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FEBRUARY // MARCH 2025

UNSATURATED SOIL GEOTECHNICS

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GEOSTRATA
February // March 2025

Departments

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// From the President

HELEN ROBINSON

Geomorphing Our Image

I've been wondering, how did YOU enter the geo-profession? Did you dress up as a Geotech professor for Halloween? When adults asked what you wanted to be when you grew up, did you say a geologist or a deep foundations contractor? Did you realize in high school, college, or later? For me, it wasn't until after grad school and working six months as a structural engineer designing single-span bridges and culverts that I decided I needed something that was more open to creativity and innovation rather than code-driven solutions.

But I'd already somewhat dismissed geotechnical engineering as a career possibility. When I was about to graduate with a bachelor's degree in civil engineering from Penn State, I decided that I wasn't ready to leave Happy Valley and began considering grad school. Even though I didn't make this decision until well into the spring semester, when many civil engineering professors had already selected grad students for the fall term, the spring of 2001 was a prime time to be a graduate student because Interstate 99 was being constructed through the heart of State College, where PSU is located. For readers not familiar with Pennsylvania highways, I-99 is a perpendicular bisector between the Pennsylvania Turnpike to the south, and I-80 across the mid-section of the state.

This construction meant that PennDOT would be funding multiple research projects, including studies on nonshrink grout for post-tensioned anchors, stresses on curved girder steel bridges, characterization of the pinnacled karstic limestone bedrock in Central Pennsylvania, and many others. Because there were no grad openings with structural engineering professors, I approached Dennis Hiltunen, my professor for foundation design. He was still looking for graduate students to participate in researching nondestructive techniques to map the top of bedrock at the future sites of several I-99 bridge abutments. Those were two wonderful summers, laying out arrays of geophones and collecting data on shear wave velocities to generate subsurface profiles. During one particularly delightful month, Hiltunen rented a CAT-315 excavator, and the grad students had a chance to operate it and take turns slamming the bucket against the ground surface to create the source waves.

Flipping Stereotypes

Despite this great experience and writing a thesis on a geotechnical topic, I still accepted a structural engineering position after grad school, thinking that was ultimately what I wanted to do. Part of my reasoning was the image I had of the geoprofession. I saw my future self at a drafting table in a high-rise building in Philadelphia, designing complex solutions to structural challenges. Standing behind a drill rig opening split spoons and classifying soils didn't fit the image. I wanted to use cutting edge technology and computer programs to compile and analyze data. I didn't see geotechnical engineering as a place where that could happen.

Twenty years later, I look back at all the amazing opportunities I've had to work on high-profile and extremely sophisticated designs, and I'm so thankful for finding a home in the geoprofession. Because I viewed my case as unique, I was reluctant to talk about my meandering journey, assuming that most in our profession had felt strongly compelled toward it. I was surprised to learn that a direct path happens much less often than I expected.

The Social Experiment

In October 2024, I attended and presented at the ASCE Central PA Geotechnical Conference in Hershey, which has a dedicated organizing committee that's delivered a great event for more than 40 years. Lunches at the Conference are buffet style, with circular tables that seat 8-10 people. After introductions and typical engineering shop talk, I asked those around the table to humor me with their career story.

Of the eight people at the table, all had made their way into geotech or related fields by accident. Four of them, including me, had started in other fields of engineering. Three had started in other majors and switched to construction, and then became specialty foundation contractors. One had a parent in a geotech-related field, but ironically said they initially didn't want to follow in their parent's footsteps and never imagined how much they would come to enjoy it.

I've been conducting this little social experiment for the past couple of years. It's so striking how few of our colleagues set out with the intention of joining the geotechnical field. Everyone has a story about how they wandered into it, or a chance occurrence that set them on this path. Contrast this with how passionate and involved our G-I members are. We stand out among other branches of civil engineering as engaged, creative, and involved in the community.

Workforce Development Initiative

Although it seems like many people don't initially plan to enter on our profession, they still end up loving it. Maybe we need to find a better way to tell our story and evoke a different image. Unfortunate stereotypes are out there, making it seem like geotech is a commodity, or construction management is the simplest of the engineering disciplines. Many college applicants are told they should consider engineering because of their affinity for math and science — and then look at the pay scale for branches of engineering and choose chemical or computer engineering from the top of the list.

Our image should be one of scientists and researchers working to understand man-made and natural nonhomogenous and anisotropic materials. Of contractors and equipment operators adapting and inventing tooling to construct deep foundations while battling weather, underground forces, tight tolerances, and time constraints. We are designers calculating bond stresses, drag forces, drivability, heat of hydration, and improvement ratios. With this true image, who wouldn't want to be part of the geoprofession?

That's where the workforce development initiative comes in. Your BOG and the G-I are teaming with other members of the Geo-Coalition to create a new image for our profession. We need your feedback and ideas on positive changes we can make to better reflect who we are and what we do. We need to get the message out to students of all ages, parents, guidance counselors, and all those who could influence young people to consider the geoprofession. I welcome your comments and ideas on how to make this happen. I would also love to hear the story of how YOU became part of the G-I family. GS

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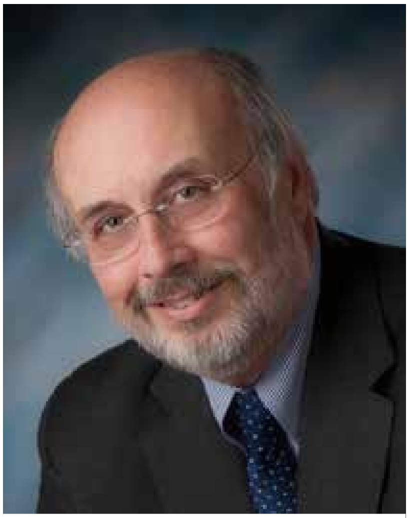
From the Editorial Board



JAMES L. WITHIAM

It's been 14 years since we last devoted an issue of *GEOSTRATA* to the theme of unsaturated soil mechanics. That long-ago issue included articles on laboratory test methods, landfill soil covers in cold regions, pavement construction, and rainfall infiltration landsliding. Of course, these are still topics of interest today, but now, more than a decade later, our "Unsaturated Soil Geotechnics" issue attempts to shine light on a few of the many advances that have surfaced in the intervening years, and hopefully we'll help readers overcome the common misperception that saturated soils represent only the worst case.

What's Inside

Before introducing content related to this issue's theme, I'm proud to say that 2025 marks the completion of *GEOSTRATA*'s 25th year of publication. We're tying that milestone in with another significant event: recognition of the 100th anniversary of the year that Karl Terzaghi began publishing his article series about the Principles of Soil Mechanics in *Engineering News Record.* (To view the entire set of articles in the series, visit *geoinstitute.org/publications/geostrata/ourroots.*) A century later, in our own series for this magazine, geohistorian Michael Bennett will recount the meticulous steps Terzaghi would take to experimentally verify his theoretical assumptions. As his protégé Ralph Peck would later write, for Terzaghi, "theory came last, not first." In the first of Bennett's "Our Roots" series, "Part I – Phenomena of Cohesion of Clay," we learn about the equipment he built and the laboratory testing he conducted to investigate the load-deformation and the shrink-swell behavior of clay. It's an instructive tale that gives us the sense of looking over the master's shoulder.

The all too common, and overly conservative assumption that soil could always become effectively saturated, can result in excessive construction costs or misunderstanding of failure mechanisms. In this issue's commentary, "Are Saturated and Unsaturated Soils Really That Different? No… and Yes," Sandra L. Houston and Xiong Zhang briefly take us through the evolution of unsaturated soil mechanics theory and practice. They compare unsaturated and saturated soil behaviors and conclude that these soil conditions aren't really that different, but it's incumbent upon geotechnical engineers to study the sources of and extent of changes in both total stress and soil water content.

Considered a zero-emission clean energy resource, the growth of nuclear energy has been stymied by the need to isolate its nuclear waste products from humans and the environment for millennia. This technical challenge has been tackled by entombing the wastes in geological repositories, where the wastes are isolated from the host rock by multiple barriers. An engineered clay barrier often serves as a low-permeability buffer around the waste canisters and the host rock that serves as a natural barrier from the environment. In "Unsaturated

Soil Mechanics in Nuclear Waste Repositories," John McCartney and Marcelo Sanchez ask and answer the question, What role does it play? They describe the laboratory testing and engineering analyses conducted to assess the performance of the granular or pelletized sodium bentonite often used. While their work isn't the elixir to solving the challenges of nuclear waste disposal, it's an interesting lesson for us all.

While theoretical understanding of unsaturated soils has advanced significantly, practical applications have lagged behind. One area, field-scale soil moisture monitoring, has faced challenges in sensor performance, instrumentation costs, and long-term maintenance, but as Majid Ghayoomi and Ali Farahani describe in "Soil Moisture From Space," that's changing. They explain how continuous monitoring using earth-observing satellites and SAR is being used to help detect regional changes in soil moisture that can signal the likelihood of events such as landslides, subsidence, or liquefaction.

In the future, we'll need to rely on increased mining for minerals that are critical to clean energy technology, the digital transformation, and attainment of sustainable development goals. To meet these societal needs, however, mining companies will increasingly need to rely on large-scale extraction of ever-lower-grade ores, which will yield vast volumes of waste mine tailings. To avoid the problems associated with traditional tailings storage facilities, such as liquefaction and downstream runout of liquidy volumes of waste, industry is considering alternative management strategies that minimize the amount of water sent to and stored in tailings facilities. In "Unsaturated Tailings Landforms," Joseph Scalia IV and Christopher Bareither introduce filtered tailings stacks as a future approach for tailings management. In addition to technological needs to rapidly dewater the tailings and dispose of them, they describe application of filtered tailings geotechnics for design of the filtered tailings stacks.

Limit equilibrium methods and Terzaghi's principle of effective stress are routinely used in engineering practice to assess the stability of slopes for saturated and dry conditions. In recent decades, however, this approach has been extended to unsaturated soil conditions by using the suction-stress-based effective stress. In "Putting the Brakes on Landslides," Ning Lu and Alexandra Wayllace illustrate this type of analysis by using a case history study of a recurring embankment slide that's triggered by infiltration of annual snowmelt located on I-70 near the Continental Divide in Colorado. They discuss how the embankment slope can be effectively analyzed using Bishop's simplified routine method of slices under variably saturated soil conditions, to capture the seasonally dependent, late spring embankment instability that characterizes the slope.

Climate changes almost all infrastructure, including components making up the nation's electric power. And because of their large footprint, electrical power distribution systems are particularly vulnerable to threats from severe weather. In "Earth, Wind, and Ice," Tommy D. Bounds, Gerald A. Miller, and K. K. (Muralee) Muraleetharan report on their analytical investigation to study the impact of soil moisture on the response of power poles during ice storms. They conclude that the impacts of soil moisture must be a factor when grid-hardening strategies are being developed. If soils at a site are sensitive to changes in moisture and influenced by drought, power poles should have larger cross-sections or be made using

// GeoCartoon

Drying up.

stronger material. At sites where soils are typically saturated and/or flooded, poles should be retrofit with guy wires or other foundation supports because during extreme loading events, it's not the pole, but the foundation that's not up to the task.

The semiarid climate in Adelaide, South Australia's capital, causes the clay above the groundwater table to remain unsaturated, with generally high suctions that aid the stability of unsupported deep excavations in the clay. It's this soil profile to which author Bosco Poon applies unsaturated soil mechanics theory in engineering practice in "Soil Nailing Thirsty Ground." The relatively deep groundwater level and predominately unsaturated and nonfissured clay ground conditions encountered at the project site were ideal for a soil nail wall designed using unsaturated soil mechanics, resulting in a lighter retaining structure and significant cost savings.

Today's infrastructure is built mostly on unsaturated soils, but contemporary design methods generally presume the soil is fully saturated. This premise is based on the idea that designing for saturated soil conditions results in conservative outcomes, but this isn't always the case. An example is assuming a fully saturated subgrade can lead to ineffective drainage designs in pavement structures. Xiong Zhang, Nripojyoti Biswas, John M. Lostumbo, and René Laprade describe their application of a woven, high-modulus moisture management geosynthetic to control subgrade moisture in "Unsaturated Moisture Management Transforms Pavement Performance." Using case histories from Alaska to Texas, they show how controlling subgrade moisture levels improves road performance and offers a cost-effective, long-term solution to managing moisture-related pavement issues.

This issue's GeoPoem is aptly titled "Vadose Zone." In it, *GEOSTRATA* Editor and Resident GeoPoet Mary Nodine takes us stratigraphically from the ground surface to the water table through the **vadose zone** — that mysterious region where matric suction is as important to soil behavior as total stress and water pressure.

I hope you enjoy reading this issue of *GEOSTRATA*, and maybe learn something along the way. If you have a question or comment, please contact me at *jlwithiam@gmail.com*. GS

This message was prepared by *GEOSTRATA* Editor-in-Chief **James L. Withiam, Ph.D., P.E., BC.GE (Ret.), M.ASCE**. He can be reached at *jlwithiam@gmail.com*.

Board of Governors Update

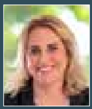
By Susan E. Burns, Ph.D., P.E., F.ASCE

The G-I Board of Governors held its regularly scheduled meeting on Dec. 17, 2024. The Board's activities focused on a range of committee and conference efforts, including planning activities for the conference schedule over the next three years. Geo-Congress 2026 will be held in Salt Lake City, Utah, in March 2026, and Geo-Congress 2027 will be held in conjunction with the other ASCE Institutes in celebration of ASCE's 175th anniversary.

Geo-Congress 2028 will be held in cooperation with the International Society for Soil Mechanics and Geotechnical Engineering, when the G-I hosts the 18th Pan-American Conference on Soil Mechanics and Geotechnical Engineering in Chicago, Ill. XVIII PCSMGE will mark 25 years since the last Pan-American conference, Soil and Rock America 2003, was hosted in Boston, Mass. In November 2024, G-I President **Helen Robinson, P.E., PMP, BC.GE, M.ASCE**, Treasurer **Anand Puppala, Ph.D., P.E., BC.GE, F.ICE, Dist.M.ASCE**, and Governors **Lucky Nagarajan, A.M.ASCE**, and **Katerina Ziotopoulou, Ph.D., P.E., M.ASCE**, traveled to the 17th Pan-American conference in La Serena, Chile, to announce the 2028 conference in Chicago, and to kick off the planning for the event. We look forward to hosting our colleagues from both North and South America, and worldwide, in three years. We look forward to seeing you there!

Geo-Institute Board members at the 17th Pan-American Conference Chile. L to r: Katerina Ziotopoulou, Anand Puppala, Helen Robinson, and Lucky Nagarajan.

2024-25 G-I Board of Governors



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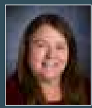
Committees: Local Involvement, Younger Members



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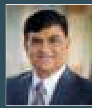
Committees: Awards, Nominations and Elections

Other Activities: *GEOSTRATA*



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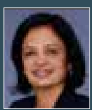

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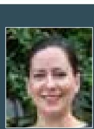
Committees: Geo-Challenge



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As I See It

Are Saturated and Unsaturated Soils Really That Different?

No... and Yes

By Sandra L. Houston, Ph.D., P.E., M.ASCE, and Xiong Zhang, Ph.D., P.E., M.ASCE

Analysis of saturated and unsaturated soils requires that the total stress and pore water pressure be known. Measuring positive pore water pressures is straightforward. Measuring negative pore water pressures, however, was a challenge for unsaturated soil characterization until Bureau of Reclamation dam engineer Jack Hilf introduced the axis translation method for suction control into geotechnical engineering in the 1950s.

Testing unsaturated soils using the axis-translation entails increasing the pore air pressure, $u_{a,}$ sufficiently so that the pore water pressure (u_w) can be increased enough to avoid cavitation of water in the pore water pressure measurement system. Axis translation requires that the total stress (σ) be increased by the same amount as u_a to maintain a constant net stress (σ-u_a), while the matric suction (u_a-u_w) is controlled or measured. Using axis translation to measure negative pore water pressure has led to the development of unsaturated soil theory using the laboratory-demonstrated controlling stress variables of net stress (σ-u_a) and matric suction (u_a-u_w), rather than σ and u_w that's used in saturated soil mechanics.

Basic Principles of Unsaturated Soil Mechanics

Before unsaturated soil mechanics was introduced in the 1960s and 1970s, geotechnical engineers already had a strong understanding of saturated soil mechanics, and the role of the stress variables σ and u_w, and Karl Terzaghi's effective stress principle. But using net stress (σ-u_a) and matric suction (u_a-u_w) as controlling stress variables was met with some mystique. Suction measurement challenges also led to the use of total suction measurement methods, and associated complexities in defining matric suction in an easily-understood manner. Regrettably, the early tensiometers used to measure matric suction (negative pore water pressure) had problems with water cavitation that weren't overcome until the 1990s, when high-capacity tensiometers became available that could measure negative u_w down to 1.5 to 2.6 MPa. So unsaturated soil mechanics had an uneven beginning compared to saturated soil mechanics.

The controlling stress variables for saturated and unsaturated soils may appear at first glance to be different. But for the most common field condition wherein unsaturated soils have interconnected air voids, and air pressure is atmospheric (u_a=0), the net stress (σ-u_a) becomes σ, and the matric suction (u_a-u_w) becomes -u_w. So at atmospheric air pressure conditions, for saturated and unsaturated conditions, soil shear strength and volume change behavior are controlled by the same two stress variables, total stress and pore water pressure. For unsaturated soils, u_w is negative, while for saturated soils, u_w can be positive or negative. For saturated conditions, σ and u_w can be combined into a single effective stress that controls volume change and shear strength response. For unsaturated conditions, however, σ and u_w cannot be combined into a single stress variable like for saturated soils. The key to unlocking questions regarding similarities and differences in unsaturated and saturated soil response lies in developing a deeper understanding of the role in soil response of the two stress variables, σ and u_w, particularly for transitions between saturated and unsaturated conditions.

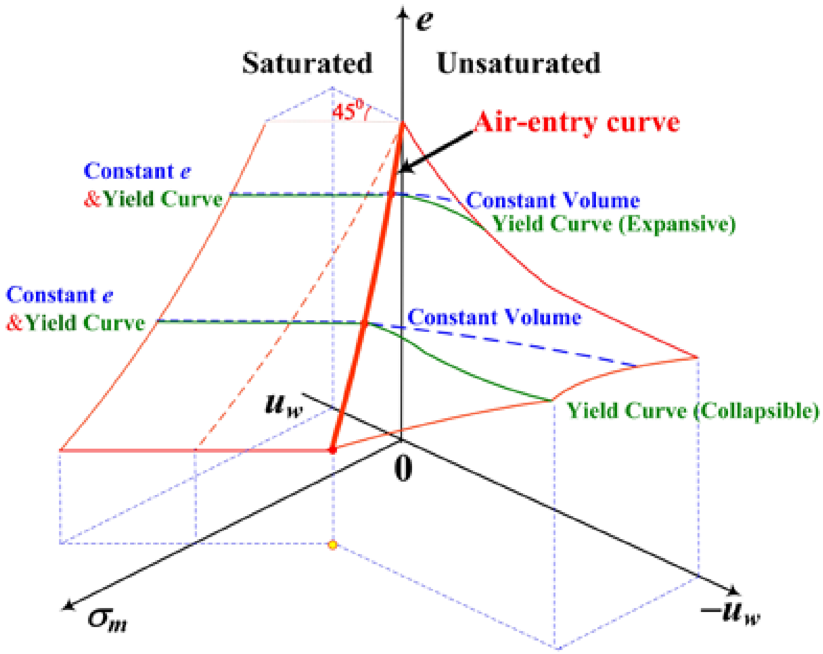

Figure 1. A schematic showing key features of the saturated-unsaturated transition under isotropic conditions.

Seeking a Smooth Transition

There's been an emphasis in unsaturated soil mechanics research to demonstrate that the unsaturated case merges smoothly to saturated effective-stress-based soil mechanics. This focus has led to ongoing searches for an equivalent "effective stress" model for unsaturated soil, but there's been a troubling inconsistency between expectations developed for effective stress for saturated soils and unsaturated soil responses for the various attempted unsaturated soil effective stress definitions. For example, using a traditional volume-change-based effective stress definition, χ-values in Bishop's-type unsaturated soil effective stress equations are both stress-path and stress-history dependent, even under isotropic conditions. Values of χ vary from positive to negative along constant volume paths, and soil yield occurs along constant effective stress paths — arguably a troublesome result.

Shear-strength-based definitions for unsaturated soil effective stress have resulted in several empirical shear strength equations that require an incremental approach and are restricted to limit equilibrium problems. Empirical unsaturated soil shear strength equations have been used extensively and successfully in the study of rainfall-induced slope failures and other limit equilibrium analyses. Although the terminology of "effective stress" is often seen in the unsaturated soils literature, it's confusing to refer to such shear-strength-based equations as "effective stress" because these equations do not function analogously to Terzaghi's effective stress for saturated soils. Saturated soil effective stress is volume-change based and can be used for both shear strength and volume change applications, whereas an unsaturated soil "effective stress" equation developed on the basis of shear strength will not work in applications of unsaturated soil volume change.

