A Hypergravity Testbed to Advance Biogeotechnics: an invaluable resource for prototyping and system-level evaluation

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Biogeotechnics, specifically bio-mediated and bio-inspired geotechnical engineering, has matured rapidly over the past two decades, becoming one of the fastest growing subdisciplines within geotechnical engineering. As typical in most science and engineering fields, biogeotechnics relies on data from physical experiments and field observations to advance technology. Obtaining field data to drive advancement can pose unique challenges, and in many cases may be cost or logistically prohibitive. Physical experiments or models are often preferable and may offer the sole feasible pathway for technology development and upscaling.

Hypergravity scaled modeling using centrifuges has been instrumental in biogeotechnics development to support the building of basic science knowledge, the validation of computational and theoretical models, and the advancement of emerging technologies towards field implementation.

The Hypergravity Testbed

Experiments at hypergravity (centrifugal acceleration) provide a unique opportunity for representing large geotechnical systems using reduced scale models. Geotechnical materials such as soil and rock have nonlinear mechanical properties that depend on the effective confining stress and stress history. The centrifuge applies an increased “gravitational” acceleration to reduced-scale physical models to produce identical self-weight stresses in the model and prototype, which enhances modeling similarity. A controlled experiment of whole system problems with well-defined boundary conditions and material properties can be built at reduced scale and tested at full-scale stress levels to learn more about fundamental mechanisms and to validate numerical simulation/analysis models.

Scaling hypergravity tests to equivalent prototypes is achieved through well-established scaling laws; for example, acceleration and gravity are increased by a factor N while length and displacement are reduced by the same factor N. The role of centrifuge modeling in the calibration/verification of analysis tools is demonstrated in Figure 1. A field problem exists (2a) that includes complex features, for which the engineer has concerns because their analysis methods have never been sufficiently validated against physical data. To validate their methods for these features, an engineer can simplify the field problem (2b), emphasizing mechanisms critical to system behavior. A reduced-scale physical model of the simplified problem can be built following scaling laws (2c) and then it can be subjected to various loads to explore the critical mechanisms. Scaling laws can then be used in reverse to express the observed physical behaviors at real-world scale (2c back to 2b). To validate that their analysis methods accurately capture critical behaviors, the engineer can analyze the simplified problem at Ng or 1g (2d or 2e). Comparisons made at 1g are common and are simple to compare to real-world systems. Scaling laws can sometimes conflict, however, and comparisons made at Ng have the advantage of including the same physical mechanisms without incorporating potential scaling conflicts. With their tools validated against the simplified problem, the engineer can generalize their analyses to their original field problem (2f) with confidence that the underlying behaviors are reasonably captured.

The use of the 9-m-radius (9m) centrifuge at UC Davis for validating nonlinear numerical models is illustrated using a research project that studied the use of soil cement panels for liquefaction remediation of an embankment. Concerns with analysis methods included unknown mechanics regarding the effects of progressive cracking in brittle soil cement materials and the reasonableness of using composite properties for the treatment zone in 2D numerical models. Past designs of soil cement remediation for dams underlain by liquefiable soils were reviewed, leading to the simplified model geometry shown in Figure 1. The model consisted of a 0.4-m-tall embankment underlain by loose, saturated sand layer and remediated with soil-cement panels at the toe (1a and 1b). When tested at 60g, the equivalent prototype embankment was 24 m tall. The model tests provided insights on overall deformations as well as local 3D behavior and crack progression in the soil cement panels throughout shaking (1d). These detailed measurements were only possible due to the large size of the model container on the 9m centrifuge. Two-dimensional nonlinear dynamic simulations using procedures common in engineering practice (1c) did not capture some of the local damage patterns but were in good agreement with global measures of deformation and response. The researchers concluded that these results provided support for the continued use of these numerical modeling procedures for design.

