. We use our cognitive abilities to characterize, analyze, and design geotechnical systems; and yet, in all cases, the quantitative analysis is not sufficient. We then perform "geotechnical art" by making assumptions on values, completing stratigraphic contours, predicting future loading conditions, selecting things like recurrence intervals, and finally committing to our decisions by legal oath via our professional licensure stamp. Collectively, this "art" consists of informed and systematic applications of judgment.

The need for judgment in geotechnical engineering is largely due to soil being a natural material, with a variability in properties in situ that far exceeds other civil engineering materials. Every site, and therefore every project, is unique. As a geotechnical engineer then, no two days are the same! This is one reason why we love our profession.

We have, by necessity, always simplified the complexity of soils. For decades, soil properties and behavior were attributed to gravimetric forces and the presence of water. Prof. Mitchell has revealed, and many others have since built on his findings, that chemistry is at work in all soils, and is the scientific basis for clay behavior. As our understanding of the role of chemistry in soils developed, the profession advanced and began harnessing chemical processes to manipulate engineering properties (e.g. lime stabilization and electrokinetics).



Biocementation treatment in 2-m-diameter tanks: Figure 1b. Shear wave velocity.



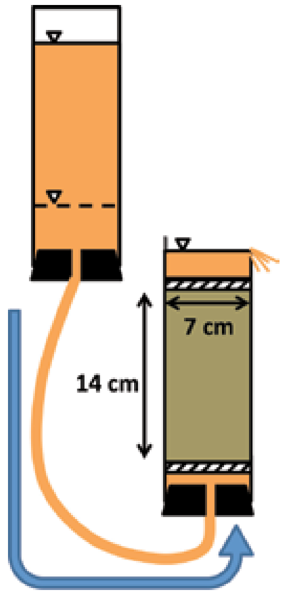
Biocementation treatment in 2-m-diameter tanks: Figure 1c. V_s mapping.

Biological processes directly influence the rate, timing, and location of the geochemical reaction network(s) that induce changes to the soil structure.

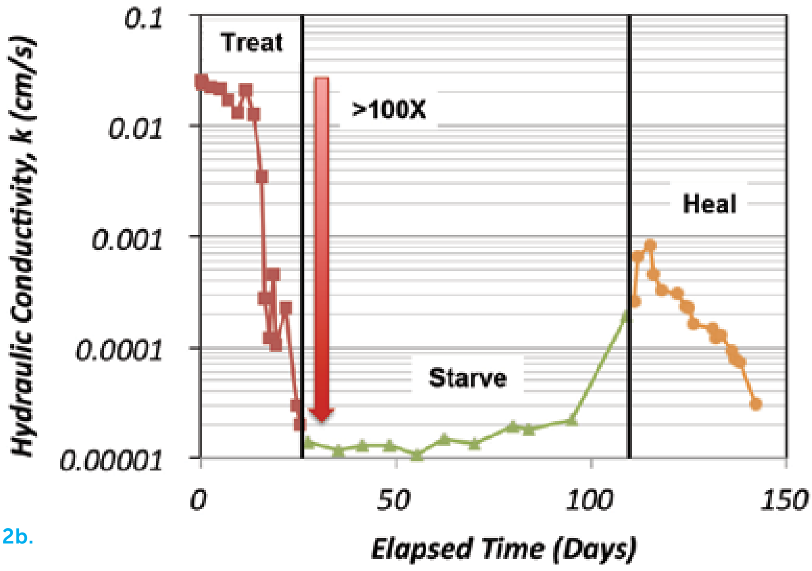
BioSoils Are Living Soils… and They Change in Time

Arguably, the next advent for the geotechnical profession is to recognize that the soil is a living ecosystem. For example, the bacterial count in near-surface soils with significant organic content often exceeds 10^9 bacteria per 1 cm^3. More than 10^6 bacteria are also present in a cubic centimeter of poorly graded quarry sand typically used as backfill or roadway subgrade materials. Our "inert" backfill materials are not so inert after all! Soil is alive!

The living nature of soil can involve biological and chemical changes that challenge our traditional understanding of time-dependent stability in soils. Such changes can improve or degrade soil properties from the as-constructed condition over the service life of a geotechnical system. Often, the net effect of detrimental changes is not sufficient to compromise the conservatism embedded in the design, but they are present nonetheless. In other cases, such as the reduction of hydraulic conductivity of landfill liners and the softening of soil slopes, we acknowledge and account for time-dependent effects.



2a.



2b.