The transition between saturated and unsaturated soil conditions occurs at what's called the air entry value, which is the value of -u_w when air enters the void space and begins to become interconnected. To understand the

	SIMILARITY	DIFFERENCE
1	Total stress and pore water pressure control the behavior of both saturated and unsaturated soils.	Terzaghi's effective stress principles are only valid for saturated soils.
2	Saturated and unsaturated soils exhibit elastoplastic behavior (recoverable and nonrecoverable strains upon loading and unloading from the virgin state), and stress-strain responses are stress-history and stress-path dependent.	For saturated soils, elastoplastic response can be viewed for isotropic conditions in 2D e-σ′ plots. For unsaturated soils, elastoplastic response is best viewed in 3D plots because σ and u_w cannot be combined into a single controlling stress variable.
3	Saturated and unsaturated soil shear strength depends on σ and u_w.	Unsaturated soil shear strength depends on σ and $-u_w$, and usually (except for clean sands or gravels) increases as u_w becomes more negative by soil drying.
4	Saturated and unsaturated soil volume change depends on σ and u_w.	When u_w is increased under constant σ, a saturated soil will always expand. An unsaturated soil may compress or expand at constant σ when u_w is increased (i.e., becomes less negative by wetting), depending on the magnitude of σ and soil type.
5	Flow through saturated soils and unsaturated soils is governed by Darcy's law.	Water moves differently through unsaturated soils than what would be expected with saturated flow thinking. The hydraulic conductivity of an unsaturated soil is a strong function of $-u_w$, and clay can have a hydraulic conductivity that's greater than sand for some unsaturated conditions.

Table 1. **Important similarities and differences between saturated and unsaturated soils.**

saturated-unsaturated transition, it's helpful, as shown in Figure 1, to separate the two soil-stress-state variables, mean total stress (σ_m) and pore water pressure (u_w), to show the soil's void ratio change to changes in stress state. For saturated soils, the constant void ratio and yield curves are coincident and inclined at 45 degrees to the σ_m and u_w axes. For unsaturated soils, the constant void ratio and yield curves deviate from 45 degrees and no longer coincide, creating the reason for keeping σ and u_w separate. Although early unsaturated soil researchers thought that only collapsible soils were problematic in defining an effective stress, this divergence occurs whether the soil is expansive or collapsible.

For saturated soils, a change in pore water pressure of 50 kPa, while holding total stress constant, produces the same void ratio change as a 50 kPa change in total stress while holding pore water pressure constant. In contrast, for unsaturated soils, a 50 kPa change in pore water pressure (negative) produces a different change in void ratio than does a 50 kPa change in total stress. As a consequence, unsaturated soil yield and constant void ratio curves diverge, which is the root to the indefinability of effective stress for unsaturated soils. It's impossible to find a single stress variable equation for unsaturated soils that satisfies all of the expectations established for Terzaghi's effective stress in terms of volume change, yield, and shear strength.

In addition to saturated and unsaturated soils sharing total stress and pore water pressure as volume change and shear-strength-controlling stress variables, there are several other bases upon which it could be said that saturated and unsaturated soils are not that different. But there are also several behaviors that differ *significantly* between saturated and unsaturated soils, largely due to the high nonlinearity of unsaturated soil responses to changes in negative pore water pressure. Table 1 highlights the most important behavioral similarities and differences between saturated and unsaturated soils.

So What's the Big Deal?

Given the prevalence of construction that occurs above the groundwater table, almost every geotechnical engineer must perform unsaturated soil investigations, analyses, and designs. But too few geotechnical engineers have any exposure to unsaturated soil mechanics theory. The all too common — and overly conservative — assumption that soil always becomes effectively saturated can result in excessive construction costs or misunderstanding of mechanisms of failure. For example, stable unsaturated soil slopes may be judged unstable where negative pore water pressure shear-strength-increase effects are not considered, and can lead to costly and unnecessary slope stabilization projects. As another example, well-intentioned gravel drain installations have failed because under high negative pore water pressure conditions, water moves more readily through fine-grained soils than through coarse-grained soils.

These points and others are highlighted in case history articles in this issue of *GEOSTRATA*. For example, Bosco Poon describes how considerable money was saved on a soil nail project by taking advantage of increased soil shear strength using conservatively estimated negative pore water pressures based on field suction measurements. Then, Ning Lu and Alexandra Wayllace discuss improvements to identify landslide triggering mechanisms by considering the shear strength reduction effects of soil wetting (i.e., less negative water pressure) and a rising groundwater table (i.e., increased positive pore water pressure) to assess the stability of an unsaturated slope. Lastly, Xiong Zhang, Nripojyoti Biswas, John M. Lostumbo, and René Laprade report on the use of geotextile wicking materials to deliver cost-savings and performance improvements of pavement systems using a novel application of unsaturated soil flow theory.

So, are saturated and unsaturated soils really that different? No, because the volume and shear strength response, for all soils, is controlled by total stress and pore water pressure. As pointed out by unsaturated soil constitutive modeler and researcher Antonio Gens, an unsaturated soil is just a state of the soil, not a special type of soil. Geotechnical engineers must anticipate and design for changes in total stress and changes in pore water pressure, regardless of whether the soil is saturated or unsaturated. But important differences exist between saturated and unsaturated soil behavior that must be considered when dealing with unsaturated soil problems. So, yes, unsaturated soils are different because they have negative pore water pressures that are water content-dependent, and their behavior is strongly and nonlinearly linked to degree of saturation. Therefore, for unsaturated soil site investigations, it's incumbent upon geotechnical engineers to study, separately, the sources of and extent of change in both total stress (e.g., from structural loads and fills) and water content (e.g., from surface water and groundwater changes).

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Terzaghi's Principles of Soil Mechanics

PART I: Phenomena of Cohesion of Clay

By Michael Bennett, P.E., M.ASCE

Karl Terzaghi was to geotechnical engineering what Babe Ruth was to baseball and Elvis was to music. Each brought an entirely new skill set to their discipline and then used those skills to revolutionize what was already there. In some ways, Terzaghi's contributions are even more outstanding. The rock and roll age was already underway by the time Elvis swiveled his hips onto *The Ed Sullivan Show*, and the Major Leagues were nearly 50 when Ruth began swatting baseballs into grandstands. By contrast, Terzaghi brought the geotechnical discipline of civil engineering into existence almost single-handedly. Knowledge on foundation and earthwork engineering problems at the dawn of the 20th century consisted of a thicket of disconnected mathematical theories, jumbled experiential know-how, and clashing theoretical and practical approaches among practitioners. It was Terzaghi who performed painstaking experimental and analytical work to construct a unified system of knowledge that gave civil engineers an effective, robust approach to explore and solve soil mechanics and foundations conundrums.

"Rarely has the development of one branch of human endeavor been so largely the result of the efforts of a single individual," his protégé Ralph Peck marveled two-thirds of a century after *Erdbaumechanik*, Terzaghi's trailblazing volume on soil mechanics, was published in 1925. Yet Peck's remark touched upon a lingering question of how the tale of that development is best told. Typically, geotechnical engineering's origin story has focused less on the history of technical contributions than on the lives of those who made them. This approach to recounting geotechnical history follows what professional historians call the "great man theory" and has resulted in a certain degree of hero worship within the profession, most notably for Karl Terzaghi. "The story of this engineer's life and career," late geotechnical professor and acclaimed engineering historian Henry Petroski noted, "sometimes takes on mythic proportions, something Terzaghi himself seems not to have discouraged."

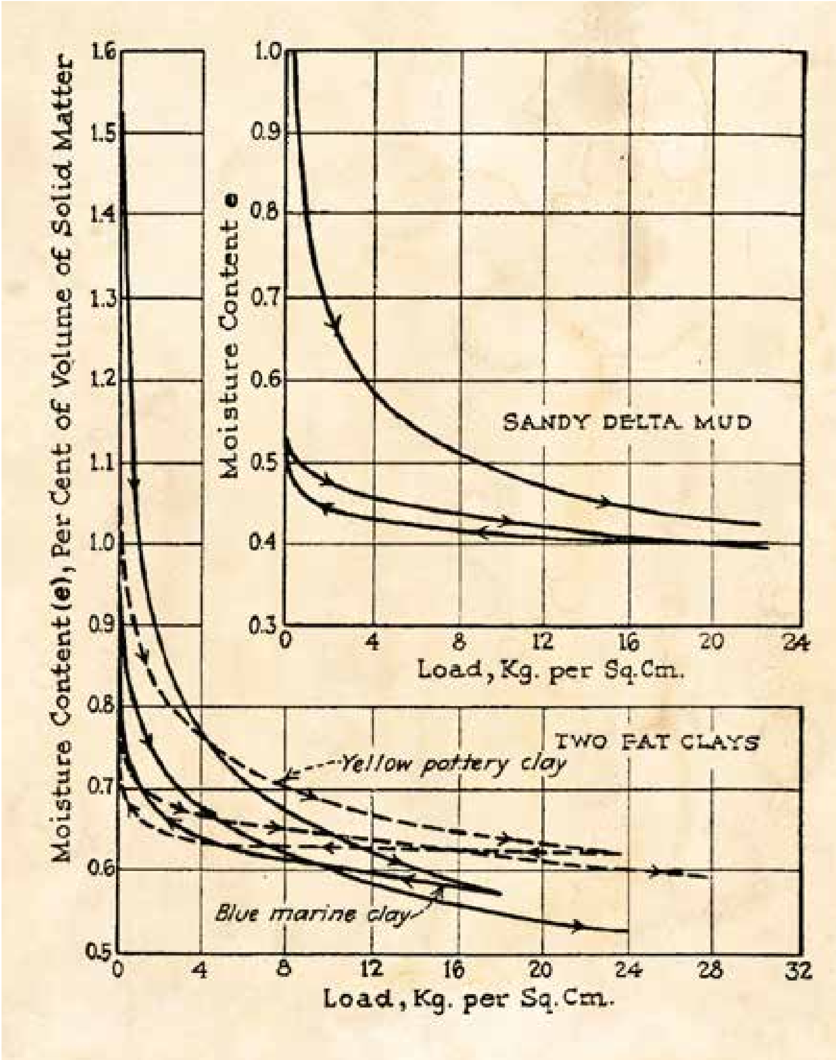
Karl Terzaghi may have smiled upon these efforts, but like all pioneers, he keenly appreciated that the truth was far more nuanced. Later in life, he called geotechnics a "revolution which had already become inevitable" by the time he started exploring the subject. He added, poetically, that he "had only laid the foundation" for the discipline and that "the edifice remained to be created." It seems worthwhile now as the discipline enters its second century, for Terzaghi's professional heirs to more carefully examine his foundational contributions to it through his eight-part *Engineering News-Record* series. (Editor's note: To read the entire series, please visit *geoinstitute.org/publications/geostrata/ourroots.*) In Part I of the series, Terzaghi, fresh off his 42nd birthday, looked at the physical nature of clays.

Part I – The Physical Nature of Clays

Terzaghi began his *ENR* article by reviewing the results of load-deformation tests he conducted during his time at Robert College in Istanbul, since renamed Boğaziçi University, during the period immediately following World War I. He had already showcased these findings in April 1924 at the International Conference on Applied Mechanics in

Delft, the Netherlands, and they had been well-received, but *ENR* offered him the chance to display them to a far larger audience. The oedometers Terzaghi had built for his consolidation tests had been snazzy in comparison to his other Istanbul lab equipment, which had largely consisted of scavenged items, such as cigar boxes and kitchen utensils. His oedometer for lower stress testing consisted of a glass cylinder roughly 5 in. high and 4 in. in diameter, filled halfway with a highly viscous clay-water mix and, above that (and a layer of filter paper), with quartz sand. The clay was then loaded using a container filled with increasing amounts of buckshot to induce deformation. The higher stress oedometer consisted of submerged brass rings into which the viscous clay slurry was placed; these specimens were then loaded using bronze plates rather than buckshot.

Terzaghi used his oedometers to incrementally load each clay specimen under pressures ranging from 0.1 to 20 kg/cm^2 (roughly 1.5 to 285 psi). He tested each specimen in a cycle of loading to 20 kg/cm^2, unloading to zero load, and reloading to 20 kg/cm^2. Between each load increment, Terzaghi removed a sample of material from the specimen to test its water content, taking pains to make sure the specimen didn't reabsorb water in the meantime. Finally, with his data compiled for the three types of clay he tested, Terzaghi plotted specimen water content versus the stress imposed on the soil. He expressed this water content as a percentage of its solid volume. Current geoprofessionals will recognize that this expression matches the modern definition of void ratio, *e*, for essentially saturated soils such as viscous clay slurries. This is precisely what Terzaghi had in mind, as evidenced by both his use of the variable *e* to connote this value, and his introduction of the term "void ratio" for *e* in later articles in his 1925 *ENR* series. Even 100 years and generations of geoprofessionals later, it's genuinely exciting to see a key geotechnical term make its debut!



Pressure-moisture curves for three clays.

Terzaghi brought plenty more modern geotechnical concepts into his discussion of these deformation test results, some explicitly and others implicitly. His plots of compressive stress versus void ratio have arithmetic x-axes, not logarithmic, but otherwise closely resemble those found in current geotechnical laboratory results. The compressive stresses were total — Terzaghi was saving his introduction of effective stress for a forthcoming *ENR* installment — but the limited height of soil and depth of water in his experiments meant that the total and effective stresses were nearly identical. From the plots, Terzaghi determined that the stresses he applied to his clay specimens drove a difference in water pressure within them. He correctly concluded that the expulsion of water from the specimens, which occurred as these pressures equilibrated, was what drove their deformation. Terzaghi thus set the stage for the introduction of consolidation in a later article in the *ENR* series. Yet even without it, the information he revealed through his plots alone is critical to current geotechnical practice. Modern geoprofessionals assess the compressibility of fine-grained soils to predict the settlement of the structures and infrastructure they design on a near-daily basis, and the conceptual framework through which they do so hearkens

> Even 100 years and generations of geoprofessionals later, it's genuinely exciting to see a key geotechnical term make its debut!

back to these early studies by Terzaghi.

The opening portion of Terzaghi's study of clay deformation under loading also highlights his keen attention to detail. One example came when he observed that the loaded clay specimens, only a few centimeters thick, nonetheless never took "less than about 24 hr." to reach hydrostatic equilibrium and stop deforming under a load increment. A century later, lab geoprofessionals running consolidation tests must still ensure that they end the load increments for these tests based on when primary compression is complete within each increment, not on the passage of an arbitrary interval of time. Another came when Terzaghi performed moisture content tests to verify that his clay specimens weren't absorbing free water during the brief periods between load increments when he unloaded them to sample material for moisture content testing. The testing established that next to no reabsorption occurred, confirming what most geoprofessionals might intuitively suspect. Yet it was utterly characteristic of Terzaghi to verify this assumption experimentally. "Only when Terzaghi felt that he understood the phenomenon on the basis of intensive study of the data from tests on real foundation materials did he turn his attention to a mathematical theory embodying the results," recounted Ralph Peck; for Terzaghi, "theory came last, not first."

Terzaghi followed his then-revolutionary review of clay behavior under stress by examining the tendency of such soils to shrink and crack as they dry. He deduced from the hydrodynamically driven compression of clay specimens under loading that their deformation as they dried must similarly be caused by a difference in water pressure. This initially puzzled Terzaghi because the numerous clay specimens that he prepared for, and observed in, air drying were under zero external load. Eventually, though, he realized that the differential water pressure driving the shrinking and cracking of the clay specimens as they desiccated actually involved *negative* pore water pressures developing along their edges and exposed surfaces. Terzaghi concluded that the water on these surfaces developed surface tension as it began evaporating that ultimately caused the specimens to crack.

Terzaghi's observations on tensile stresses in clays dovetail nicely with a section, a few paragraphs later, on variations in the properties of capillary water and demonstrate the same technical insight and expertise he had already shown in his studies of clay deformation under loading. A century later, far more detailed work has superseded his early forays into unsaturated soil mechanics. Elements of the subdiscipline have certainly found their way into routine geotechnical work. For instance, geoprofessionals in the lab realize that inadequately saturated sand samples undergoing triaxial testing can develop negative pore water pressures. If these fall to -14.7 psi (-1 atm.), the pore water can undergo cavitation, forcefully releasing gas out of solution and essentially ruining the test results.

However, Terzaghi's insights on unsaturated soil mechanics and capillary water behavior have yet to gain as much traction in geotechnical practice as his observations on the deformation of loaded clays. The current standard of care among geoprofessionals is to assume that groundwater pressure is zero above the phreatic surface, which is assumed to coincide with the water table, and increase linearly below that. This conservatism can be prudent, such as when it leads to not counting on unreliable negative pore water pressures above the phreatic surface for additional soil shear strength. On some level, though, such assumptions are less conservative than they're reflective of a lack of broader understanding of the fundamentals of such matters. Australian researcher David Isaacs, tackling questions of pile dynamics a few years after Terzaghi penned his 1925 *ENR* articles, referred to the distinction as one of "factors of safety" versus "factors of ignorance." Only more recently have geoprofessionals started to question some of their long-standing practices regarding unsaturated soil mechanics (coincidentally the theme of this issue of *GEOSTRATA*) and capillary water behavior.

One final topic Terzaghi examined in Part I of his article series was the swelling of clays. His thoughts on this subject have not necessarily held up as well as his insights on those he had reviewed earlier. Terzaghi started off strong by noting that unloaded, unsaturated clay specimens with access to free water swell due to the difference in water pressure across the specimen, provided that their volumes can change. (In modern geo-parlance, he might say that such swelling can only occur if a drained condition exists.) However, Terzaghi then concluded on this basis that cohesion in clays was entirely due to surface tension.

Geopractitioners in 2025, of course, have a significantly better and more nuanced understanding of the nature of clays. They appreciate how influences such as these soils' mineralogy, specific surface area, and cation exchange capacity contribute to their behavior. Discoveries of the geotechnical importance of these factors began playing out even within the prime of Terzaghi's career, and he readily adapted his ideas to the new findings. In the mid-1940s, he and Ralph Peck had Ralph Grim, Peck's colleague at the University of Illinois and a pioneering researcher of clay behavior, review and provide suggestions for a section on clay composition in their book *Soil Mechanics in Engineering Practice*. The final version of the section represents a quantum leap forward from Terzaghi's relatively rudimentary thoughts on the subject in 1925. Still, it's far easier to write such retrospective criticisms of Terzaghi's pioneering work than it was for him to undertake that work without any body of geotechnical knowledge to consult. The tally of his mistaken technical ideas during that time pales in comparison to the list of those he got right, and Part I of Terzaghi's 1925 *ENR* series ably demonstrates that.

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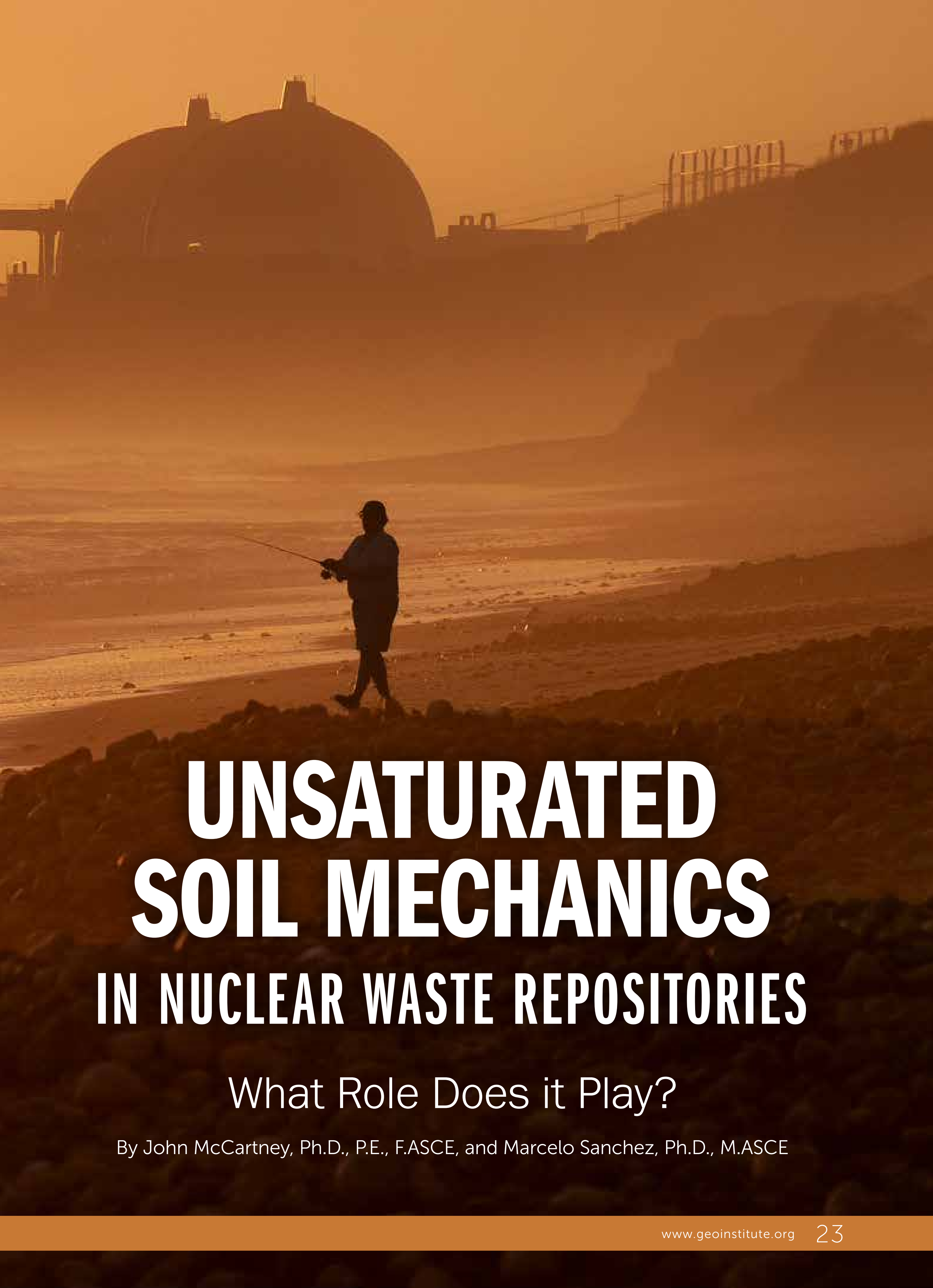
The now closed San Onofre Generating Station.