The Center for Geotechnical Modeling centrifuge facility at the University of California Davis has served as a testbed for the NSF ERC Center for Bio-mediated and Bio-inspired Geotechnics (CBBG) since its inception. In this capacity, the CGM has provided a robust platform for CBBG researchers to both accelerate development and comparatively evaluate the performance of new technologies with each other and against technologies and practices that are routinely used in practice. The following examples highlight centrifuge use in both bio-mediated and bio-inspired applications.

Bio-mediated Technology Highlight: Upscaling of MICP for Liquefaction Mitigation

Bio-mediated processes for ground improvement, including microbially induced calcite precipitation (MICP) and microbially induced desaturation (MID), are novel technologies for improving liquefiable sands via natural pathways. These bio-mediated processes strategically control the timing, rate, and magnitude of biogeochemical reaction networks that depend on microbial activity. For MICP, the precipitation of calcium carbonate generates brittle cementation of the soil particle matrix, whereas for MID the generation of nitrogen gas bubbles partially desaturates the soil. Centrifuge tests of both technologies by researchers from UC Davis and Arizona State University have clearly shown that resistance to liquefaction triggering increases, and consequences, in terms of settlements and deformations, decrease. The degree of improvement, which depends on the concentration and distribution of improvement, can be significant with both methods. The mechanisms by which the improvement is realized, however, differs substantially, as revealed in the centrifuge tests with dense instrumentation arrays, CPT profiling, and imaging techniques.

Upscaling of MICP to field applications has required multidisciplinary, multiscale research programs to address the breadth of issues that must be understood and controlled, which range from bio-stimulating native bacteria, to controlling treatment byproducts, developing design methods, and establishing QA/QC protocols. The synergistic use of the 1m and 9m centrifuges has been particularly useful for addressing several systems-level MICP priorities for which future technology adopters in industry have requested guidance. The use of centrifuge modeling to address some of these needs is highlighted in Figure 3 and described in the following three paragraphs.

Researchers studied MICP-treated soil profiles on the 1m centrifuge (Figure 3a upper image) using soil penetrometers, shear wave velocity measurements, and the shake table to gain insight into how the CPT q_c-based liquefaction triggering curve shifts when MICP cementation is used to improve a loose, liquefiable sand deposit. Results in Figure 3a (lower image) demonstrate, for example, that the achieved cementation level of about 5 percent calcite by mass, increased the cone tip resistance, q_c, measurement by up to 8x, and shear wave velocity increased by about 600 m/s (not shown).

A subsequent study, summarized in Figure 3b, used the 1m centrifuge to study how depth of MICP treatment of a liquefiable soil will affect both settlement and accelerations realized at the ground surface. Two competing performance conditions exist in the treatment strategy, reducing settlement and minimizing dynamic loading at the ground surface (to reduce loads transferred into a surface structure). A suite of densely instrumented centrifuge models was constructed with the MICP treatment zone extending to varying percentages of the 8.2-m liquefiable soil depth. Settlement was minimized, as expected, when the entire depth was treated. However, this maximized the dynamic loading at the ground surface due to the increased stiffness (Figure 3b). In contrast, improving 75 percent of the depth provided a balanced response; the limited liquefaction of the underlying loose soil resulted in a significant reduction in the ground surface acceleration, albeit at the expense of slightly increased settlement (Figure 3b). These small centrifuge model tests exemplify how numerous tests can be performed efficiently to isolate and study specific mechanisms.

More realistic details, including the effects of soil stratigraphy, treatment zone geometry, and soil-structure interaction, were incorporated in a system-level model using the 9m centrifuge (Figure 3c). The complex model evaluated how the MICP improvement could minimize the consequence of liquefaction on shallow foundation performance when underlain by an idealized heterogenous subsurface (Figure 3c middle image). An example result demonstrating the reduction in settlement during a single 0.15g event shows that the absolute settlement was significantly reduced.