Figure 2. **Biofilms for temporary hydraulic conductivity reduction: (a) test setup, (b) formation, starvation, decay, and re-healing stages.**

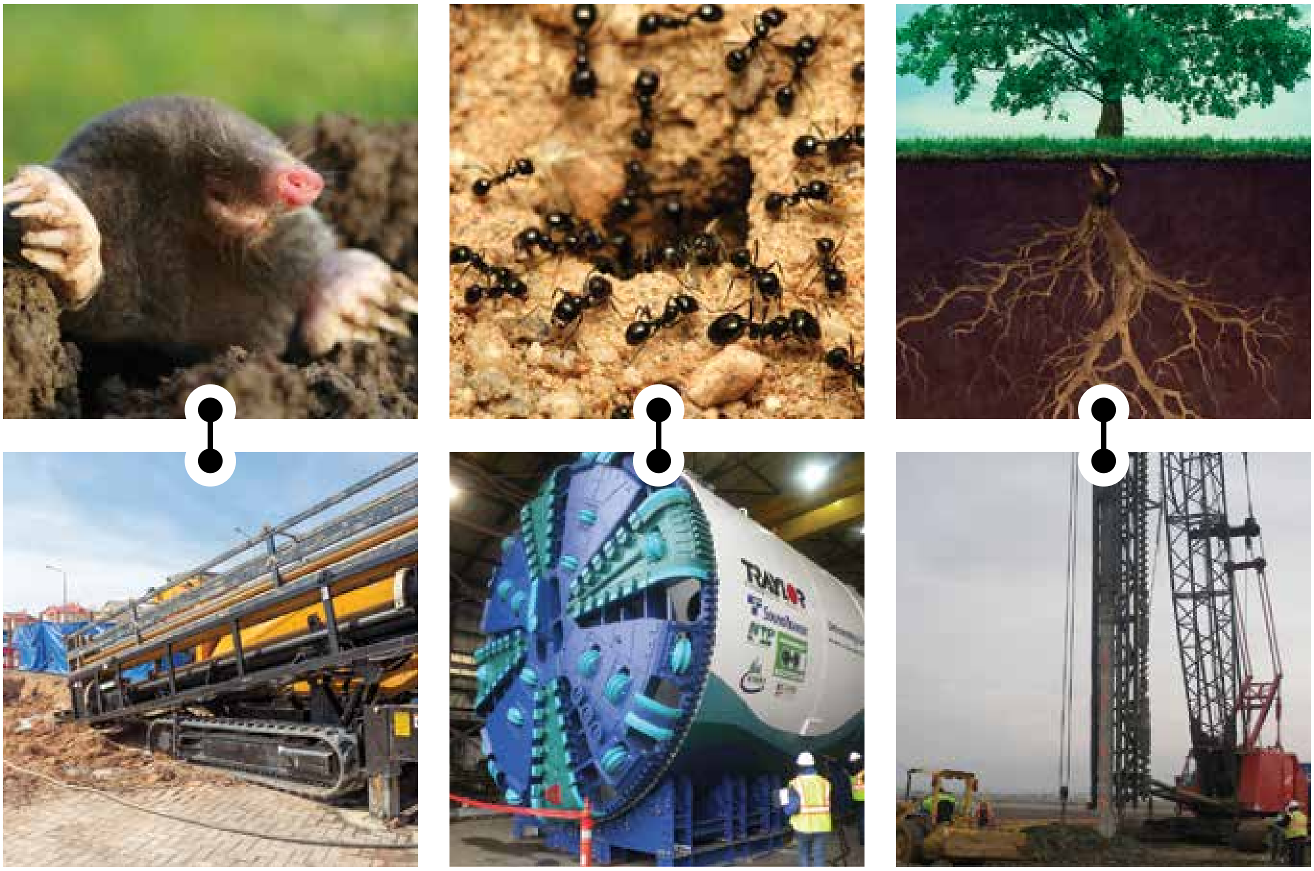


Figure 3. Biological analogs to our geotechnical systems.

Bio-mediated Solutions… Engineering Solutions Mediated by Biological Processes

Over the past 15 years, geotechnical researchers have formed interdisciplinary teams with microbiologists and geochemists in an effort to merge their knowledge and identify bio-mediated processes that may be accelerated in time to induce changes in soil that result in significant improvements in engineering soil properties. While great progress has been made with some promising processes presented herein, we are still in the early days of discovery.

Why is the role of biology critical in this interdisciplinary endeavor? Biological processes directly influence the rate, timing, and location of the geochemical reaction network(s) that induce changes to the soil structure. In some cases, the process creates a permanent inorganic precipitate that could also be solely produced using chemistry in a beaker on the lab bench; by mediating this process, we can control the reaction and enable such processes to occur uniformly within a soil mass. In other cases, an organic polymer may form around bacteria, and its stability is directly coupled to continued bacterial growth; when the bacteria die, the change in engineering properties also reverts.