UNSATURATED SOIL MECHANICS IN NUCLEAR WASTE REPOSITORIES

What Role Does it Play?

By John McCartney, Ph.D., P.E., F.ASCE, and Marcelo Sanchez, Ph.D., M.ASCE

Nuclear energy is considered a zero-emission clean energy resource that's key to reducing our country's reliance on fossil fuels. One challenge with nuclear energy is that spent uranium fuel remains radioactive and must be isolated from humans and the environment for millennia, so the safe, long-term disposal of radioactive waste is a major technical challenge. The most common disposal approach under consideration internationally is storing waste canisters in deep geological repositories.

While the U.S. Department of Energy has pursued the idea of a centralized geological repository for commercial nuclear waste at the Yucca Mountain facility in Nevada (Figure 1), technical, economic, and political issues remain. Until this point, most nuclear power plants in the U.S. are storing spent fuel on-site until a repository is available, like at the San Onofre Power Plant, which hastens the need for research and development on this topic. Other possible long-term storage options have been investigated, but geological repositories remain the main option for the future. For example, subsea storage was investigated, but has since been banned by international treaties, and deep borehole storage follows a similar concept to geological repositories, but without the same level of construction quality control.

Geological repositories for high-level nuclear waste and spent nuclear fuel are based on the multibarrier concept. The barriers include a metallic canister encapsulating the HLW/SNF, an engineered clay barrier that serves as a low permeability buffer around the canister, and the host rock that serves as a natural barrier from the environment. The multibarrier concept should provide sufficient waste isolation to limit the migration of radio nuclides to the biosphere for extended periods of up to a million years, according to some regulations. The main candidate rock types are granite and claystone. Alternate designs that don't use a bentonite layer have also been implemented in rock salt, like in the Waste Isolation Pilot Plant, which is used for defense-related waste. Construction of a repository will involve the excavation of a network of horizontal access drifts, located approximately 400 m below ground level or deeper to provide suitable isolation from the environment.

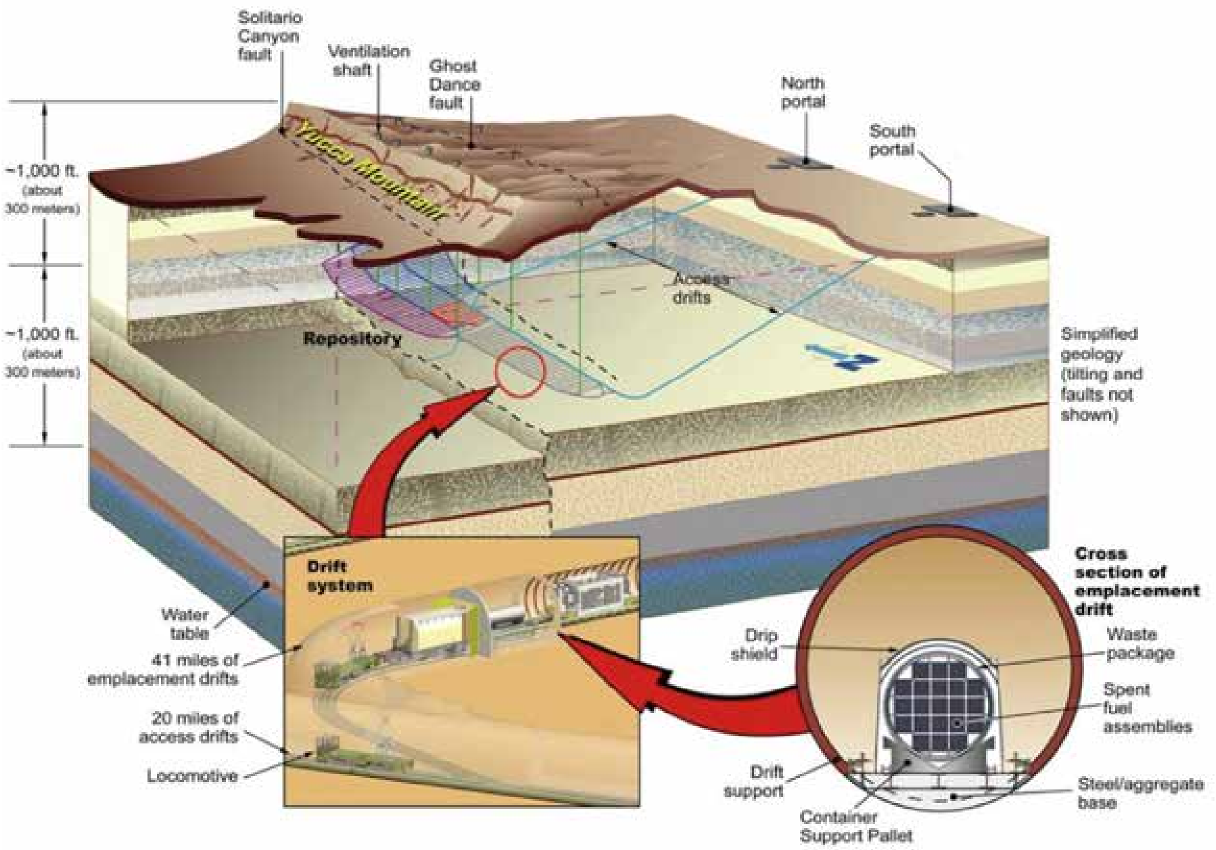


Figure 1. Conceptual layout of a possible Yucca Mountain high-level nuclear waste geological disposal facility. (Image courtesy of U.S. Department of Energy.)

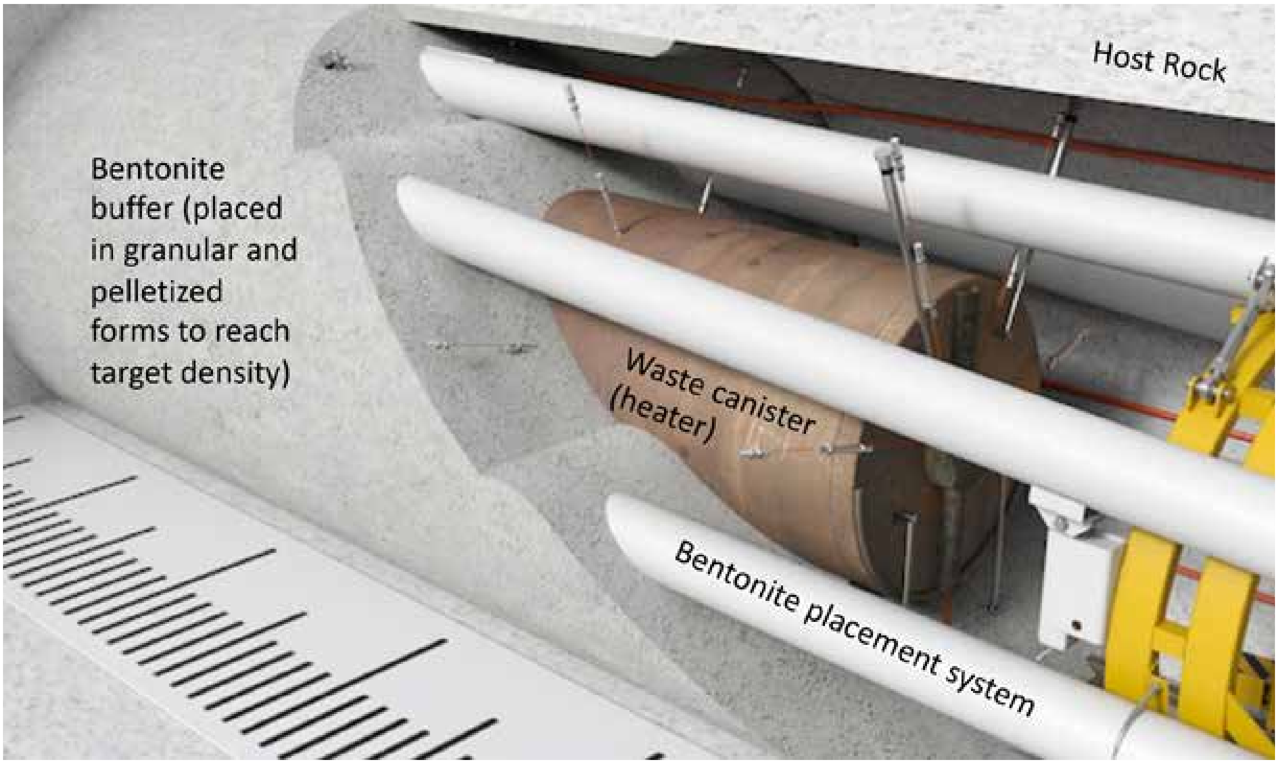


Figure 2. A typical geological repository illustrating the multibarrier concept of a metal canister placed into the host rock with surrounding bentonite backfill (modified after Grimsel Test Site).

Features of HLW/SNF Repository Waste Burial

A key component in a HLW/SNF geological repository of relevance to geotechnical engineers is the engineered clay barrier or engineered barrier system, or EBS, between the cylindrical waste canister and the surrounding host rock, which consists of granular or pelletized sodium bentonite. In most geological repositories (Figure 2), the waste canister is placed horizontally within a cylindrical cavity drilled into the host rock atop a pedestal of compressed bentonite, after which loose bentonite in granular or pelletized form is packed into the space between the canister and host rock. The bentonite buffer is initially unsaturated with a low initial gravimetric water content of about 10-15 percent and, when placed loosely around the canister in granular form, has a density of 1.3 Mg/m^3 and a degree of saturation of 0.35. The bentonite buffer must become saturated to provide a low-permeability seal around the waste canister, a process that's referred to as "hydration." The transient process of hydration is complex and requires unsaturated soil mechanics to predict.

One challenge with nuclear energy is that spent uranium fuel remains radioactive and must be isolated from humans and the environment for millennia, so the safe, long-term disposal of radioactive waste is a major technical challenge.

Several field and numerical studies have demonstrated that the bentonite buffer absorbs water from the surrounding host rock and tends to swell as it hydrates, generating stresses due to the restraint provided by the relatively rigid host rock and waste canister. At the same time, the waste canister increases in temperature due to the radioactive nature of the waste, leading to thermally induced drying of the bentonite near the heated canister. Because large variations in porosity and permeability are anticipated across the clay barrier backfill thickness, there's a challenge in predicting the saturation time of the clay barrier. A schematic highlighting the coupled heat transfer and water flow processes and gradients in thermo-hydro-mechanical properties is presented in Figure 3.

As the bentonite near the heater dries due to outward vapor diffusion, it will shrink and dry out, which results in a

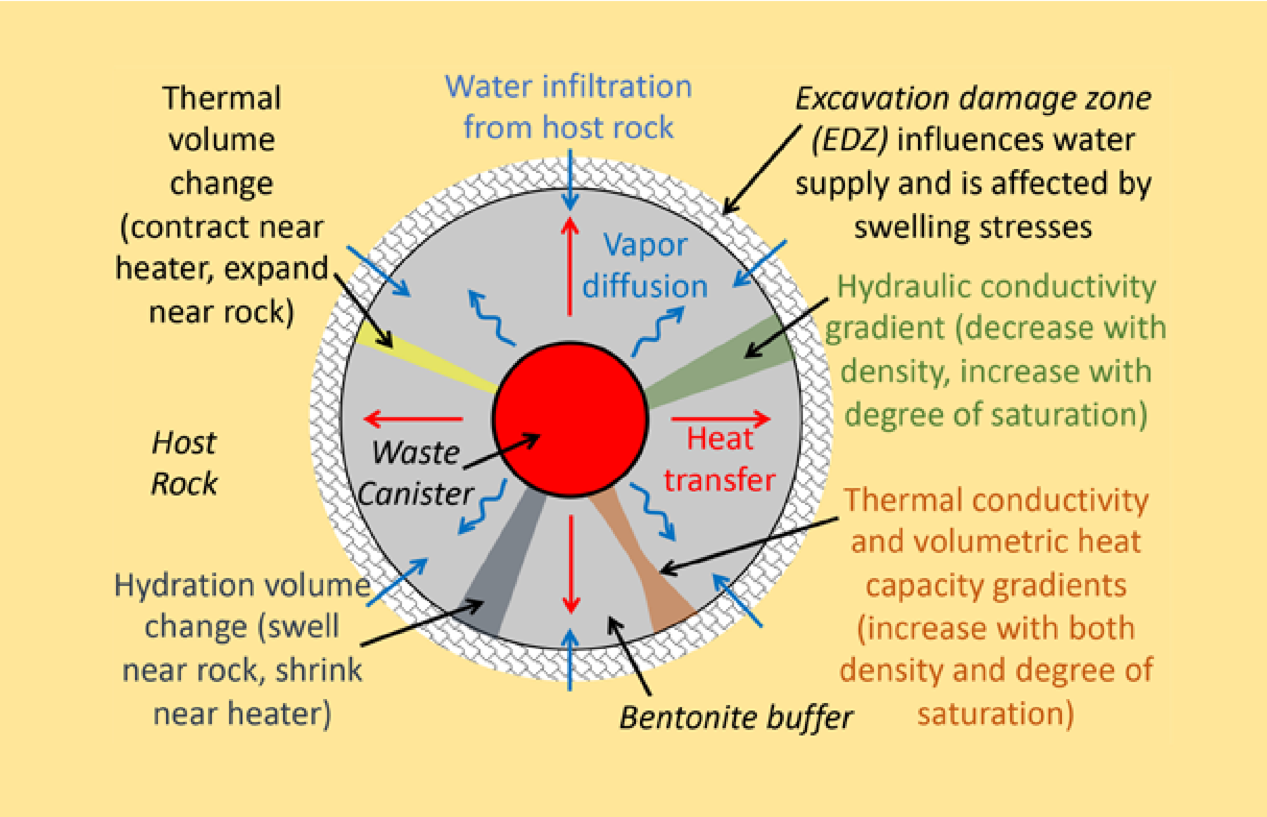


Figure 3. A summary of coupled heat transfer and water flow processes in a bentonite buffer.

possible increase or decrease in thermal conductivity and hydraulic conductivity (depending on the magnitudes of changes in volume and degree of saturation). As the bentonite near the host rock hydrates due to inward liquid water flow, it will swell, and the hydraulic conductivity and thermal conductivity will increase to their values at saturation. Concurrent chemical interactions, including the dissolution/precipitation of minerals and cation exchange, may also affect the behavior and thermo-hydro-mechanical properties of the clay barrier. These types of chemical reactions are slow, so geochemical phenomena become more noticeable over the long term.

Predicting EBS Performance

Experimental and numerical investigations are required to gain a thorough understanding of these complex thermo-hydro-mechano-chemical THMC processes, which control the evolution and long-term performance of an engineered barrier system. Experimental EBS investigations span from microstructural tests to large-scale field experiments, including laboratory "element-scale" tests that evaluate the behavior of an element of soil within the buffer. For example, a good understanding of the clay microstructure is crucial because the behavior of unsaturated compacted clays is largely controlled by electrochemical phenomena occurring at the clay mineral level.

Laboratory tests conducted under controlled conditions help elucidate the effects of temperature, fluid pressures, stresses, and chemical variables on the behavior of unsaturated bentonites, aiding in the development of the associated THMC constitutive models. Instrumented full-scale experiments replicating actual repository conditions are essential for validating geological disposal concepts and THMC numerical models under real operational conditions. In these experiments, electrical heaters simulate the heating load produced by HLW/SNF products.

As for numerical investigations, a theoretical formulation is required to integrate the relevant THMC phenomena into a consistent and unified framework. Once the mathematical formulation is implemented numerically, the resulting computational code can be used to design repositories for HLW/SNF. It's worth mentioning that numerical modeling is a key component in this type of problem, as very long-term predictions (sometimes involving hundreds or thousands of years) are generally required in such analyses. THMC models not only capture these coupled physical processes, but also consider the highly coupled THMC properties. The EBS will be subjected to complex THMC processes. They will be triggered by heat released by the HLW/SNF, hydration of the clay from the surrounding rock, increments of stress induced by progressive wetting and swelling of the compacted bentonite under highly confined conditions, and chemical interactions.

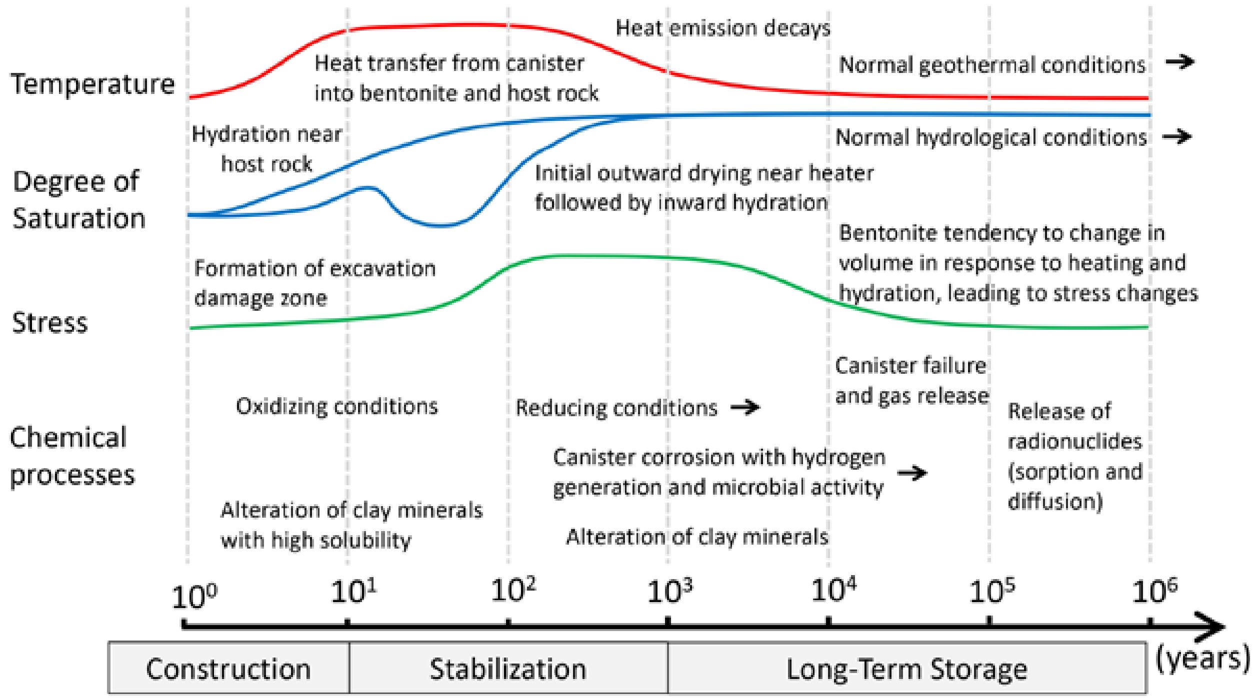


Figure 4. **Thermo-hydro-mechanical and chemical processes in a geological repository.**

Bentonite Buffer Behavior

The combined hydration and heating of unsaturated bentonite may lead to unexpected behavior due to the coupling between THMC processes. For example, in the FEBEX, or Full-scale Engineered Barrier Experiment demonstration project at the Grimsel Test Site in Switzerland, where an electrical heater reached temperatures approaching 100°C, the hydration of the bentonite buffer didn't proceed as quickly as expected. It's been suggested that this unexpected behavior of the EBS was due to the presence of physicochemical phenomena not typically accounted for in standard THMC numerical formulations. Among the potential phenomena impacting on the EBS performance are:

- A progressive reduction in clay permeability associated with the dynamic nature of the clay microfabric, which tends to expand and compress the large macropores between clay aggregates with the associated reduction in permeability
- Thermally induced drying, leading to a decrease in hydraulic and thermal conductivity near the canister
- The presence of a threshold gradient for water flow
- Thermo-osmotic effects

More information is needed to understand the impacts of the relative rates of hydration and heating for the different heating/hydration paths experienced across the buffer radius.

Although the bentonite in a repository is constrained, density gradients may occur within the buffer as the bentonite nearest the host rock swells as it hydrates, while the bentonite closest to the canister experiences thermal volume change. A schematic of the different processes in a bentonite buffer over the course of its lifetime (over 100,000 years) is shown in Figure 4.

The key to understanding the relative rates of hydration and heating on bentonite buffers is knowing the effects of temperature and volume change on the coupled thermo-hydraulic properties of the unsaturated bentonite. These properties include the:

- Soil-water retention curve, or SWRC
- Hydraulic conductivity function, or HCF
- Thermal conductivity function, or TCF
- Volumetric heat capacity function, or VHCF

Many simulations of heat transfer and water flow in bentonite buffers use thermo-hydraulic properties measured at room temperature because models to consider the effects of elevated temperatures aren't yet available for expansive clays. The thermo-hydraulic properties are closely linked with the density of the soil, so the tendency to swell during hydration may lead to localized changes in these properties.

Temperature Drives Performance

Current understanding of how temperature affects the thermo-hydro-mechanical and chemical behavior of the clay buffer is primarily based on studies involving temperature up to 100°C. However, authorities from different countries around the world tasked with developing and delivering geological repositories recognize that enabling safe functioning at temperatures much higher than 100°C (e.g., 200°C) would allow better optimization of the design, emplacement strategies, interim storage, and costs. For example, closer spacing of waste packages or the use of specialized dual-purpose canisters could result in improved performance. While most geotechnical engineers would expect that application of temperatures above 100°C would dry the bentonite, because of the low permeability of the bentonite and the fact that the pore water pressures in the host rock may be very high (on the order of 1 MPa), the THMC processes may occur in super-heated conditions. High Temperature Effects on Bentonite Buffers, or HotBENT, is a new field demonstration that's currently underway at the Grimsel Test Site in Switzerland. This demonstration will provide useful monitoring results from a complex boundary value problem under actual field boundary conditions.