The model complexity achievable on the 9m centrifuge in this example is substantially increased over the earlier two 1m centrifuge examples, which allows more realistic conditions to be investigated. As is evident, the 1m and 9m centrifuges can be used synergistically, with the 1m centrifuge providing an opportunity to parametrically study a relatively simple mechanism, while the 9m centrifuge allows for more complex mechanisms and conditions to be modeled, which in many cases serves as a closer analog to field conditions.

The ongoing centrifuge test program has provided, and will continue providing, data sets and insights for validating numerical modeling of MICP-treated soil, developing target MICP ground improvement quantities to mitigate liquefaction triggering, and developing guidance for design of field-scale solutions. The impact of the centrifuge-generated data has been enhanced when connected to complimentary laboratory and field data, as well as with numerical simulations. In aggregate, the centrifuge work has well-positioned MICP as an implementable bio-mediation technology.

Bio-inspired Technology Highlight: Root-inspired Anchors

Hypergravity centrifuge modeling has served a similar role for the advancement of bio-inspired technologies, including, for example, snakeskin-inspired piles and natural root-inspired anchors. The article on bio-inspired geotechnics in this issue by Martinez and Frost (see pp. XX-YY) details upscaling from the laboratory to the field of "snakeskin piles," which have anisotropic surface roughness that can be optimized to the desired performance (e.g., reducing installation forces while increasing pullout resistance). Centrifuge modeling provided early proof-of-concept data, and later a comprehensive evaluation of installation forces and snakeskin pile performance when subject to monotonic and cyclic loading. The following paragraphs discuss research on bio-inspired anchorage systems inspired by roots that creatively leveraged hypergravity modeling and advanced 3D printing technology.

The pullout capacity of natural plant and tree-root systems exhibit up to 10x performance efficiency relative to conventional piles and footings on a capacity-to-weight ratio metric. The potential to realize even a fraction of this performance gain in geotechnical anchorage systems has driven a wide range of root-inspired anchorage research by multiple groups. The myriad possibilities in the solution space are endless, so progress toward a practical solution requires isolating and interrogating parameters and mechanisms that are of first-order importance to pull-out performance.

Centrifuge modeling, in combination with 3D-printed, root-inspired anchor analogs, has proven particularly useful in these efforts, as it has allowed for systematic control of individual parameters and isolation of mechanisms. An ongoing research study by UC Davis and the Korea Advanced Institute of Science & Technology, or KAIST, is examining the interacting combinations of embedment depth and confining stress, as well as variations in root architecture complexity and material stiffness. Natural root systems are typically shallow, which is driven by the competing demands of structural capacity and uptake of water and nutrients. However, it's well established that capacity of anchors and foundations increases with confining stress, implying that deeper embedment is desirable for increasing capacity. This simple principal is made complicated as the failure mechanism during pullout changes as a function of embedment depth and size. Near-surface embedment results in a shallow failure mechanism that daylights to the ground surface, while deep embedment results in a failure mechanism that is largely contained at depth. Due to the 3D complexity (including that root-inspired elements have varying diameters), the centrifuge modeling program was designed to isolate and separate these effects.

The UC Davis/KAIST study is highlighted in Figure 4. Figure 4a and b shows images of model assembly and the pull-out system during testing, respectively. To study geometric effects, pull-out tests were performed at varying g-level while maintaining constant effective stress on the anchor by embedding the anchor elements at varying depth (i.e., 15mm depth at 60g, 36mm @ 25g, 90mm @ 10g). Example results in Figure 4c show the performance of a root-system anchor across three tests, with a constant confining stress of 13.1 kPa at the root centroid. As evident, the load-displacement performance characteristics are highly dependent on the embedment depth, with the stiffness and peak capacity being increased with embedment depth, and the characteristics during post-peak softening shifting to an alternate failure mechanism.

The root-inspired anchorage system project has benefited from the hypergravity testbed, which has enabled unique, early upscaling of the research concepts with substantial, quantitative proof-of-concept data. Subsequent centrifuge testing has enabled more advanced examination of the inter-relationships between first-order design parameters and has enabled researchers to develop models for computing the pull-out capacity of non-linear structural elements.