Microbially mediated calcite precipitation (an inorganic mineral precipitation technique) is the process that has shown the greatest promise and research focus to date. Recent research treating large 2-m-diameter tanks of soil has demonstrated that it is possible to solidify loose, uncemented sand (relative density, D_r = 40 percent, initial shear wave velocity, V_s = 120 m/s) into a sandstone-like material (V_s = 970 m/s) over a period of 10 days, while controlling the spatial distribution of improvement (Figure 1: note that the final V_s gradient across the tank was produced by design to calibrate a numerical model). Moreover, this process is possible through bio-stimulation, wherein bacteria already present in the sand (native bacteria) are first stimulated with nutrients to increase in population and activity, and then used to mediate the calcite cementation process. Calcite precipitation in the void space and particularly at particle-particle contacts increases soil stiffness, strength, and liquefaction triggering resistance, and decreases permeability. The resulting potential applications are wide ranging and include liquefaction mitigation beneath existing structures, stabilization of unsealed roadways, control of groundwater flow, and contaminant immobilization.

The growth of biofilms, or bacterial communities that secrete a gel-like substance known as EPS (extra-cellular polysaccharide), has been shown to coat coarse-grained soil particles and plug voids for short-term modification of soil properties. The generation of EPS within sands can effectively reduce hydraulic conductivity by more than 100 times over a period of about two weeks (Figure 2a). Recent column experiments have demonstrated that this process also can be achieved by stimulating native bacterial populations. Once reduced, the hydraulic conductivity reduction can remain stable for more than 60 days, after which it degrades (Figure 2b). If desired, retreatment can sustain or recover the full reduction, or alternatively, the biofilm could be allowed to degrade, and the hydraulic conductivity can attenuate back to its natural condition. This type of short-term reduction is very attractive for dewatering excavation projects, for example, since the hydraulic conductivity reduction is only temporary.

Bio-Inspired Solutions... Engineering Solutions Inspired by Biological Analogs

Ant excavation processes are 100-1,000 times more efficient than current tunnel boring machines. Root systems are 10 times more efficient than current ground reinforcement/foundation systems. Moles advance through soils with amazing efficiencies (Figure 3).

Activities such as these cannot be directly harnessed for geotechnical applications, but the principals and processes they employ, processes that have been optimized by nature over millennia, can be used to inspire new geotechnical solutions.

A majority of geotechnical solutions and their associated construction processes have been driven by the construction industry. Consequently, current technologies are largely feasibility and direct-cost focused; optimization has largely been in the form of incremental improvements.

The goal of bio-inspired geotechnical solutions is to reconsider the performance requirements for a geotechnical system and identify new solutions that leverage, to the extent appropriate, efficiencies optimized in the biological analogs. Biological analogs for excavation, reinforcement, penetration, erosion control, densification, etc., can be readily identified. One example of where this approach may have significant potential is in pile foundations and soil retention systems. Nearly all deep foundation and soil reinforcement systems employ linear, constant, cross-sectional elements to transfer the structural load to the surrounding soil. The biological analog, the tree root system, is 10 times more efficient and highly spatially non-linear. After separating out the physiological role of tree roots (i.e., water and nutrient uptake), it is possible to identify the structural function and associated topology of the root system. The knowledge gained from this type of study enables us to explore the potential performance increase that is possible