There are significant uncertainties about how the effects of such high temperatures will affect the SWRC and other thermo-hydraulic properties because most studies focused only on temperatures less than 100°C. Various temperatures will affect the water retention differently due to capillary and adsorption mechanisms. At lower matric suctions closer to saturation, higher temperatures will lead to a reduction in water retention due to capillary mechanisms. At the maximum matric suction close to dry conditions, a reduction in water retention is also expected. However, in the lower ranges of degree of saturation that govern the processes in the center of the buffer between the drying front from the waste canister and the hydration front from the host rock, an increase in water retention may be expected up to a certain point because of changes in adsorption. These changes are highlighted schematically in Figure 5. Although the effects of temperature look minor in the figure, the logarithmic scale deemphasizes changes in suction on the order of thousands of kPa with temperature. Because the TCF, VCHF, and HCF are closely linked with the SWRC, changes in the thermo-hydraulic properties at high temperatures may alter the rate of hydration and the corresponding barrier performance of the EBS. Increases in temperature also affect the properties of liquid water, including the viscosity and unit weight, which play a significant role in the magnitude of the hydraulic conductivity.

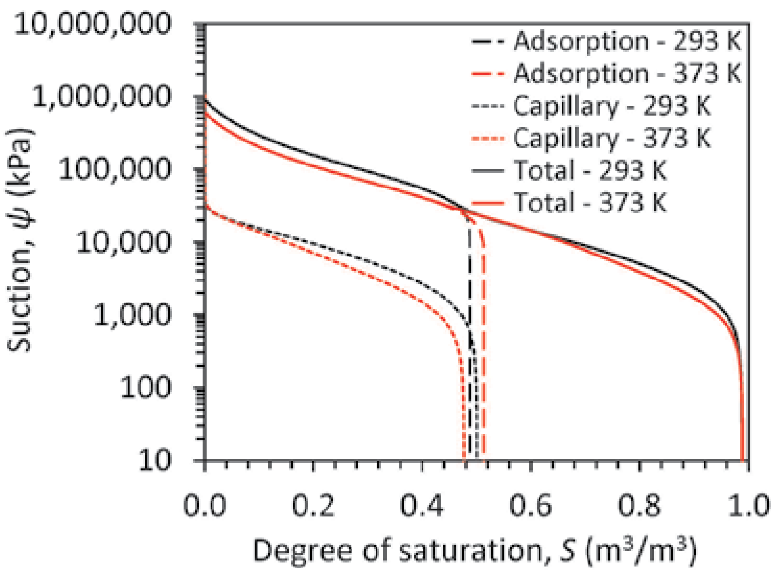


Figure 5. The effects of temperature on the SWRC over the full range of suction.

> No country has yet implemented a system for the permanent and safe storage of this hazardous waste.

High temperatures are also expected to change the swelling behavior of bentonite due to physicochemical phenomena. It's been observed that the swelling pressure of calcium bentonite, saturated with divalent cations, will tend to decrease with increasing temperature, but the swelling pressure of a sodium bentonite saturated with monovalent cations will tend to increase with increasing temperature. The physicochemical phenomena behind this dissimilar behavior have yet to be investigated in detail. Achieving a target swelling pressure is a key to providing the mechanical protection discussed previously, and accurate prediction of this property will be essential when selecting suitable bentonites for a geological repository.

In addition to performing field-scale demonstrations like HotBENT, tank-scale tests in the laboratory may provide insights into the coupled processes to help better simulate the boundary value problem associated with bentonite buffer systems. A typical tank-test setup is shown in Figure 6. The high temperatures are applied at the location of the heater; stresses are maintained by an axial piston; and hydration is applied from the outer radial boundary. Sensors within the bentonite can track changes in water content, relative humidity, temperature, and thermal conductivity.

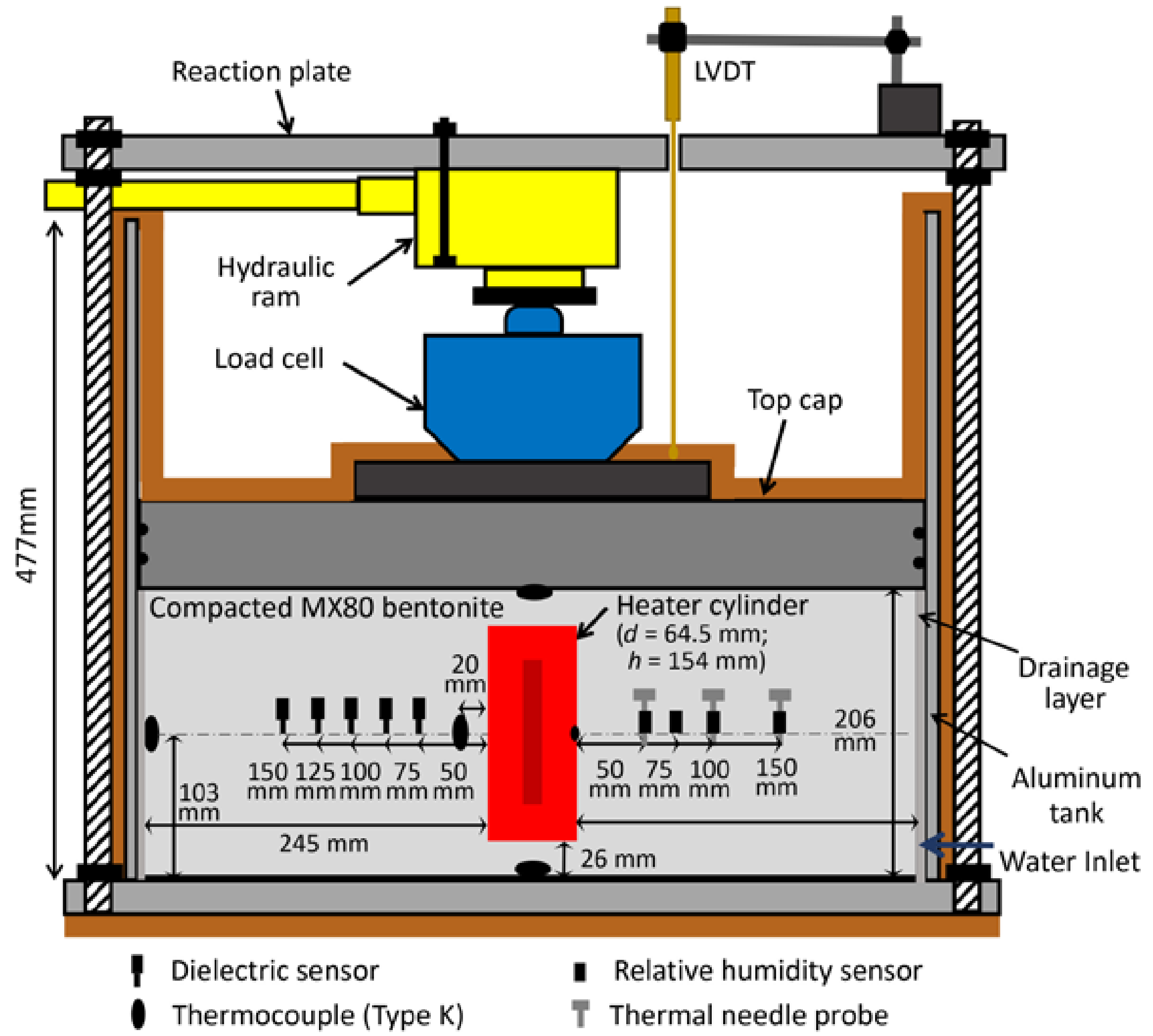


Figure 6. An instrumented tank-scale test to evaluate the THMC boundary value problem during buffer heating and hydration.

Where's This Headed?

The disposal of HLW/SNF remains an unresolved problem; no country has yet implemented a system for the permanent and safe storage of this hazardous waste. The current status varies by country, with most nations still in the planning, research, or pilot stages. Finland is perhaps the country that's progressed the most in this area, with its Onkalo Repository under construction and expected to become the world's first permanent geological repository for spent nuclear fuel. The site is designed to house waste in copper canisters that are resistant to corrosion and encased in bentonite clay, deep underground in granite rock. Sweden and France have selected sites for the construction of their underground repositories. Other countries, like Switzerland and Canada, have identified potential disposal sites and are in advanced stages of the selection process. Some other countries are making progress, but are at early stages. The U.S. is still defining its permanent disposal concept; in the meantime, most HLW is stored on-site at nuclear power plants in dry casks or spent fuel pools.

This unique geotechnical engineering application has undoubtedly expanded our understanding of the response of unsaturated clays, particularly when subjected to very high temperatures of up to 200°C. More research is still needed in this complex area, especially regarding the long-term behavior of EBS materials. GS

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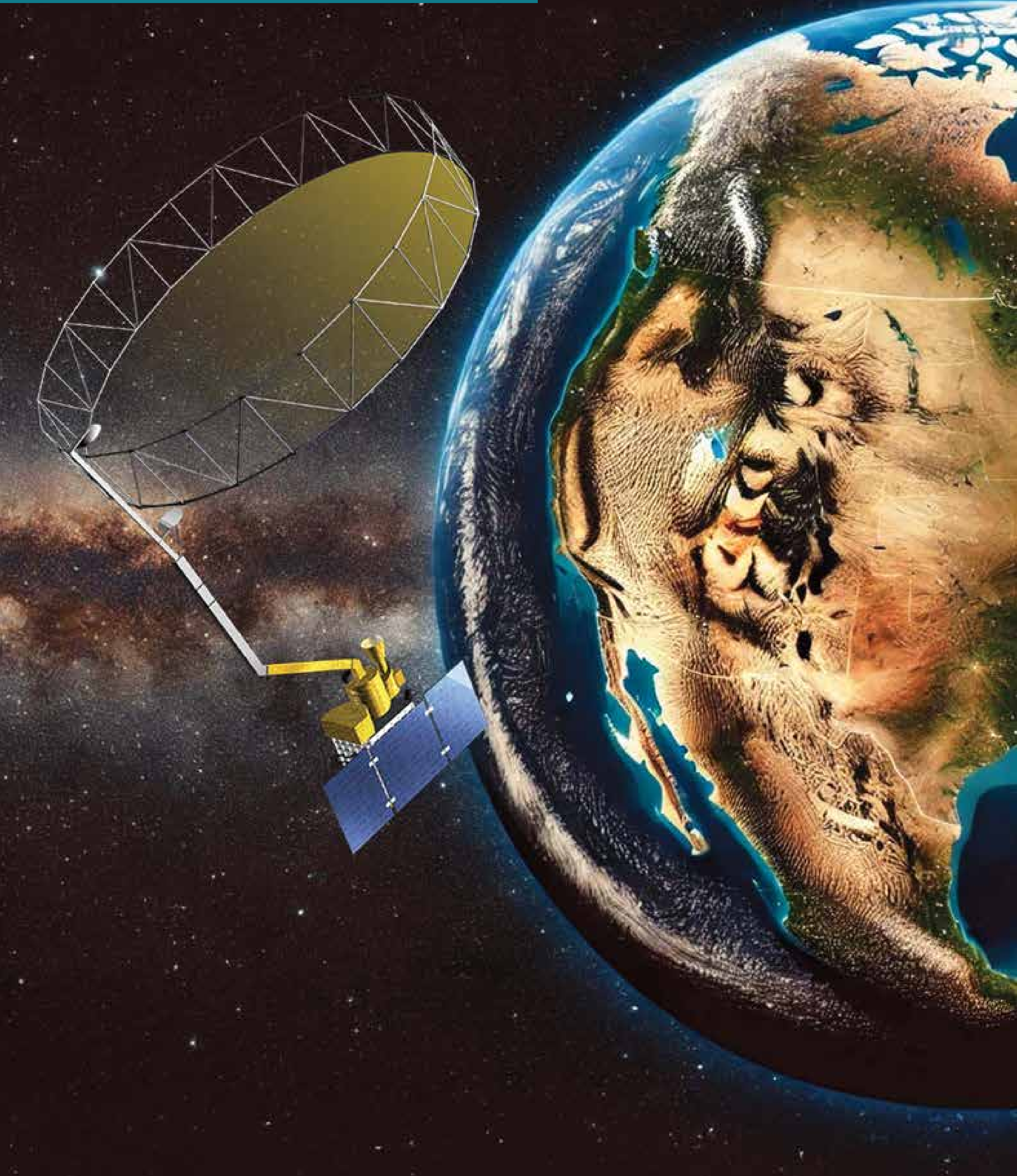

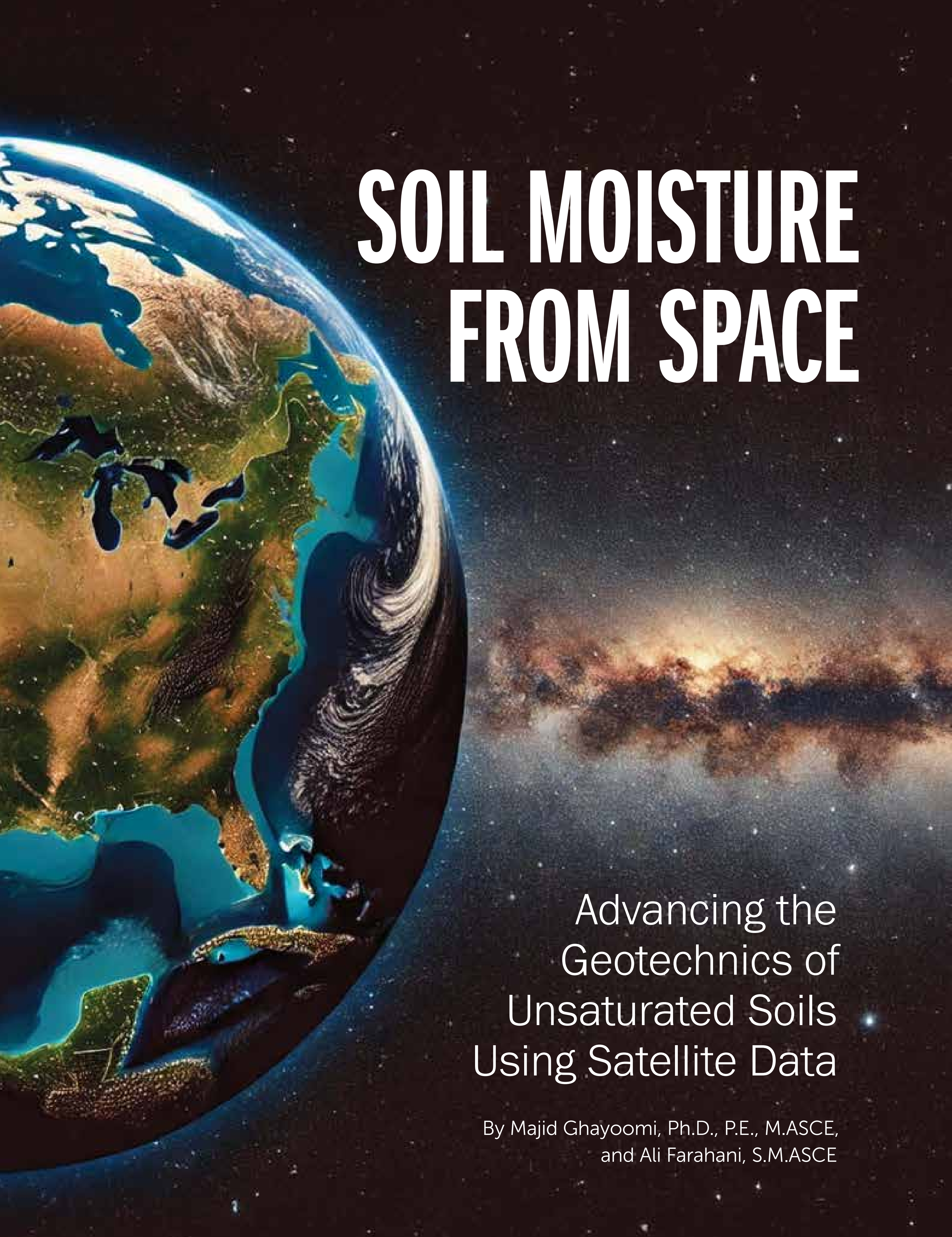

SOIL MOISTURE FROM SPACE

Advancing the Geotechnics of Unsaturated Soils Using Satellite Data

By Majid Ghayoomi, Ph.D., P.E., M.ASCE, and Ali Farahani, S.M.ASCE

Unsaturated soil in vadose zones form transition layers between the atmosphere and groundwater that vary both spatially and temporally as a result of ground conditions and climatic factors. These changes will add to the uncertainties in assessing soil hydromechanical properties, such as infiltration, water retention, and hydraulic conductivity. Thus, we need to find ways to deal with such uncertainties in geotechnical engineering applications. As global climate continues to change, incorporating soil moisture data into geotechnical practice will become increasingly critical for addressing evolving environmental and geotechnical risks, particularly when dealing with unsaturated soils, because it directly influences essential soil properties like strength and stiffness.

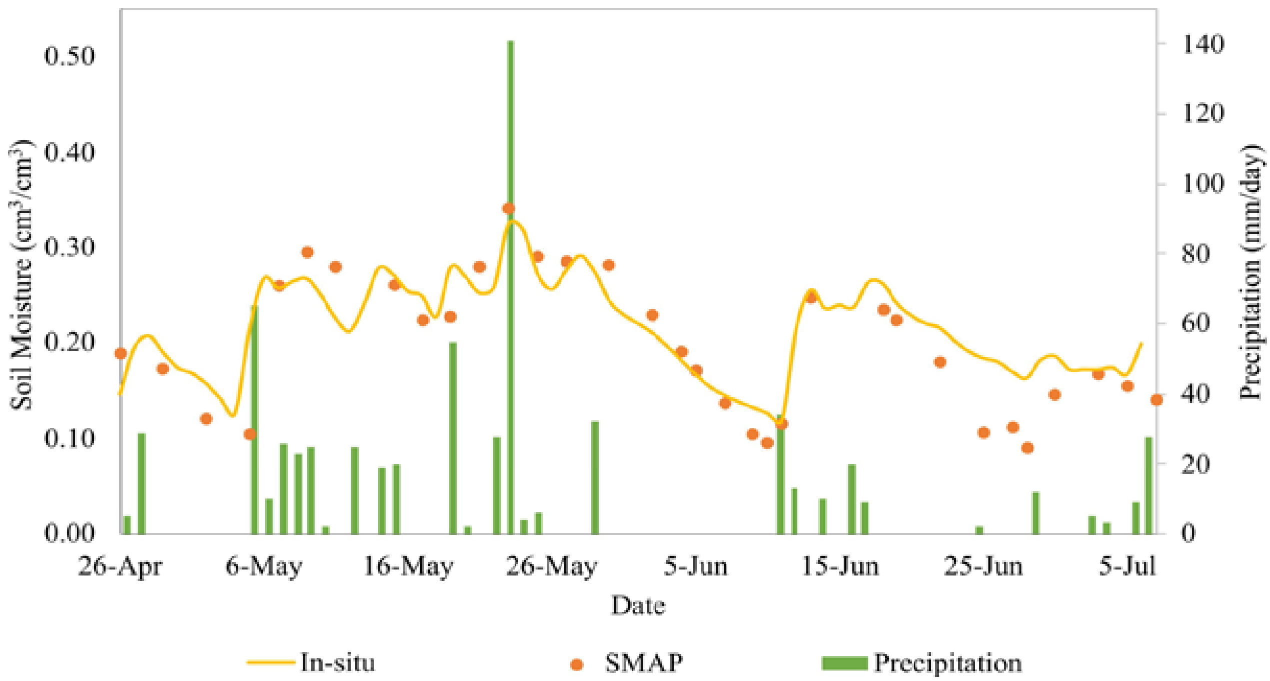

Figure 1. A temporal behavior of the station-averaged soil moisture and SMAP surface soil moisture during 2015 (after Chen et al. 2017).

While theoretical understanding of unsaturated soils has advanced significantly, practical applications have lagged behind, primarily due to the complexity of principles like matric suction and the difficulties in field measurements. Further, the use of advanced laboratory testing for soil-water interaction characterization has gained much attention in the last two decades, leading to benchmark data for material-level parameter identification. However, field-scale soil moisture monitoring has faced challenges in sensor performance, instrumentation costs, and long-term maintenance that's halted soil-moisture tracking at the global scale.

Traditionally, soil moisture has been measured using ground-based sensors that rely on the dielectric properties of soil. While these sensors offer high accuracy, they're limited to small spatial domains and require significant effort to deploy across large or complex terrains. This localized approach often results in a fragmented understanding of soil moisture distribution, as moisture levels can vary widely due to factors like topography, vegetation, and climatic conditions.