Training the next generation of engineers

As can be seen in the examples above, models on the 9m centrifuge are complex, complete boundary value problems. Graduate student and post-doctoral researchers gain tremendous experience as project engineers in executing a centrifuge test. For each test, after completing their design, researchers spend up to two months in the laboratory, building, testing, and dissecting their experiment. The CGM hosts researchers from across the US and abroad and provides the technical training and oversight necessary to achieve a high standard of research quality. New researchers learn physical modeling techniques and sensor and data acquisition procedures as well as develop engineering designs for their research application. Researchers, acting as project managers, supervise assistant researchers, productively direct staff, work with outside vendors, and manage non-personnel resources. The CGM follows an apprenticeship model to introduce new researchers to centrifuge testing. Apprentices working with experienced researchers “learn while doing” within a safe, supervised environment. Feedback from past researchers, and their current employers, has indicated that the experience gained in centrifuge research has equipped them well for their future careers in industry and academia.

Future Opportunities in Hypergravity Experiments and Model Testing

The positive contribution centrifuge modeling has had, and continues to have, in the rapidly developing field of biogeotechnics serves as a good example of the opportunities provided by hypergravity testing. This progression, in fact, mirrors the progression historically observed in other subdisciplines of geotechnical engineering, including fundamental mechanics, earthquake engineering, onshore and offshore foundations, ground improvement, and more. In all cases, centrifuge modeling enabled building of basic science knowledge, validation of advanced computational models from the component to holistic system level, and validation of innovative mitigation strategies.

Worldwide, the centrifuge is established as an accepted and important tool for research in geotechnical engineering. For example, 40 percent of the papers published in the ASCE *Journal of Geotechnical and Geoenvironmental Engineering* in 2020 include references to geotechnical centrifuge tests. The evolution and growth of centrifuge modeling in the U.S. has been strongly supported by the National Science Foundation, including at UC Davis, where NSF funding established the 9m National Geotechnical Centrifuge (1978-1987), and then supported upgrades and operations under NEES (2000-2014) and NHERI (2015-ongoing).

A recent international workshop on hypergravity experiments and model tests identified significant opportunities for collaboration between centrifuge experts and researchers in fields where hypergravity research is not yet prevalent. Gravity affects many physical parameters, including weight, buoyancy, convection, pressure, stress, pressure gradients, and potential energy. These parameters in turn affect secondary parameters like flow rate, frictional resistance, stability, advection, and consolidation. These secondary parameters play roles in many processes, such as the large-scale behavior and stability of earth dams, rock slopes, tectonic structures, combustion and fire, ice shelves, thermal oceanic circulation, stability of foundations for offshore wind farms, foundations for roads and buildings in thawing permafrost, and nuclear waste disposal. The ability to adjust gravity also can be a valuable tool by which experiments illuminate microscale phenomena like the stability of liquid bridges between particles and interactions between gravity forces and interparticle cohesive forces.

Opportunities for new hypergravity research thus span a wide range of engineering and scientific disciplines, including many subdisciplines of civil and mechanical engineering, materials science, geosciences, glaciology, arctic sciences, oceanography, combustion sciences, and plant physiology. Many centers that operate centrifuges are enthusiastic about expanding the range of scientific questions their facilities are exploring through collaborations with scientists and engineers in other disciplines, and those interested in new opportunities are encouraged to reach out with questions.

The centrifuge facilities at UC Davis are available for use by all, and NSF operations support allows NSF-funded users access to the facilities at minimal cost to the user. The CGM provides guidance, training, and support for a diverse user base (e.g., more than 100 researchers under more than 50 principal investigators on more than 50 projects by more than 10 agencies/companies since 2000). Potential users are invited to leverage this local expertise in developing novel applications of hypergravity testing.

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