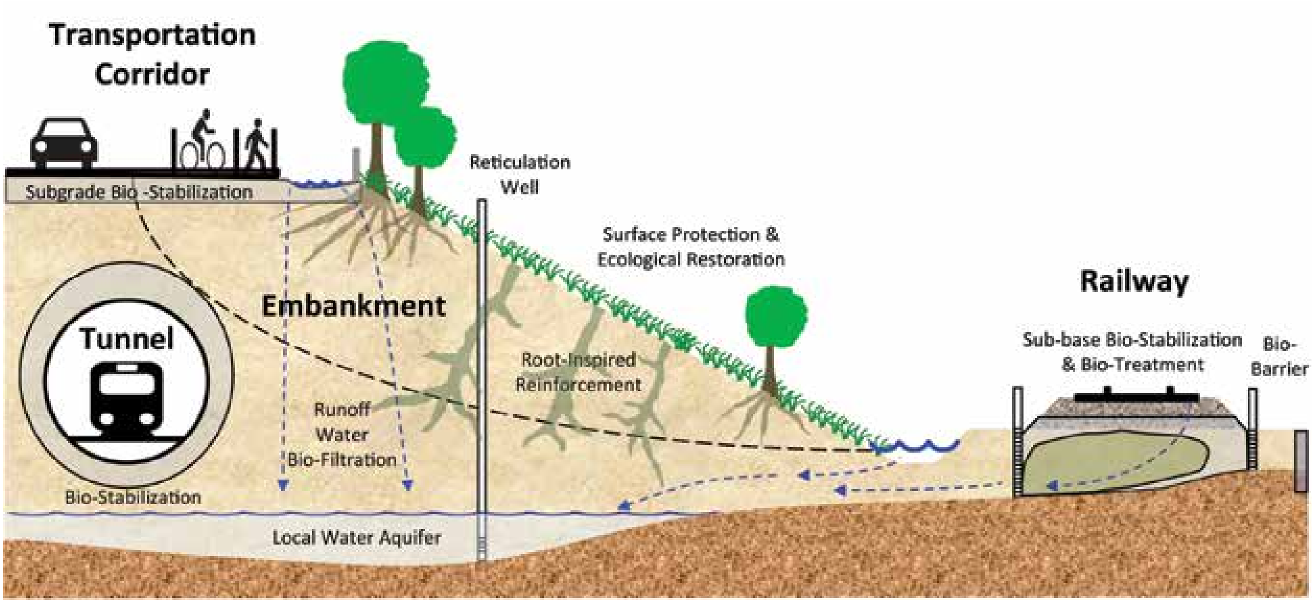


Figure 4. Vision of bio-mediate and bio-inspired solutions along a travel corridor.

with a root-inspired foundation or reinforcement element. It also allows for examination of the potential methods for constructing such a system.

Biogeotechnics… A New Emphasis Is Coming to the Mainstream

Collectively, biogeotechnics, or the development of bio-mediated and bio-inspired geotechnical solutions, constitute a rapidly growing emphasis in geotechnical engineering. In the coming decades, it will likely become part of mainstream geotechnical engineering (Figure 4). This field lies at the confluence of geotechnical engineering and microbiology, geochemistry, zoology, and plant science, as we come to recognize that life sciences are relevant to geotechnical engineering!

The development of biogeotechnical solutions forces a paradigm shift in which we, as geotechnical engineers, must recognize and consider soil as a living ecosystem, and not as a sterile, non-reactive, stable material. As geotechnical engineers, we must be trained — or re-trained — to think and be informed as biogeotechnical engineers.

Sustainability… Adding to the Bottom Line of Safety + Cost

The responsibility of the civil engineer is to safely provide essential services to society and the built environment, both to individuals and the community at large. This is the highest priority. In a capitalistic marketplace, a second priority is cost. The desired services are to be provided safely using the most economical solutions. These two criteria (safety and cost) have driven, and continue to drive, final selections. This approach, in combination with an assumption of nearly unlimited materials (e.g., cement) and resources (e.g., fuel), has led to the development of material- and energy-intensive, brute force, geotechnical solutions, and construction procedures.

We have now realized that there is a societal cost to these approaches. Emissions from these conventional construction methodologies are causing air quality degradation, ozone depletion, global warming, and sea level rise. Moreover, the materials and resources that are employed are finite. We cannot continue with business as usual in the decades to come.

As a result, we must re-evaluate how we make decisions. We must add sustainability to the existing criteria of safety and cost. The impact of a given technology can be quantified in terms of carbon footprint, embodied energy, etc. A comparative analysis between alternate solutions, wherein the carbon footprint is assigned a monetary value (e.g., social carbon cost), will help us, as a profession, realize the impact that geotechnical systems have and provide a basis for quantitative comparison between alternate solutions. Preliminary work in this area has shown that the carbon footprint between different ground improvement methods can differ by 10 times, and different earth retaining systems can differ by more than 3 times.

The criteria of safety must be uncompromised, but the cost calculations must include a solution's sustainability in addition to capital costs. The challenge, of course, is that capital costs are measured in real dollars out of the investor's wallet, while the sustainable costs are measured in equivalent dollars that everyone will experience, often at a later date. As a result, integration of sustainability and the societal impact into decision making must be led by government and forward thinking private investors.

The Path Forward

Bio-mediated and bio-inspired technologies hold promise to provide the sustainable geotechnical solutions that our society requires. There is an opportunity to re-consider, re-define, and re-design geotechnical solutions from this basis. For this to be realized, we must encourage broader exposure in our students' education curriculum, continue pursuing new ideas through research, and engage with and educate current geotechnical practice of this emerging opportunity.

Be a bio-inspired geotechnical engineer! GS

Acknowledgements

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