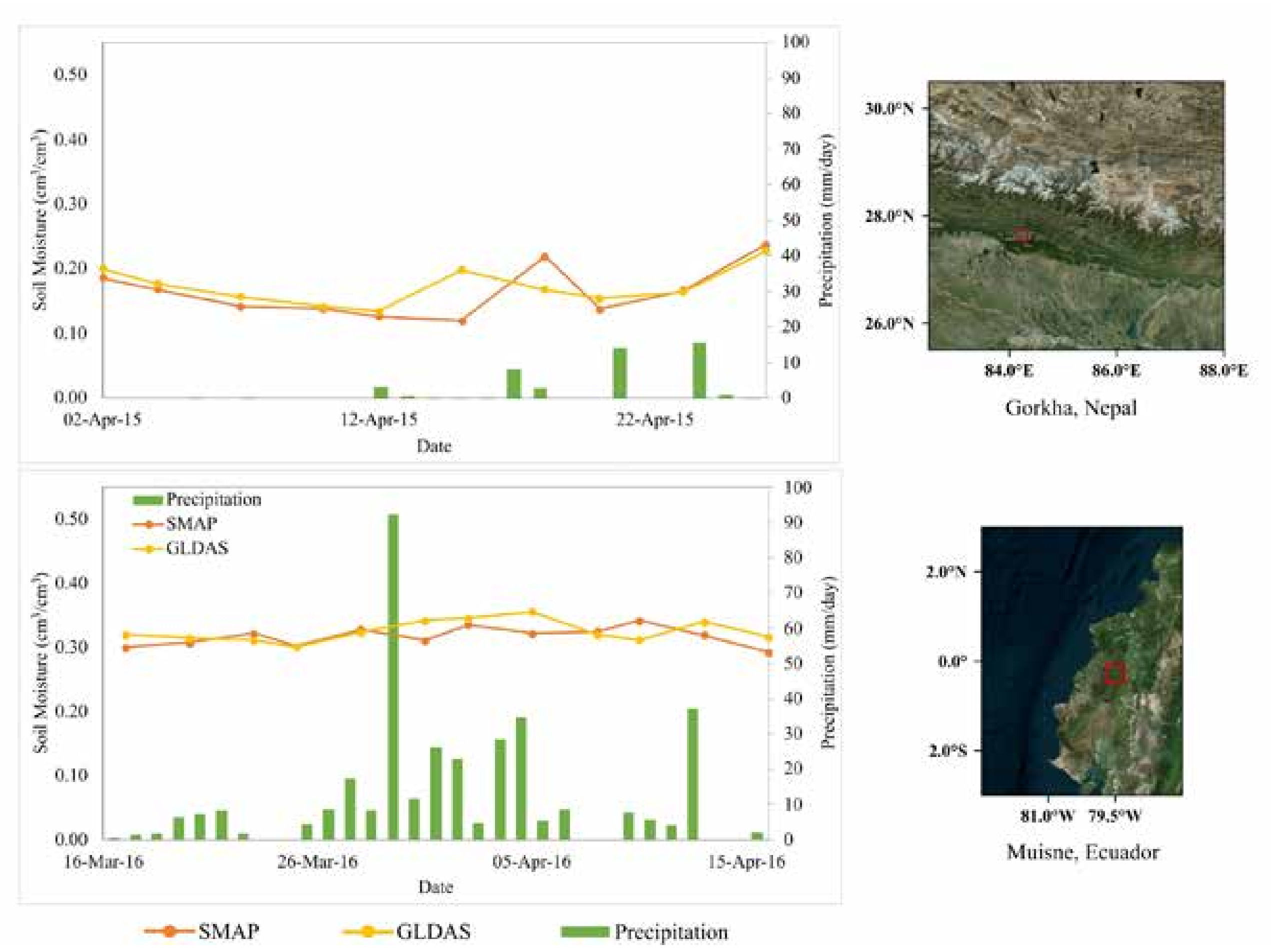

Figure 2. **Time series of SMAP and GLDAS soil moisture data for designated areas in Nepal and Ecuador in the month preceding the reference earthquake in these regions.**

Remote Sensing: A Game Changer

In recent years, remote sensing has become a cornerstone in geotechnical engineering, revolutionizing the way we monitor and respond to geohazards like landslides, floods, and earthquakes. Technologies such as synthetic aperture radar, or SAR, lidar, and satellite optical imagery have enabled the precise measurement of ground movements, damage patterns, and the creation of 3D digital elevation models, even across vast and inaccessible areas. These tools provide invaluable data for understanding the mechanics of geotechnical failures and are increasingly used to develop proactive disaster management strategies.

While remote sensing has widely been applied to large-scale geohazard monitoring, its transformative potential extends to another critical domain — soil moisture assessment. Soil moisture is a key determinant of many geotechnical processes. By using technologies like earth-observing satellites and SAR, engineers can now monitor soil moisture at a scale and resolution previously unattainable. This continuous monitoring helps detect changes in soil moisture that can signal the likelihood of events such as landslides, subsidence, or liquefaction — further reinforcing the link between soil moisture variability and geotechnical hazards.

The ability to integrate remote sensing data on soil moisture with traditional geotechnical models allows engineers to predict and mitigate risks with greater accuracy. For instance, SAR's ability to measure surface changes regardless of weather or lighting conditions enables the detection of subtle shifts in soil moisture that may precede major geohazard events. Despite its potential, remote sensing remains underutilized in this context, but as the technology advances, it promises to offer deeper insights into the variability of soil moisture and its geotechnical implications, ultimately leading to more resilient infrastructure and risk-management practices.

Spaceborne Soil Moisture Data and Geotechnical Engineering

Advancements in remote sensing technologies have introduced space-borne techniques as powerful tools for monitoring soil moisture over vast areas with high temporal resolution. Among these, microwave sensors have proven particularly effective in capturing surface soil moisture, or SSM, across large regions. Notable satellite missions such as the Soil Moisture Active Passive, or SMAP, Advanced Microwave Scanning Radiometer 2, and Soil Moisture and Ocean Salinity provide near-global coverage and have become essential in fields like agriculture and hydrology. These sensors, operating across various frequency bands — including L- (1-2 GHz), C- (3.7-4.2 GHz), and X-band (8-12 GHz) — are well-suited for soil moisture measurement retrieval due to their ability to penetrate cloud cover and deliver consistent measurements under diverse weather conditions. The L-band, in particular, is highly effective for detecting soil moisture, making it valuable for monitoring moisture in various land cover scenarios, including forests and agricultural lands.

Integrating satellite soil moisture data into geotechnical engineering offers significant advantages. This approach enhances the understanding of unsaturated soils across a range of applications, such as slope stability assessments and disaster risk management. By combining remote sensing data with traditional in-situ measurements, engineers can achieve a more comprehensive understanding of soil moisture dynamics, leading to more accurate predictions and informed decision-making in geotechnical projects.

SMAP Revolutionizes Soil Moisture Monitoring

The SMAP mission, launched by NASA in January 2015, represents a significant advancement in the monitoring of global soil moisture dynamics. The radar could have provided SMAP observations with a much higher spatial resolution, but it stopped transmitting data six months later. Nevertheless, equipped with an L-band radiometer, SMAP measures soil moisture content in the top 5 cm of the soil column with exceptional accuracy and a spatial resolution of 9 km, using the Backus–Gilbert optimal interpolation technique. This method allows SMAP to achieve a finer spatial resolution and higher accuracy than its predecessors, such as the Tropical Rainfall Measuring Mission and Advanced Microwave Scanning Radiometer 2. With its near-global coverage and frequent revisit times of every 2–3 days, SMAP provides detailed and consistent observations that are critical for understanding the intricate relationships between soil moisture,

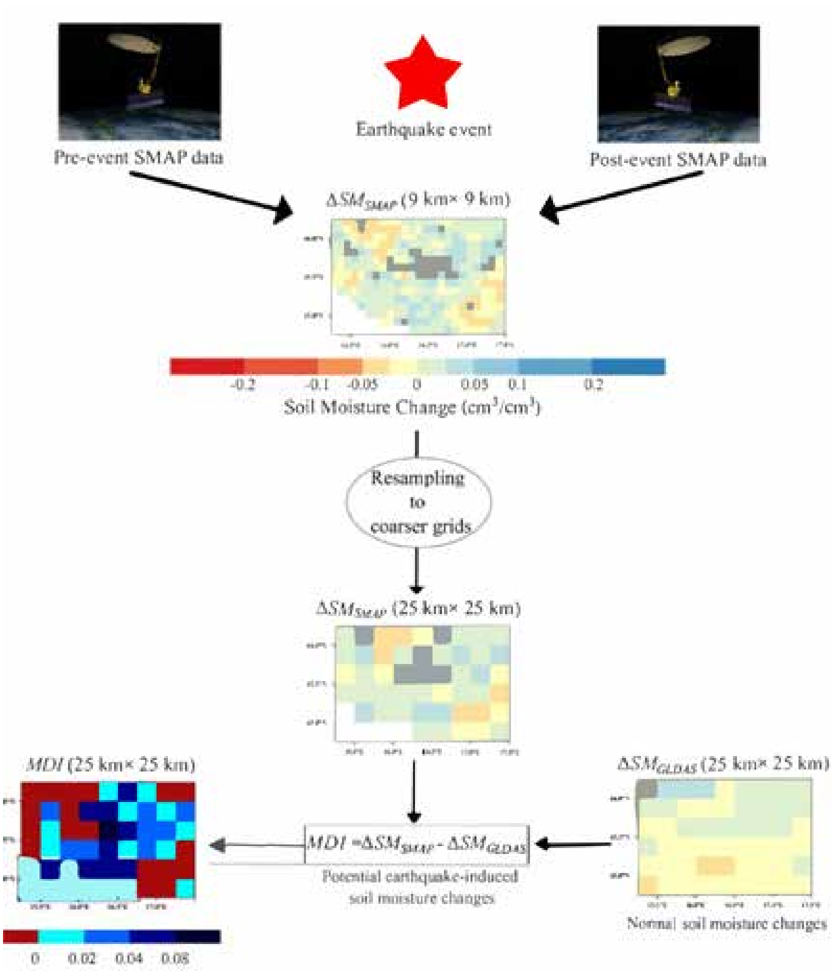

Figure 3. The procedure of estimating MDI.

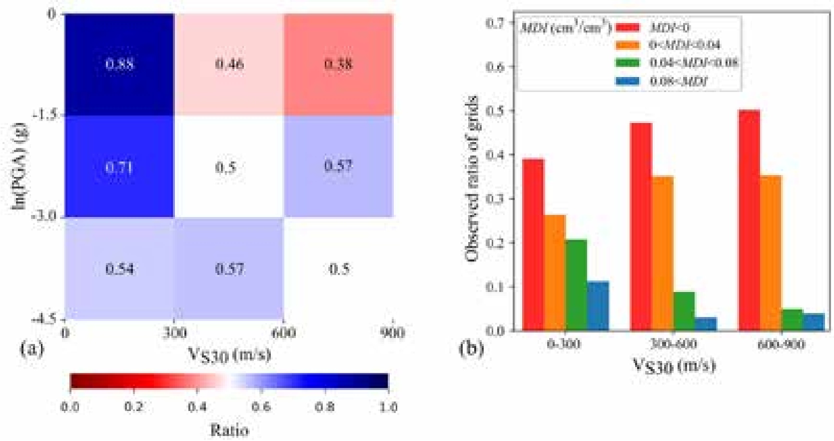

Figure 4. Statistical correlations between MDI, V_{S30}, and PGA. a) Ratio of grids with positive MDI as a function of ln(PGA) and V_{S30}; and b) Ratio of grids with different MDI ranges as a function of V_{S30}.

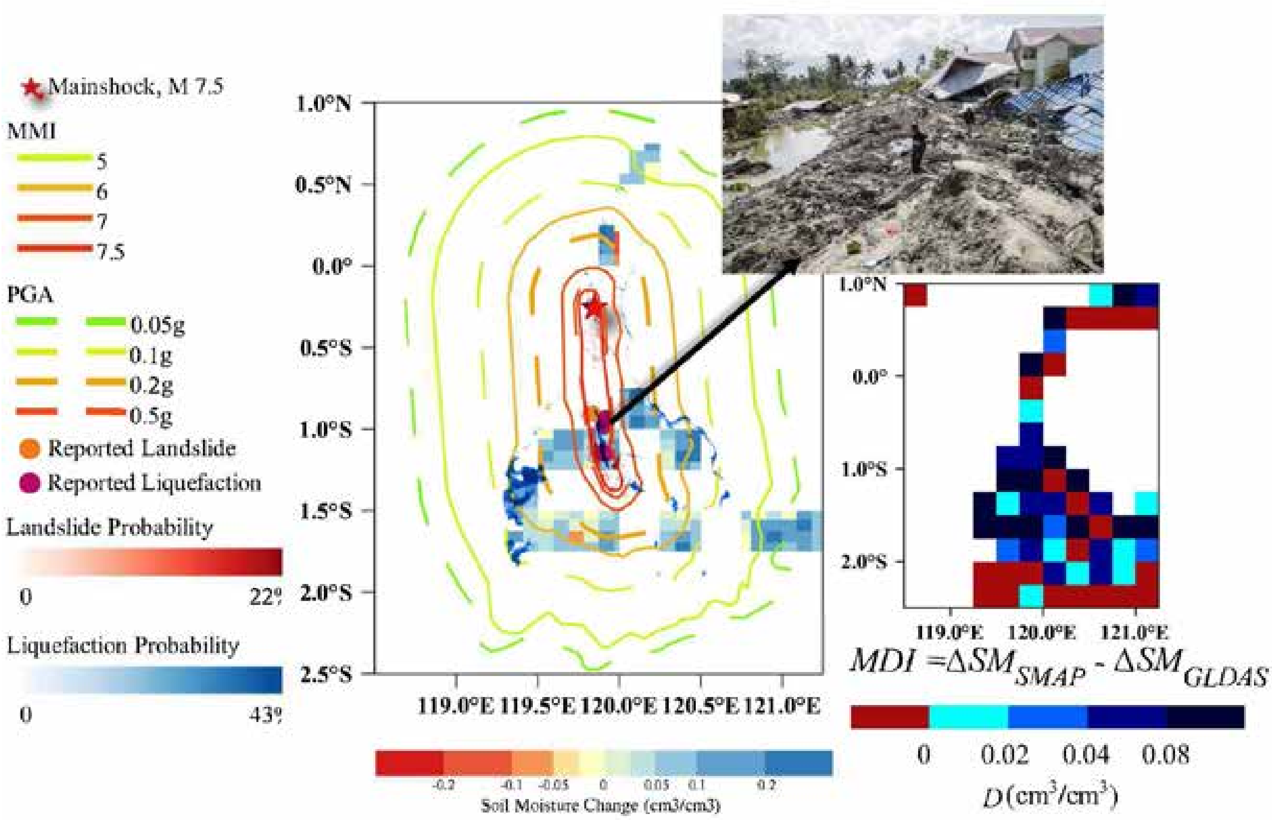

Figure 5. ΔSM_{SMAP} (9 km × 9 km) in grids with MDI > 0.08cm³/cm³ integrated with seismic records for the 2018 earthquake in Palu, Indonesia.

climate variables, and land surface processes. SMAP observations have been widely validated since the relevant datasets were released in April 2015. Figure 1 shows an example of temporal behavior of SMAP surface soil moisture data, along with the in-situ measurements for the Little Washita Watershed region in Oklahoma.

In addition to surface data, SMAP offers insights into deeper layers, such as the root zone (typically the top 1 m of soil, where plant roots primarily access moisture for growth) and groundwater, which are critical for soil stability and plant growth. By capturing factors like precipitation, temperature fluctuations, and infiltration, SMAP provides a comprehensive dataset that enhances our understanding of how moisture variations impact soil behavior. While SMAP has been widely used in fields like agriculture, weather forecasting, and natural hazard monitoring, its application in geotechnics presents a missed opportunity. SMAP's data are invaluable for understanding current soil moisture conditions, predicting future trends, and assessing geotechnical hazards, particularly in the context of climate change, where shifts in precipitation and Earth's surface temperature will significantly impact soil behavior.

SMAP and Earthquakes

Among the various geotechnical challenges influenced by soil saturation, this article provides a concise overview of the use of SMAP data in studying seismic soil response. Global Land Data Assimilation System, or GLDAS, employs meteorological inputs to land surface models to simulate variables like soil moisture. However, GLDAS cannot detect short-term changes in soil moisture, such as those caused by earthquakes. Previous research has demonstrated that GLDAS and SMAP soil moisture products exhibit similar spatial patterns and show strong agreement with in-situ soil moisture measurements, with both datasets achieving an accuracy generally below 0.04 cm^3/cm^3. To compare GLDAS and SMAP for longer periods in normal conditions (i.e., without an earthquake), Figure 2 shows that SMAP follows a similar trajectory to model-based soil moisture data from GLDAS for two regions in Nepal and Ecuador in the month preceding the earthquake in these regions. Therefore, GLDAS can be used alongside SMAP to isolate earthquake-induced moisture variations from those driven by atmospheric changes. As illustrated in Figure 3, in this study, soil moisture before and after seismic events is denoted by SM_{Pre} and SM_{Post}, respectively. Changes in soil moisture (i.e., ΔSM) are calculated for both SMAP and GLDAS products by subtracting SM_{Post} from SM_{Pre}. Compared to SMAP, GLDAS data have a coarser spatial resolution. To maintain consistency,

STUDY REGION	EARTHQUAKE/SEISMIC ZONE	MAGNITUDE	MAXIMUM INTENSITY
Central Croatia	December 29, 2020 Petrinja Earthquake	6.4	VIII
Aegean Sea, Greece	October 30, 2020 Samos-Izmir Earthquake	7	VII
Eastern Anatolia, Turkey	January 24, 2020 Elazig Earthquake	6.7	VIII
Sulawesi, Indonesia	September 28, 2018 Palu-Donggala Earthquake	7.5	IX
Eastern Iburi, Japan	September 5, 2018 Hokkaido Earthquake	6.6	VII
Puebla-Mexico City, Mexico	September 19, 2017 Puebla-Mexico City Earthquake	7.1	VII
Kaikoura, New Zealand	November 13, 2016 Kaikoura Earthquake	7.8	VIII
Central Italy	August 24, 2016 Central Italy Earthquake	6.2	IX
Muisne, Ecuador	April 16, 2016 Muisne Earthquake	7.8	VIII
Kumamoto, Japan	April 15, 2016 Kumamoto Earthquake	7	IX
Meinong, Taiwan	February 5, 2016 Meinong Earthquake	6.4	VIII
Illapel, Chile	September 16, 2015 Illapel Earthquake	8.3	VIII
Gorkha, Nepal	April 25, 2015 Gorkha Earthquake	7.8	VIII

Table 1. Study regions and earthquakes.

SMAP-based soil moisture change data (i.e., ΔSM_{SMAP}) are resampled to match the 25 km × 25 km grid of GLDAS, down from its original 9 km × 9 km resolution. The difference between the SMAP and GLDAS soil moisture change values, ΔSM_{SMAP} and ΔSM_{GLDAS}, helps identify areas where seismic activity has led to surface soil moisture increases (MDI>0). Figure 3 illustrates this process of calculating the Moisture Difference Index, or MDI, for seismic regions.

MDI, soil properties, and earthquake characteristics are expected to be closely linked. A proxy for soil density, derived from topographic slope (i.e., the steepest elevation gradient at any point), is shear wave velocity, V_{S30}, for the top 30 m of the subsurface, measured at a global scale with 1 km × 1 km resolution. Essentially, topography can be useful to infer subsurface soil properties and is based on the principle that steeper slopes correlate with denser soil and higher shear wave velocities.

For a dataset of 11 target major earthquakes within the SMAP life span (i.e., since 2015), shown in Table 1, Figure 4 shows statistical correlations between MDI, V_{S30}, and Peak Ground Acceleration. Areas with higher PGA and lower V_{S30} are more likely to experience elevated MDI. Despite the spatial resolution limitations, this approach demonstrates that SMAP can detect earthquake-induced increases in surface soil moisture, which can be indicative of some ground failures like soil liquefaction,

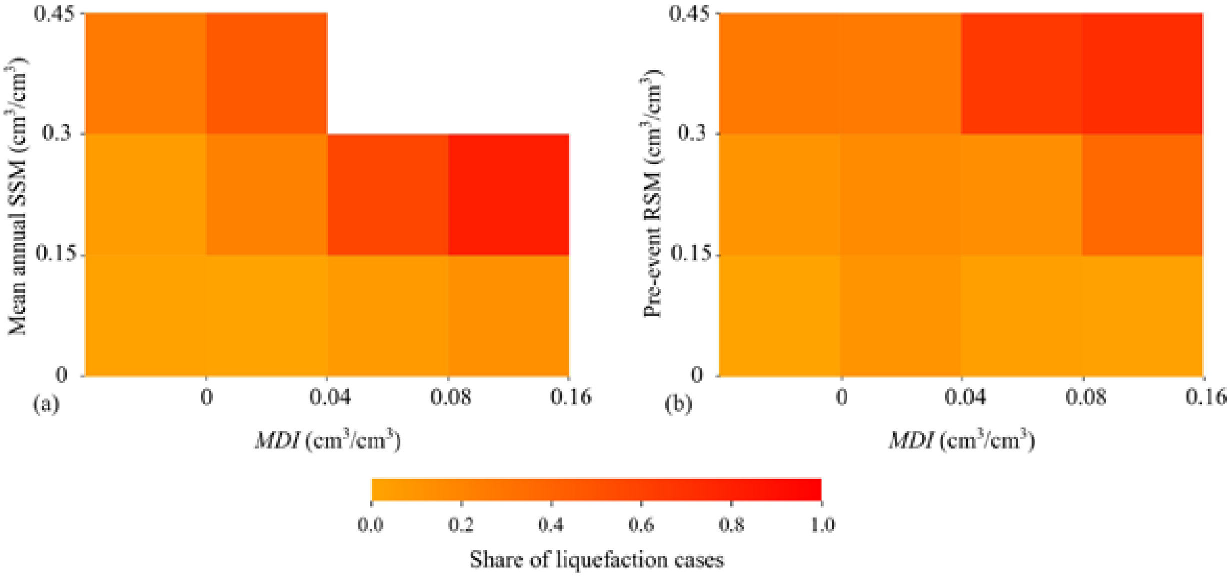

Figure 6. Share of liquefaction cases as a function of MDI versus a) average SSM in one year prior to event, and b) pre-event RSM. (White cells depict a lack of data.)

coastal inundation, lateral spreading, and flow slides. Figure 5 shows how this information can be used by earthquake reconnaissance teams to generate near-real-time maps of post-earthquake soil moisture conditions. This allows for the prioritization of areas that have experienced significant moisture increases, in combination with ground failure predictive model outputs, during field surveys. For instance, regions showing both high MDI and a high probability of liquefaction are prime candidates for having undergone liquefaction. In fact, a well-calibrated MDI database may be sufficient for predicting liquefaction potential. However, the current spatial resolution of MDI data remains a limitation, necessitating further research and advancements in remote sensing technology for higher precision.

Soil saturation is also a key factor in modeling earthquake damage, especially ground failures. For example, in geospatial models for landslides and soil liquefaction, previous studies have relied on soil saturation proxies based on historical climate data, groundwater models, and topographical factors. These proxies include proximity to water bodies, the compound topographic index, a global dataset of groundwater depth, and mean annual precipitation. Although these proxies are generally well-correlated with ground failure occurrences, they don't account for the variability of soil saturation or the actual saturation conditions immediately before an event. This can lead to over or underestimation when predicting ground failures for a specific earthquake. In this context, SMAP offers a significant improvement by capturing real-time soil saturation data, leading to more accurate ground failure assessments.

Precipitation emerges as a key hydrological factor influencing soil moisture, yet SMAP's soil moisture products demonstrate a more dynamic response to atmospheric conditions. For example, the annual average of SSM in the year leading to soil liquefaction events encompasses precipitation and all other influencing factors affecting soil saturation conditions over the entire preceding calendar year. Moreover, the season and month in which an earthquake occurs could impact the occurrence of surface liquefaction manifestation in certain regions. Thus, pre-event SMAP soil moisture data can be valuable in understanding the relationship between actual soil moisture conditions and soil liquefaction potential. SMAP's soil moisture data, with its stronger correlation to the liquefaction occurrence, presents itself as an effective alternative to traditional soil saturation proxies like precipitation data in liquefaction modeling.

Figure 6 illustrates the correlation between pre-earthquake soil moisture content and potential earthquake-induced changes in soil moisture (i.e., MDI) with occurrences of soil liquefaction across the target earthquakes outlined in Table 1. Figure 6a presents a heatmap depicting the proportion of liquefaction cases for our target earthquakes (i.e., the ratio of liquefaction cases to the total number of both liquefaction and nonliquefaction cases) as a function of MDI and the mean annual surface soil moisture, or SSM, in the year preceding the liquefaction events. Figure 6b shows a similar distribution for MDI and pre-event root zone soil moisture, or RSM. The findings suggest that, at higher MDI values (exceeding 0.08 cm^3/cm^3) and elevated SSM or RSM levels (above 0.3 cm^3/cm^3), the likelihood of liquefaction is greatest. Generally, as each of these parameters increases across the heatmap, the share of liquefaction cases rises.

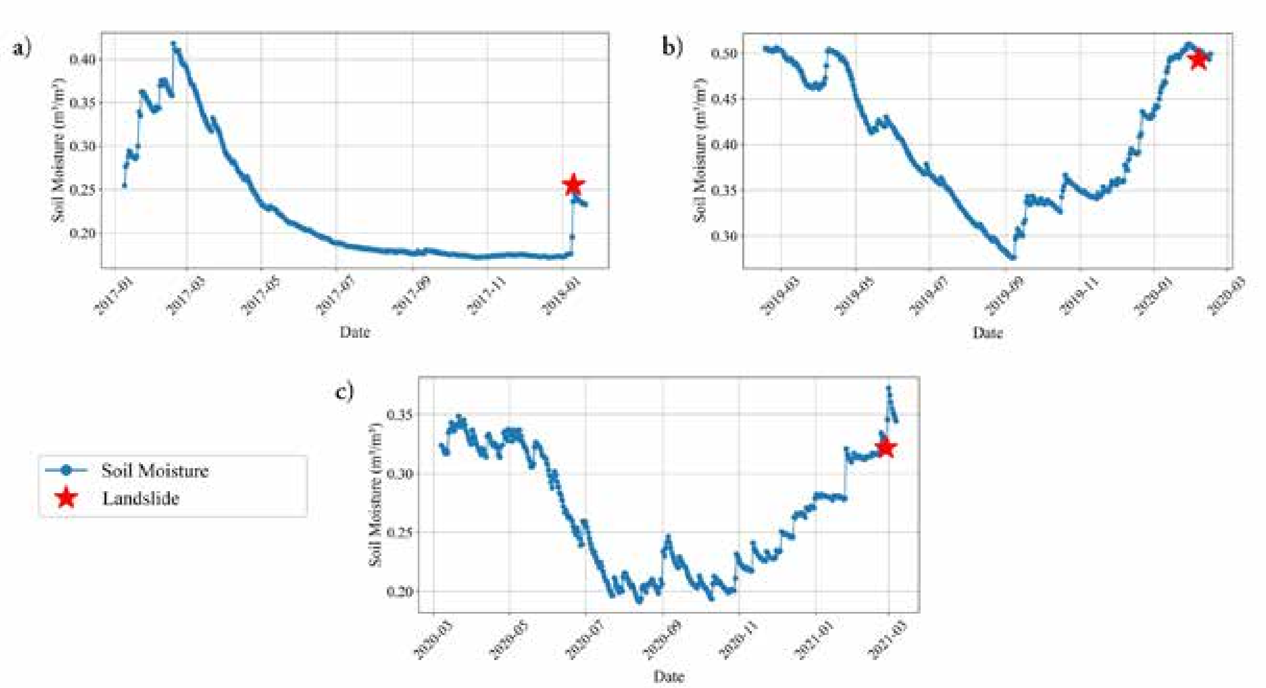

Figure 7. Time series of soil moisture for three regions in the U.S. that experienced rainfall-induced landslides: a) Montecito, Calif., b) Oregon Coastal range, and c) Kentucky-West Virginia border.

Looking Ahead

In addition to its demonstrated applications in seismic response, SMAP's potential for analyzing unsaturated soil challenges can be extended to a variety of other critical geotechnical issues. Potential geotechnical applications of SMAP include landslide prediction, sinkhole collapses, and freeze-thaw cycles, with some studies already investigating these areas. For instance, Figure 7 illustrates the soil moisture time series for three regions in the U.S. that encountered rainfall-induced landslides. In each case, landslides occurred during periods of elevated soil moisture levels, highlighting the strong relationship between increased SMAP soil saturation data and the onset of slope failures in these areas. Additionally, there's potential to use SMAP for studying expansive soils, which undergo moisture-driven volume changes, and drought-induced subsidence, where soil compacts as moisture is depleted, both of which are critical for infrastructure management in vulnerable regions.

Looking ahead, ongoing advancements in remote sensing technology are expected to further improve the spatial resolution of soil moisture data and enhance the measurement penetration depth (so-called root-zone soil moisture estimation). As satellite missions and data processing techniques continue to evolve, the role of remote sensing in geotechnical engineering is likely to expand, making it an increasingly indispensable tool for managing the complexities associated with unsaturated soils.

Upcoming satellite missions like NASA's ISRO Synthetic Aperture Radar, with its spatial resolution of up to 3-10 m, offer even greater promise. While NISAR will provide much finer spatial resolution compared to SMAP's 9 km resolution, SMAP's superior temporal resolution of three days versus NISAR's approximate 12 days offers a unique opportunity. By combining NISAR's high spatial resolution with SMAP's frequent updates, a downscaled version of SMAP data can be created, providing more localized soil moisture information. This integration of data will enable engineers to capture small-scale moisture variations while maintaining high temporal accuracy, improving models for a range of geotechnical problems, such as infrastructure stability in areas with variable soil conditions or managing the impacts of climate change on soil performance. The synergy of these datasets will likely revolutionize geotechnical monitoring and prediction.

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While looking like ancient Central American ruins, these mounds are at the leading edge in innovation of future tailings and mine waste management strategies.

UNSATURATED TAILINGS LANDFORMS

Is the Future of Tailings Management Filtered Tailings Stacks?

By Joseph Scalia IV, Ph.D., M.ASCE, and Christopher Bareither, Ph.D., P.E., M.ASCE

The future of humanity and our environment will need to rely on increased mining for minerals that are critical to clean energy technology, the digital transformation, and attainment of sustainable development goals. To meet societal needs, mining companies increasingly rely on large-scale extraction of ever-lower-grade ores, which yield vast volumes of tailings. Tailings are the residuum from liberating economically valuable minerals from ore. Modern tailings are sand- to clay-sized particles produced as a slurry that includes multiple times their weight in process water. Tailings management is largely about recovering this water and building a stable structure with the solid particles.

Figure 1. **An example of slump testing of tailings at (a) 65 percent, (b) 75 percent, and (c) 85 percent solids contents (solids content = weight of solids/total weight). (Photo courtesy of Kendall Monley.)**

Conventionally, slurry tailings are managed by discharging behind an embankment to form a "tailings storage facility," or TSF. The scale of these facilities can be immense, as they're some of the largest structures created by humans. Tailings embankments are often made from the coarse and freely draining portion of a mine's tailings. However, unlike water dams, these embankments are generally constructed to be freely draining — the goal is to get water out, not keep water in. Slurry tailings settle to form interbedded layers of loose material, typically saturated and contractive during shear. Eventually, if the climate is favorable, these materials will become denser, stronger, and potentially unsaturated, but this process can take decades. In the interim, tailings embankments must be carefully monitored and maintained because they retain potentially liquefiable and flowable material. Like a water dam, if the outer structural zone is breached, the retained tailings and water flow outward. However, the outward flow is more like a lahar than a flood — a dense slurry of tailings and water. Unfortunately, we've seen all too frequently the devastation that can occur when tailings embankments fail.

TSFs generally remain in place forever. In some limited cases, economically recoverable minerals in tailings may warrant "remining" and reprocessing. But even then, what's removed will only be a tiny fraction of the total volume, perhaps a fraction of one percent. Tailings may also be beneficially reused as construction materials or other products, but there's often a mismatch between the scale of tailings and the economics of reuse. Mines are often located in such remote places that it becomes economically impractical to ship sufficient volumes of material to even make a dent in the quantity of the tailings being managed. Thus, geotechnical engineers have and will continue to be confronted with how to best manage the residuals of mining and prevent loss of human life and damage to the environment.

Published in August 2020, The *Global Industry Standard for Tailings Management* (*globaltailingsreview.org/wp-content/uploads/2020/08/global-industry-standard-on-tailings-management.pdf*) requires that new tailings facilities consider alternative tailings management strategies to address environmental, technical, and socioeconomic impacts. Key in these alternative technologies is the concept of rapidly dewatering tailings to minimize the amount of water sent to and stored in tailings facilities. Dewatered tailings are constructed into unsaturated tailings stacks or mixed with mine waste rock to form commingled monofills termed "geo-stable tailings."

The difference made by dewatering

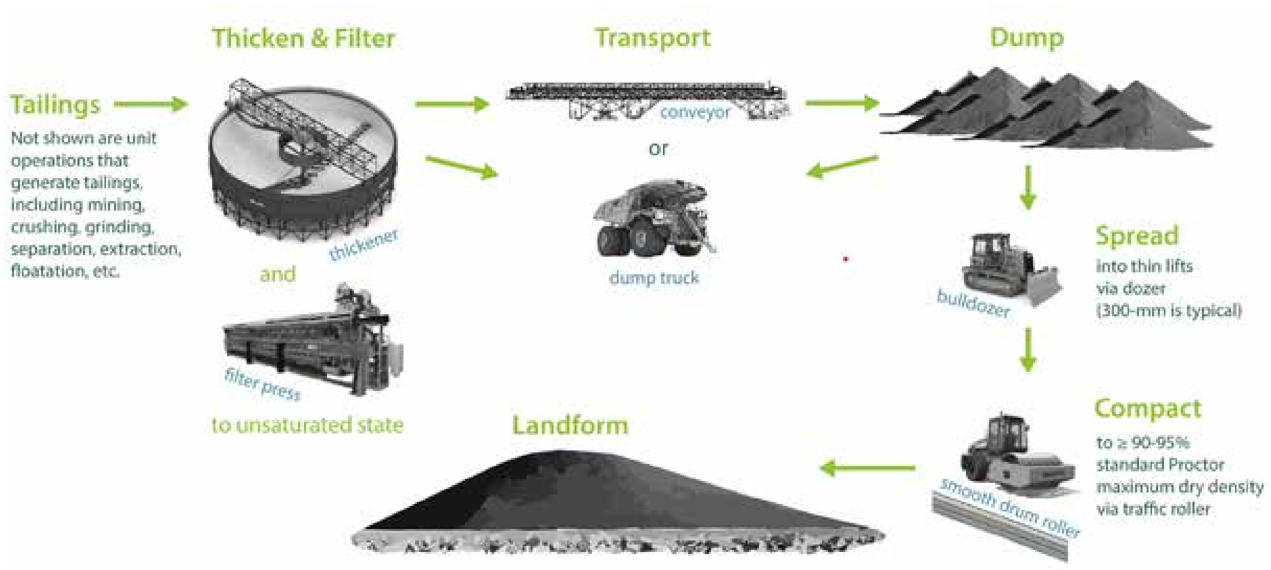

Figure 2. **State-of-practice for constructing a typical filtered tailings stack.**

is shown in slump test results presented in Figure 1. Tailings start in a slurry consistency. Then, through dewatering, the tailings solids content is increased until an unsaturated soil-like consistency is achieved. Tailings can then be placed and densified to form a physically and chemically stable landform.

> Geotechnical engineers have and will continue to be confronted with how to best manage the residuals of mining and prevent loss of human life and damage to the environment.

Building Filtered Tailings Stacks

The construction process of a filtered tailings stack is illustrated in Figure 2. Tailings are first sent to a thickener, where the water is liberated through a combination of flocculation and gravity settling. The thickener discharge is then sent to a tailings filter, often a vacuum belt, vacuum disk, or pressure filter, where water is vacuumed or physically squeezed out to form an unsaturated tailings filter "cake." The filter cake is then transported, either via trucks or overland conveyors, and dumped on the stack. The current standard of practice is to then spread tailings into thin lifts and compact using smooth drum rollers to greater than 90 or 95 percent of standard Proctor maximum dry unit weight. To optimize compaction, the filter cake water content is targeted to near standard Proctor optimum water content — corresponding to approximately 80 percent degree of saturation.

Filtered Tailings Geotechnics

The design intent for a filtered tailings stack is that the resulting landform will behave in a dilative manner during shear so it will *not* have the potential to liquefy or produce a catastrophic flow-type failure. Achieving a dilative tailings mass with unsaturated placement is the key to building denser and more stable tailings landforms. Potentially liquefiable materials and ponded water retained in a traditional tailings embankment aren't contained within a filtered tailings stack. Filtered tailings stacks have been used by the mining industry since the mid-1980s, but have historically only been used at some smaller mining operations. This practice is changing with the increased focus on stability, but there's a long way to go.

Critical geotechnical behaviors associated with filtered tailings stacks are portrayed schematically in Figure 3. Global stability must be achieved, but local bearing capacity of stacking and compaction equipment must also be considered. Stacked tailings are placed in an unsaturated condition. As subsequent overlying tailings are placed, the combination of

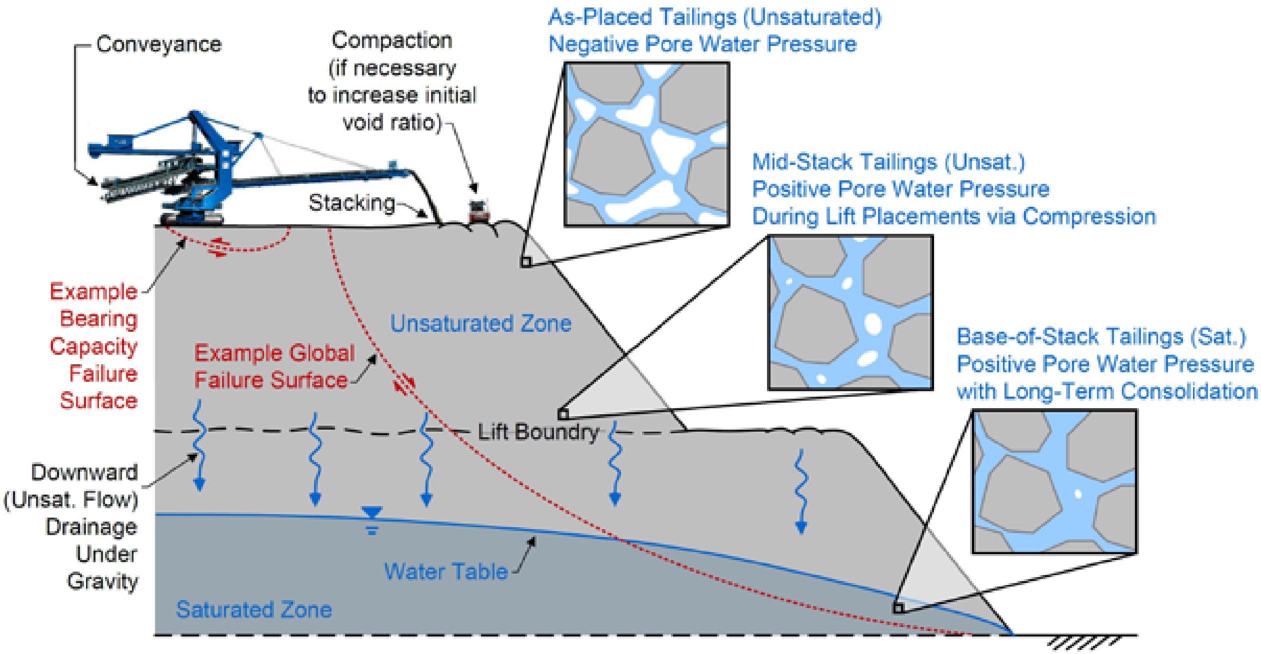

Figure 3. **Example of building a filtered tailings landform.**

compression and seepage yield higher degrees of saturation, so that, eventually, a water table is formed. Within the saturated zone, consolidation will slow densification. Thus, incorporating the unsaturated characteristics of filtered tailings is critical for assessments of stability and seepage. For example, understanding the necessary degree of compaction at placement requires forecasting future unsaturated compression and saturated consolidation of placed tailings. Initial undercompaction may yield unacceptable weak zones with the filtered tailings stack. Overcompaction will represent a significant extra cost — particularly at the scale of tailings management. Overcompaction may also lead to perched water tables within a stack, so applying unsaturated soil mechanics is critical to filtered tailings stack design!

The unsaturated properties of filtered tailings are mine-specific, and thus must be determined on a project-by-project basis. These properties are crucial because of the significance of water to the stability of filtered stacks. Tailings practitioners are accustomed to building structures that strengthen with age due to dissipation of excess pore water pressure. Filtered tailings, however, have the potential to do just the opposite by weakening because capillary forces are reduced if a filtered tailings stack resaturates with subsequent lifts or precipitation.

Soil (i.e., tailings) water characteristic curve testing is a core component of filtered tailings geotechnical characterization. These tests follow standard methods such as ASTM D6836 (Standard Test Methods for Determination of the Soil Water Characteristic Curve for Desorption), including using hanging columns, pressure extractors, and chilled mirror hygrometers. Tests are often conducted at a range of void ratios to reflect the range of densities that will occur in a stack. These data are then paired with saturated hydraulic conductivities via numerical analyses to predict fluid flow behavior. Compression tests on unsaturated specimens are also used to predict the evolution of void ratios under unsaturated conditions. These data are critical to understanding evolving critical state behavior — if the tailings are anticipated to be dilative or contractive. Strength testing and stability analyses are also critical to filtered tailings design, but often the current state of practice is to conservatively assume saturated conditions, particularly when tailings will be near saturation.

Filtered Tailings Geochemistry

Because mine tailings aren't inert, the potential environmental impact of long-term geochemical behavior must also be considered as part of stacked tailings disposal. These behavioral factors include dust, surface and groundwater quality, and coupled chemico-bio-physical changes that may impact stability. Filtered tailings geochemistry is largely governed by tailings hydrology and by unsaturated hydrology. Dense placement yields low seepage rates and high degrees of moisture retention. If the combination of a tailings' unsaturated behavior and climate are sufficient, tailings may retain moisture content that's sufficiently high to prevent oxygen ingress and limit rates of long-term acid rock drainage and metals leaching. Even if sufficient moisture retention is unattainable because of local climatic conditions, the denser state and greater homogeneity of filtered tailings stacks relative to conventional tailings will yield lower fluxes and reduced environmental impacts. It's thought that the greater density of filtered tailings slows the rate at which changes that may impact stability occur, such as dissolution of soluble mineral phases increasing void

Figure 4. Commingled filtered tailings and waste rock test pile.

ratio (potentially turning a dilative tailings contractive) or, conversely, precipitation of minerals yielding pore clogging and decreased hydraulic conductivity.

Innovation Is Needed

The production of filtered tailings needs to go bigger… a lot bigger! Currently, most filtered tailings operations are smaller than 10,000 tons/day, and the world's largest filtered tailings operation is about 40,000 tons/day. For reference, many large metals mines operate at 100,000 or more tons/day, with the largest operating past 400,000 tons/day. So what's holding filtered tailings back? The two key factors are cost and the need for someone to go first. Innovation needs to make larger production happen, including additional cost-effective ways to dewater tailings, technologies to move dewatered tailings efficiently, and methods and equipment to optimally place and appropriately compact tailings — and all of these improvements require knowledge of unsaturated behavior, including unsaturated fluid flow, compression, and strength and deformation behavior. Finally, until the value of filtered tailings on the full social and environmental costs of tailings management is understood, filtered tailings will face headwinds in adoption. The mining industry is currently working on value frameworks that better incorporate the full costs of closure, the need for perpetual care of conventional tailings facilities, and the many other costs of mine waste management.

Geo-stable Tailings Stacks

Another paradigm shift in tailings management is the commingling of tailings and waste rock, known as geo-stable tailings. Waste rock is the rock that must be removed to access valuable ore. At many mines, the mass of waste rock far exceeds that of ore. Waste rock tends to be physically stable and is traditionally managed in stacks, but waste rock can be geochemically unstable, leading to acid rock drainage due to water, oxygen, and omnipresent microbes. Because of the large open pores present in piles of waste rock, perfect conditions for acid rock drainage can ensue. ARD from waste rock often represents the largest and longest-lived environmental impact from a mine. Geo-stable tailings posit that we can use attributes of waste rock (high strength) and tailings (small pores) to build stable landforms. Geo-stable tailings can range from tailings-dominated matrices with waste rock floating in tailings (think of a raisin floating in oatmeal) to waste-rock-dominated matrices (rock on rock contact) with tailings filling the rock pores. Effective mixing of these

In the future, as tailings are managed in filtered tailings stacks, there will be a growing need for more geotechnical engineering practitioners who are fluent in unsaturated soil (and tailings) behavior.

materials can occur because the tailings are dewatered to an unsaturated condition, and capillary forces in the tailings produce particle adhesion which limits size segregation. The choice of a mixture ratio is based on site-specific material constraints, largely if the mine has more waste rock or more tailings, and other management drivers, including the availability of land for conventional tailings storage facilities and the acid-rock-generating potential of the waste rock.

An example of a 5-m-high, tailings-dominated geo-stable tailings test pile is shown in Figure 4. The waste rock floating in a matrix of filtered tailings is visible. These piles were constructed and monitored for two years as part of an early study to explore commingled behavior. From these tests, we learned that geo-stable tailings can successfully prevent acid rock drainage because of their unsaturated behavior. The geo-stable tailings act akin to a water-balance cover, where infiltrating precipitation during the rainy season was stored near the pile surface and then released back to the atmosphere, preventing deep percolation. We also saw how natural processes alter the unsaturated characteristics of the near-surface tailings, which underscored the importance of considering the temporal evolution of these materials, and the need for long-term field trials.

Construction of geo-stable tailings stacks is not dissimilar to that of filtered tailings stacks. At scale, this is envisioned to occur via a series of drops along an overland conveyor, where material mixes at each transfer — although no large-scale demonstration of geo-stable tailings has yet occurred. Materials may also be mixed with heavy equipment, with a pug mill, or by other means. Mixed tailings and waste rock are then stacked to form a commingled tailings and waste rock monofill.

Like filtered tailings stacks, geotechnical engineers must consider questions around unsaturated flow and volume change. However, with these management strategies, the compression and seepage behavior are modified by the rock fraction, which may impact negatively or enhance geotechnical behavior. The intent is to create a landform with superior characteristics to those of either of the constituent materials — and ideally do so at large scales.

Geo-stable tailings are being driven forward by an industry consortium of mining majors: Antimina, Barrick, BHP, Freeport-McMoRan, Glencore, Gold Fields, Newmont, Vale, Teck, and Rio Tinto. Consortium members are working to develop knowledge and procedures to unlock commingling at scale. Members are currently at varying stages of preliminary laboratory testing and building large-scale and multiyear test piles across the globe, with results to be released in the coming years.

Embracing Tailings Challenges

Filtered and geo-stable tailings represent a better future of mine waste management that will enable the construction of more physically and chemically stable mine waste landforms. Filtered and geo-stable tailings landforms can be created to meet environmental and societal needs. For example, created landforms can provide recontoured slopes intended to produce similar or enhanced ecological behavior to the pre-mining condition, or provide a stable site for next generation land uses, such as for solar farms. These advances are critical at a time when increased mining is needed. However, these advances are not business as usual and will require clever geotechnical engineers working across disciplines and sharing knowledge across the mining industry to advance unsaturated tailings management.

In the future, as tailings are managed in filtered tailings stacks, there will be a growing need for more geotechnical engineering practitioners who are fluent in unsaturated soil (and tailings) behavior. We encourage environmentally minded students and practitioners, particularly those interested or knowledgeable in unsaturated soil behavior, to consider a career in tailings. You'll always be busy and never be bored! GS

Acknowledgements
We wish to acknowledge our graduate students at Colorado State University, who have worked or are working in filtered or commingled tailings. Our understanding of this subject is informed by learning with and from them.

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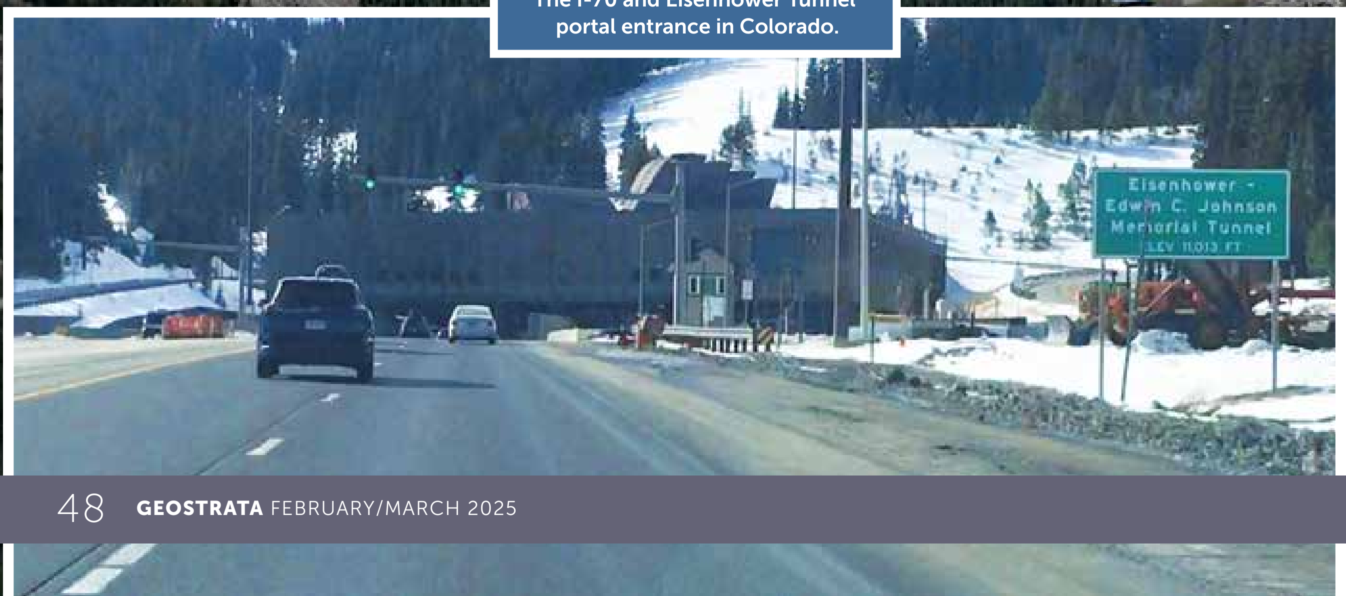
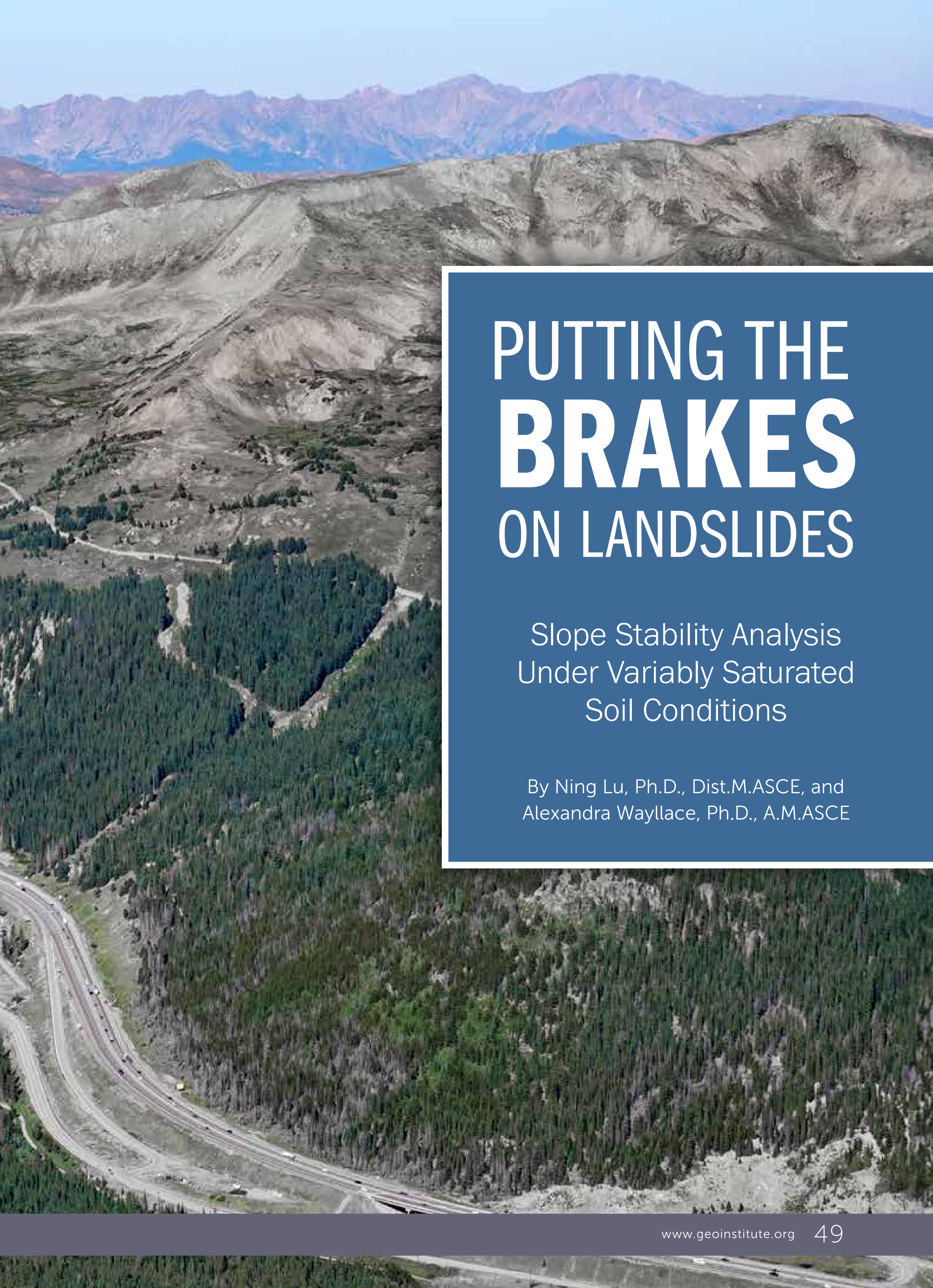
The I-70 and Eisenhower Tunnel
portal entrance in Colorado.





PUTTING THE **BRAKES** ON LANDSLIDES

Slope Stability Analysis Under Variably Saturated Soil Conditions

By Ning Lu, Ph.D., Dist.M.ASCE, and Alexandra Wayllace, Ph.D., A.M.ASCE

Terzaghi's principle of effective stress and limit equilibrium methods are commonly used in engineering practice to assess the stability of slopes for saturated and dry conditions. In recent decades, however, this approach has been extended to unsaturated soil conditions by using the suction-stress-based effective stress. For example, it's been used to analyze and predict rainfall-induced slope failures along railway embankments at sites near Edmonds, Wash. It's also been successfully used at other sites to assess hurricane-induced slope instability in Asheville, N.C., natural rainfall-induced failures of cut slopes near Hadong City and Puhang City in South Korea, the excess precipitation-induced slope failures near the village of Rüdlingen in northern Switzerland, and rainfall-induced slope failures in the northeastern part of Oltrepò Pavese in northern Italy, among others.

This article illustrates the effectiveness of using this type of analysis of an unsaturated soil slope by highlighting a case history study of an unstable slope located near the Continental Divide in Colorado. We discuss how a recurring roadway embankment slide that's triggered by annual snow-melt water infiltration can be effectively analyzed using Bishop's simplified routine method of slices under variably saturated soil conditions. This seasonally dependent, late spring embankment instability is accurately predicted to illustrate the simplicity and capability of the extended classical methodology for effective stress stability of partially saturated soil slopes.

The Evolution of Slope Stability Analysis Methods

The classical methods of soil slope stability analysis were developed early in the last century to assess the failure potential of natural and engineered slopes, excavation cuts, roadway embankments, and earthen dams and levees. Based on the concept of limit equilibrium, the classical methods define the limiting state when the shear stress along a preset dry or saturated failure surface in a slope is in just-stable mechanical equilibrium with the shear strength of the slope material. A salient assumption is that the pore water pressure is zero above the water table and compressive below the water table so that Terzaghi's effective stress equation can be used. In reality, the pore-water pressure above the water table could be tensile, leading to different effective stresses than for saturated conditions.

In recent decades, with a suction-stress based, unified effective stress formulation, classical methods have been extended to slopes under variably saturated conditions. The necessary parameters for the slope stability analysis for the classical (dry or saturated) and variably saturated parameters are compared in Table 1. For partially saturated soil conditions, only a few parameters, in addition to those used for the classical methods, are needed to account for variations of soil suction, water content, and suction stress for slope stability analysis. A case study is presented to illustrate how slope stability analysis can be effectively done for both saturated and unsaturated conditions.

The parameters θ_r, α, and η, are probably not familiar to most readers. The parameter θ_r represents the amount of adsorbed water for a given soil. The parameter α represents the inverse of capillary suction below which a soil starts to desaturate. The parameter *n* reflects the range of a soil's pore sizes. All three parameters can be determined from the standardized laboratory testing.

I-70 Site Geography, Geology, and Hydrology

The annually recurring landsliding site is on a heavily traveled section of I-70 in the Rocky Mountains of Colorado, located about 2.5 km west of the western portal of the Eisenhower-Johnson Memorial Tunnel in Summit County, Colo. Opened in 1979, the 2.7-km-long tunnel carries traffic on I-70 under the Continental Divide. At an elevation of 3,251 m above sea level, it's one of the highest vehicular tunnels in the world. The tunnel's average monthly traffic count in 2023 exceeded 1.1 million vehicles.

As pictured in Figure 1, the unstable slope consists of the I-70 embankment fill and underlying slope soil and rock (outlined in red cross-hatching in Figure 1a), and a region above the fill (outlined in blue in Figure 1a) that's the source of annual snowmelt water infiltration that drives the instability of the embankment fill. Annual episodic embankment settlements occur

Classical (saturated) → Unsaturated

Soil type	Cohesion c' (kPa)	Friction angle ϕ' (°)	Saturated hydraulic conductivity K_s (m/s)	Saturated moisture content = porosity θ_s (m³/m³)	Residual moisture content θ_r (m³/m³)	Inverse of air-entry pressure α (kPa⁻¹)	Pore size parameter n (unitless)
Sand	0	35 ~ 60	10^{-4} ~ 10^{-6}	0.35 ~ 0.45	0.01 ~ 0.05	0.3 ~ 0.5	2 ~ 8.5
Silt	0 ~ 50	35 ~ 45	10^{-6} ~ 10^{-8}	0.38 ~ 0.45	0.03 ~ 0.08	0.03 ~ 0.3	1.5 ~ 5.0
Clay	10 ~ 100	30 ~ 45	10^{-7} ~ 10^{-9}	0.40 ~ 0.60	0.05 ~ 0.12	0.003 ~ 0.03	1.1 ~ 3.0

Table 1. **Parameters needed for slope stability analysis under variably saturated conditions.**

Figure 1. **Aerial and ground-level photos of I-70 embankment fill. (Map data © 2018 Google Earth.)**

beneath the highway, causing extensive pavement cracks, uneven road surfaces, and significant traffic disturbances. In past decades, releveling the pavement surface with asphalt became a routine exercise every few years.

Geologic investigation of the site shows the I-70 embankment fill is constructed atop decomposed gneiss and gneiss bedrock, while the outer portion of the embankment toe is constructed over alluvium. A geologic cross section cut through the unstable zone (Figure 2) shows that four distinct materials underlie the highway:

- Colluvium and fill from spoil or waste from the boring of the tunnel
- Highly fractured decomposed gneiss
- Intact gneiss
- A thin layer of alluvium near the toe of the slope

Bedrock composed of intact gneiss located at depths of 12-15 m below the highway surface presumably acts as a hydrologic barrier.

Infiltration at this location is driven largely by the melting of a deep snowpack that accumulates in winter. The average snow depth that accumulates between November to April is 1.07 m and varies from 0.50 to 2.76 m. This snowpack melts in late spring and early summer (May to June) to yield an average of 0.36 m of water with substantial variability ranging from 0.19 to 0.90 m. During summer, the seasonal precipitation is similarly variable because heavy rainfall can trigger debris flows and shallow landslides. Because the annual snowmelt process takes from several days to weeks, much of the water infiltrates into the slope, as well as the embankment and underlying sediments above the bedrock.

Measurements from piezometers installed in the eastbound, westbound, and toe-of-slope boreholes (Figure 3) show that the water table is located at depths of 15-25 m beneath the highway and adjacent downslope embankment. Subsurface drainage conditions suggest that the water table is approximately parallel to the slope. Atmospheric data, including precipitation and snow-water equivalent (i.e., SWE) were obtained from the SNOTEL Station 505 at Grizzly Peak, maintained by the Natural Resource Conservation Service, that's about 12 km from the project site. Rainfall infiltration occurs when there's no snowpack and temperatures are above freezing; snowmelt infiltration occurs when there are negative changes in SWE from snowpack melts. While influenced by episodic infiltration events, examination of the measured depth to groundwater across the embankment shows the water table has varied by as much as 9 m from season to season and year to year between 2011 and 2018. An unusually pronounced spike was monitored below the upslope of the highway on the westbound shoulder, as shown in Figures 2 and 3.

Since the tunnel was opened in 1979, records of pavement surface movements over the decades indicate that the highway pavement surface has moved downward episodically at an average rate of 3 cm/yr, leading to about 0.6 m of pavement settlement that's accumulated on the eastbound lanes (see the asphalt wedge in Figure 2). In recent years, borehole inclinometers have been installed that extend to depths up to 35 m in the embankment shown in Figure 2. Cumulative displacements measured from October 2008 to August 2009 are as high as 5.8 cm. Posterior readings on those inclinometers weren't possible because they had sheared off. A new set of inclinometers installed in 2012 confirm the location of the failure plane; cumulative displacements monitored from 2012 to 2015 are 0.8 cm. As defined by the dashed red line in Figure 2, the monitored data indicate that the failure surface is located beneath the highway and between the interface of the intact bedrock and the fractured, decomposed gneiss.

Samples cored from the site were tested for the shear strength and hydrologic properties needed for slope stability analysis, including unsaturated soil properties. Shear strengths were obtained from laboratory direct shear tests, and hydrologic properties were obtained from laboratory soil water retention and hydraulic conductivity tests.

Based on the seven-year site monitoring (Figure 3), the subsurface hydrologic and mechanical behavior can be grouped into four characteristic periods (Figure 4) for the year 2013:

- Stage I: Steady water table from November of the previous year to early March
- Stage II: Small water table rise under the highway shoulder due to the snowmelt from early March to end of May
- Stage III: Large water table rise in slope due to the rainfall from early May to end of July
- Stage IV: Steady water table decline from August to November

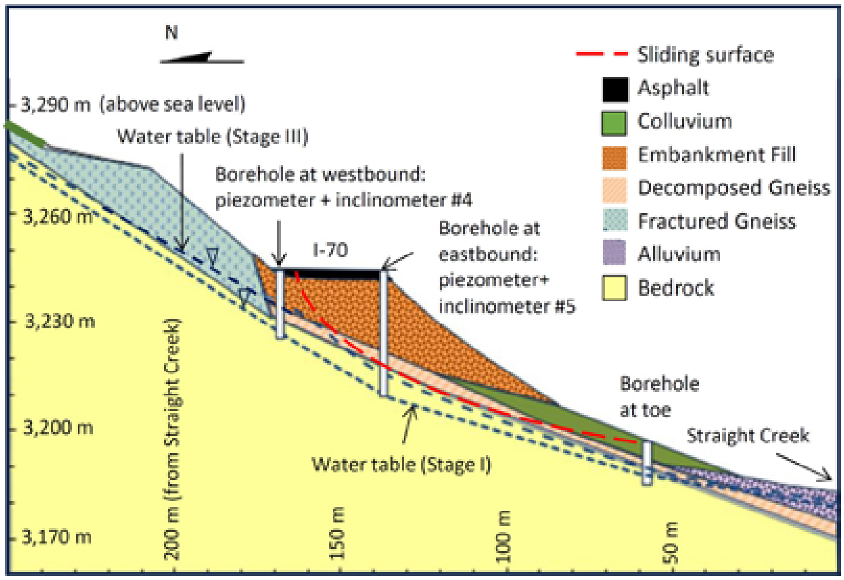


Figure 2. The geologic cross-section A-A′ as identified in Figure 1a. Note that this figure also shows the location of the water table for Stages I and III.

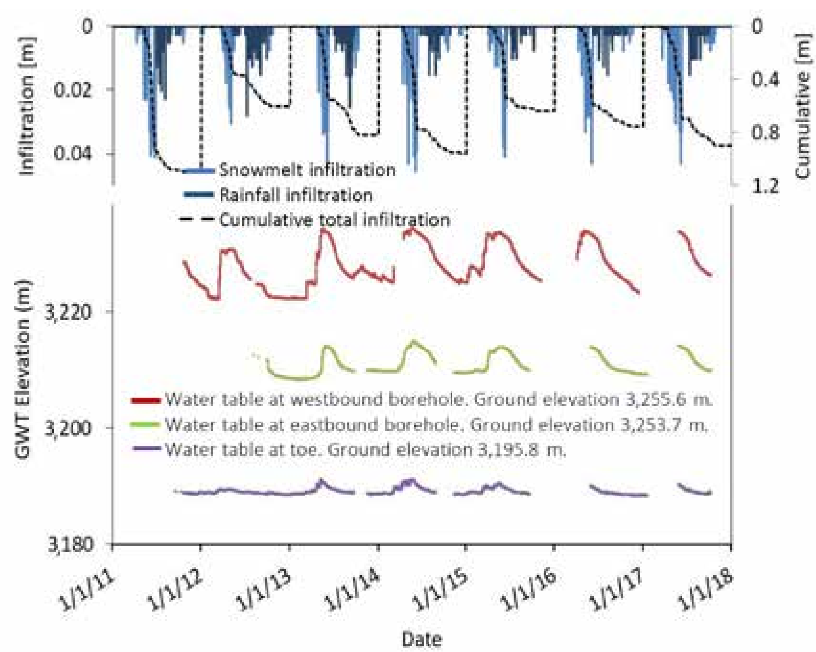


Figure 3. Measured groundwater levels and infiltration estimates.

Slope-stability Analysis with the Suction Stress and Water Table Variation

We used an extended formulation of Bishop's simplified method of slices (Equation 1), in combination with a transient, 2D finite element model, to understand quantitatively how this relatively deep landslide responds to variations of infiltration supplied from snowmelt. The analyses examined two controlling variables: the location of the water table and

$$FS = \sum_{k=1}^{m} \frac{\dfrac{c'b_n + W_n tan\phi' - \sigma_n^s b_n tan\phi'}{I(\alpha_n, \phi', FS)}}{\sum_{n=1}^{m} W_n sin\alpha_n} \qquad \text{Equation 1}$$

where:

$$I = \cos\alpha_n + \frac{tan\phi'}{FS}\sin\alpha_n$$

and

σ_n = total normal stress of the n^{th} slice [kPa]
σ^s_n = suction stress at the base of the n^{th} slice [kPa]
u_a = pore air pressure [kPa]
u_w = pore water pressure [kPa]
b_n = width of the n^{th} slice [m]
W_n = weight of the n^{th} slice [kN]
m = number of slices
α_n = angle of base of the n^{th} slice [°]
FS = slope's factor of safety

FS = slope's factor of safety
γ_{dry} = dry unit weight = 16 [kN/m³]
c' = drained cohesion = 0 [kPa]
ϕ' = drained internal friction angle = 23 [°]
θ = volumetric water content [m³/m³]
θ_s = saturated volumetric water content = 0.41 [m³/m³]
K_s = saturated hydraulic conductivity = 1.2E-5 [m/s]
θ_r = residual volumetric water content = 0.065 [m³/m³]
α = inverse of air-entry pressure = 0.076 [kPa⁻¹]
n = pore size parameter = 1.89 [-]

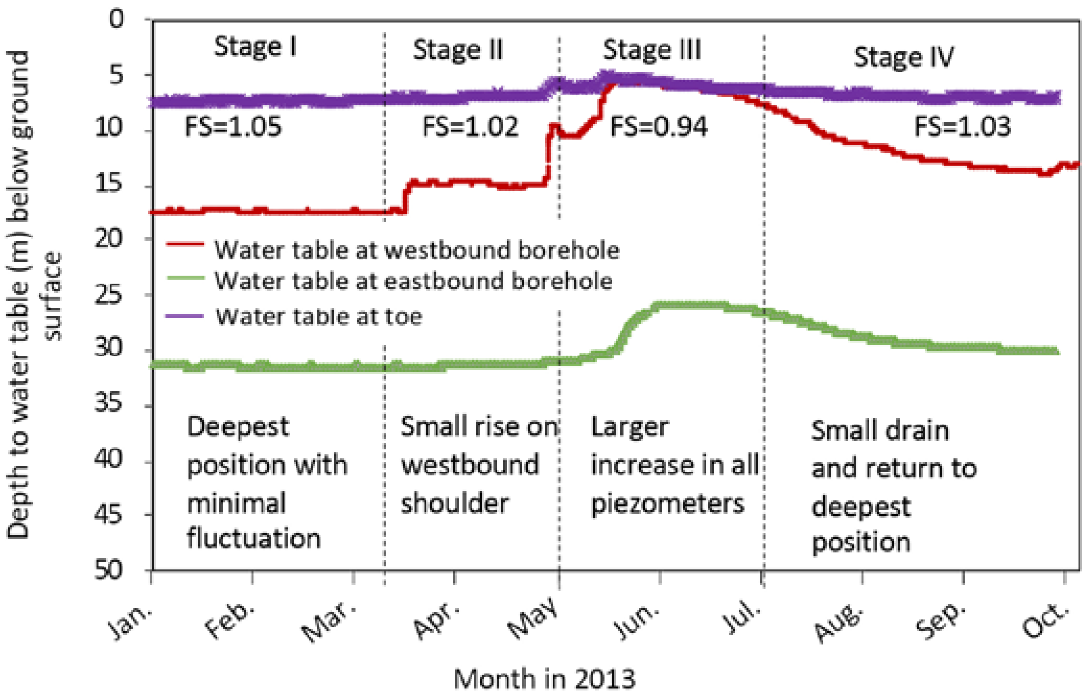


Figure 4. Slope stability analysis results.

the suction stress above the water table. The finite element numerical model was developed for the embankment slope cross-section (Figure 2) to calculate time-dependent soil moisture, suction, and suction stress fields. The measured shear strength and hydraulic properties defined in Table 1 were used as input data for the numerical model. The recorded water table variations from Figure 3, together with the measured hydrologic and strength parameters, were used to calibrate the model. The extended Bishop's simplified method of slices is used to calculate the factor of safety along the identified sliding surface. The resulting factor of safety for each characteristic stage is shown in Figure 4.

In the four stages, factors of safety were calculated using the average water table position for that corresponding stage. During Stage I, from November to early March, when snow falls but little infiltration occurs, the calculated FS is 1.05 when the water table was the lowest. During Stage II, from early March to the end of May, when snow melt and water infiltrates into the embankment slope, the resulting rise in the water table decreases the calculated FS to 1.02. From May to July during Stage III, when rainfall occurs and directly infiltrates into the slope, the surge in the level of the water table reduces the FS to 0.94, resulting in the embankment slides observed during this period. After June, rainfall events reduce dramatically, so from July to November during Stage IV, the calculated FS increases to 1.08, causing movements to cease. The computed timing and period of the embankment instability match well with the large slope deformations monitored by the installed inclinometers at the site.

These analyses show that for marginally stable slopes, variations in either the water table location or suction stress in the vadose zone can mobilize or arrest slope movement. Suction stress, as expressed in Equation 1, is a component of effective stress that's caused by a soil's water content. Suction stress is equal to the product of soil suction and the effective water content when it's negative, and equals the pore water pressure when it's positive. By explicitly considering the impact of water content changes on effective stress and water table position, the classical slope stability analysis method can be extended to provide a reliable and accurate means to describe the physical mechanisms that lead to perennial and episodic landslide movements driven by snowmelt and rainfall infiltration at this site.

Applying This Handy Slope Stability Analysis Tool

Evaluation of field measurements from a problematic slope adjacent to I-70 in Colorado shows that the depth of the water table varies by as much as 9 m from season to season and year to year, and is controlled by episodic infiltration events. By field monitoring of piezometers and inclinometers, and conducting the transient variably saturated numerical slope stability analysis, it became clear that rapid surges of the water table, soil water content, and soil suction stress are the causes for the embankment sliding in early summer when the FS drops below 1.00. Recent analysis also examined feasible options of remediations to brake the sliding of I-70, including rerouting the snowmelt and rainfall from the upslope, and effective horizontal drains on the embankment.

With the suction-stress-based effective stress formulation, classical methods of slope stability analysis can be handily extended to slopes under variably saturated soil conditions. Using this effective stress formulation, shear strength parameters remain unchanged, but are expanded to include three additional parameters for unsaturated hydraulic properties to quantify variations of soil water content, suction, and suction stress. This approach provides a fundamentally sound, yet practically efficient and accurate method to analyze the stability of unsaturated soil slopes.

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Impact of Soil Moisture on the Response of Power Poles During Ice Storms

EARTH, WIND, AND ICE

By Tommy D. Bounds, Ph.D., P.E., M.ASCE, Gerald A. Miller, Ph.D., P.E., M.ASCE, and K. K. "Muralee" Muraleetharan, Ph.D., P.E., G.E., F.ASCE

It's easy to ignore the electrical distribution network that so seamlessly provides power to homes and businesses throughout the country. That is, of course, until the power goes out. Power outages within the distribution network can be the result of everything from fallen tree branches to wildlife getting entangled in the wires. While we can't control or predict events caused by wildlife or people, we strive to prevent those caused by threats we understand. Many strategies exist for preventing threats to our nation's power distribution network, ranging from preventative vegetation management to hardening the network. If enough of these strategies are employed, surely efforts to increase the reliability of the network should succeed.

Figure 1. Leaning power poles – foundation failure.

Despite this understanding and the industry's best efforts, recent events have highlighted the fragility of the distribution network and the consequences when it fails. As climate change intensifies, the distribution network will be exposed to increasing threats, including more intense and frequent versions of threats we're already familiar with, such as ice storms, wind events, hurricanes, tornadoes, droughts, and wildfires. At the same time, the distribution network is under increasing pressure due to the demands of modern society. The distribution network is a key part of the electrical system, tasked with powering the necessities of modern life as well as providing the electricity required to power critical hospital equipment, cars, data centers, and everything in between. Failure of the network can lead to loss of life and devastating economic impacts. The distribution network is constantly under many different threats. This article focuses on the impact of ice storm loading, and how soil moisture content can affect the failure mode of power poles within the distribution network.

Behavior Response of Power Poles During Ice Storms

The electrical distribution network — the last leg in the journey to deliver electricity from the source to end users — is largely comprised of power poles and electric lines. And as the last leg, it's also the largest component spatially in the network. Its large footprint and the fact that many of its components are exposed to nature make it particularly vulnerable to threats from severe weather.

In the U.S., ice storms are a common winter occurrence in the southern Great

Plains of Nebraska, Oklahoma, and Texas. Moreover, the frequency of ice storms in both the central and northeastern U.S. has been increasing. During ice storms, it's common for ice to accumulate on power lines and the surfaces of their structural support system over a relatively short period of time. When this happens in isolation, it can cause power lines to sag and break, and if high winds are also part of the storm, the damage to power lines is intensified. Ice also accumulates on the power poles, and the increased loading of the ice-covered power lines can cause the power poles to fall over, lean, or break. The behavior of power poles during ice storms is of particular interest largely due to the time required to repair or replace them. A broken power line can be a relatively quick fix, but a power pole may require resetting or replacement depending on the type of failure.

Power poles can essentially fail in two modes. Failure can happen from excessive movement or leaning of the power pole (Figure 1). An excessively leaning power pole is not safe due to the additional forces and moments that can be induced in the power pole, particularly near the base. Excessively leaning power poles that are ignored can also impact adjacent power poles, causing them to lean as well due to the out-of-plumb loading on the lines. An excessively leaning power pole is a sign of soil or foundation failure at the base. The other failure mode is pole breaking (Figure 2). Power poles break when the moment capacity of the power pole is exceeded, often leading to power line breakage. The repairs and restoration time for these two failure modes varies. A leaning power pole may not require immediate attention and may not cause power failure. The repair can be as simple as resetting the power pole and providing guy wires for support. But the repair of a broken pole requires that the pole be replaced, which involves advancing and preparing a new socket for the pole and reconnecting the lines once the pole is set. This process understandably requires a larger crew and more time to repair.

Figure 2. Broken power poles – moment capacity exceeded.

Both types of failure have been observed for similar loading conditions. Naturally, it's curious how two failure modes can materialize for what seem to be similar loading conditions. Ignoring effects from differences in age and quality of the wood in power poles, it becomes clear that the soil must be a factor.

The Role of Soil Moisture

It's well accepted that moisture can have profound impacts on the behavior of soils, especially clayey soils. In general, a given clayey soil will be softer when fully saturated than when dry. This phenomenon is due to soil suction acting on the individual soil particles at the micro scale. Suction draws the soil particles together into a tight matrix, which leads to an apparent cohesion in the soil and a higher soil stiffness. Considering the profound impact water can have on the behavior of these soils, foundation failure of a power pole is much more likely if the soil is saturated and soft. Conversely, pole breakage should be more likely if the soil is dry and very stiff. In this case, when a power pole leans, the soil is stiff enough that movement is restricted at the base of the pole, and the bending moment near its base increases. Once the moment capacity of the power pole is exceeded, the pole breaks, and literally the lights go out.

Droughts and pluvial events in the southern Great Plains are becoming more intense and common. These two weather events represent two extremes for soil moisture. As soil moisture variability becomes more pronounced, the influence of soil moisture needs to be incorporated into routine analysis.

Putting It All Together

The Numerical Simulations

Due to the complex nature of this problem, it's very difficult to perform field tests in real time. So to demonstrate the effect of changing soil moisture on the behavior of power poles during an ice storm event, we present the results of numerical simulations that consider power pole embedment in four soils ranging in plasticity from silt to fat clay. In the analyses, we correlate soil suction with moisture content so the relationship between stiffness and moisture content varies for each soil. In sum, the stiffness for fat clay is very sensitive to changes in

SOIL TYPE	FRICTION ANGLE (°)	SATURATED COHESION (PSI)	UNSATURATED COHESION (PSI)
Silt	30	2	3
Silty Clay	27	3	8
Lean Clay	25	5	14
Fat Clay	20	10	31

Table 1. **Soil properties.**

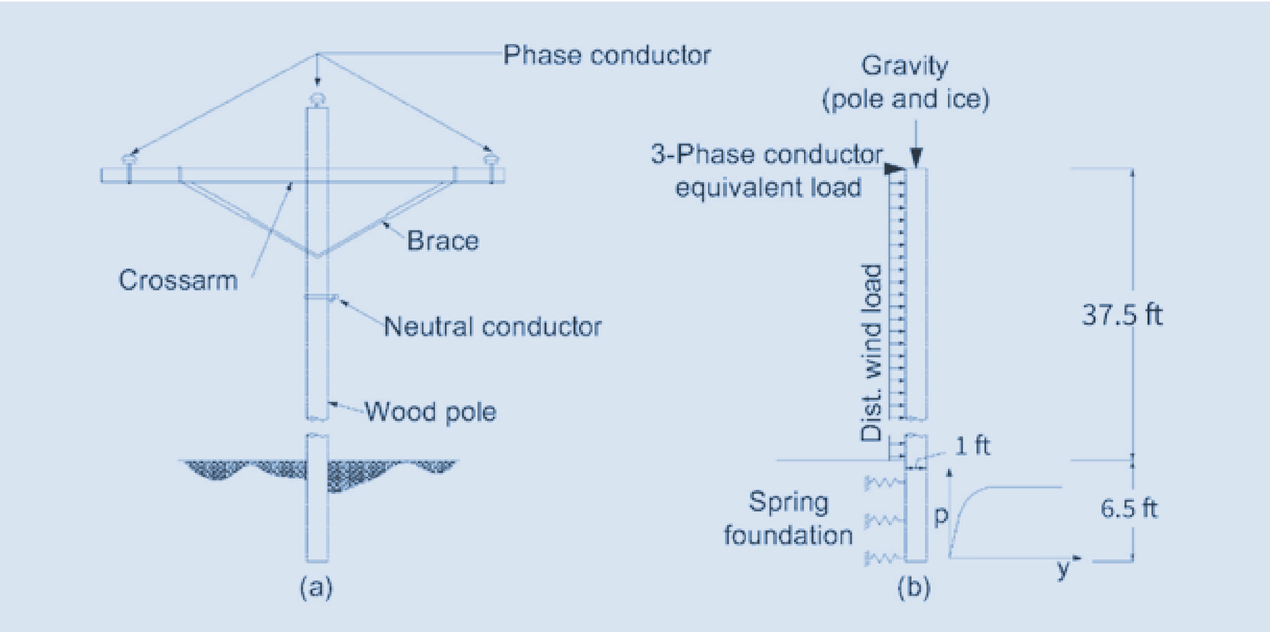

Figure 3. **Typical power pole and loading: a) three-phase power pole, and b) loading on power pole.**

moisture; silts are barely sensitive to any changes in moisture; and silty clay and lean clay fall in between.

This range of soils was considered to emphasize the importance of soil type on the analysis and behavior of power poles during extreme loading. The analyses considered saturated and unsaturated soil conditions separately. Soil moisture content varied with depth in the unsaturated analysis. The variation of soil moisture with depth was estimated using seepage analysis and by subjecting the soil profiles to drought conditions. Drought conditions were simulated using weather data collected from a drought event in Oklahoma. Soil strength and stiffness for the demonstration soils were modified using apparent cohesion for the unsaturated soil profile.

For these analyses, the apparent soil cohesion was taken as a function of moisture content, which varies with depth in the soil profiles. The soil cohesion and friction angle values at a depth of 3 ft in each of the soil profiles are presented in Table 1. This depth corresponds to the midpoint of the embedded portion of the power pole. LPILE utilizes p-y curves to predict the behavior of piles in soil. The p-y curves used for the analysis were created using a procedure developed by Mokwa, Duncan, and Helmers and reported in *GSP 100, New Technological and Design Developments in Deep Foundations.* The p-y curves produced are a function of the apparent cohesion and the friction angle for the soil. Essentially, there's a family of p-y curves for each saturated and unsaturated soil condition.

The 44-ft-tall, three-phase power pole (Figure 3) assumed for the analyses was modeled using LPILE. All the power poles were modeled as an elastic, nonyielding, tapered section with a top diameter of 8 in. and a base diameter of 1 ft. The poles were embedded to a depth of 6.5 ft in each of the soil types studied, and then "tested" systematically using varying soil strengths and stiffnesses according to the saturation conditions. Ice loading on the power pole was varied from a thickness of 0.25 to 1.0 in., while the wind speed was varied from 40 to 80 mph. The wind direction was applied perpendicular to the power pole to represent the worst loading case scenario. Wind loading was applied as a uniform distributed load along the pole. Loading from the line (conductors) was applied to the power pole as an equivalent load based on the ice weight and the wind forces. Wind loading was determined from the wind speed and the varying diameter of the conductors because a power line with a thicker layer of ice will attract more wind.

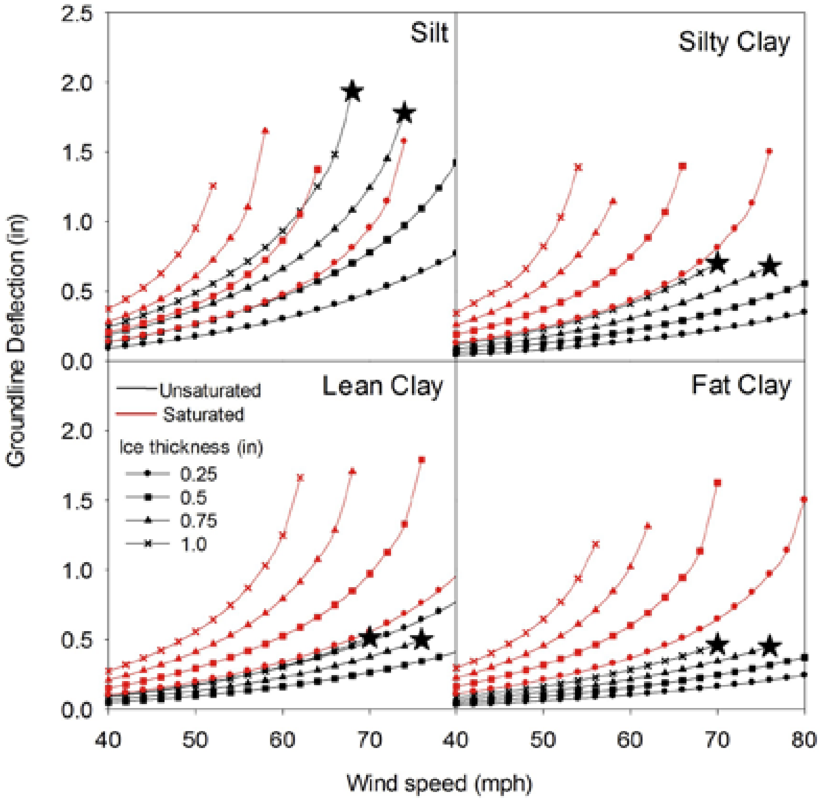

Figure 4. Simulation results.

The Numerical Results

The results from the analyses are summarized in Figure 4. This research was originally reported by Bounds, Hou, Miller, and Muraleetharan in *GSP 343, Pore-scale to City-scale*. Black stars in the figure show that the maximum allowable bending moment for the power pole is exceeded, and pole breakage would occur at that point for the poles considered. Pole breakage was only observed for loading scenarios with a black star. Some of the other analyses were not successfully computed due to excessive groundline deformation, so in these instances, the maximum allowable bending moment was not exceeded. Most of the saturated analysis experienced excessive groundline deflection.

The analyses support the hypothesis that saturated soils experienced more groundline deflection that's indicative of foundation failure. Power poles embedded in unsaturated soil experienced less ground line deflection, which results in larger bending moments. The maximum allowable bending moment was exceeded two times for each scenario considered. Exceedance of the maximum bending moment only occurred for the two maximum ice thicknesses and unsaturated soil conditions. When pole breakage occurred, the wind speed was the same for each scenario with the exception of the silt site. For the silty clay, lean clay, and fat clay sites, when a power pole was loaded with a 1.0-in. ice thickness, it failed at a wind speed of 70 mph, and at a wind speed of 76 mph when the power pole was loaded with a 0.75-in. ice thickness. Poles at the silt site failed at slightly lower wind speeds, but also suffered from excessive deformation. If the allowable bending moment of the power pole isn't exceeded, power poles in unsaturated soil will perform better during ice storms than a power pole in saturated soil. Soils that are sensitive to changes in moisture, such as fat clays, for example, had the largest variation in behavior for the loading conditions analyzed.

Don't Overlook the Soil Moisture

The impacts of soil moisture must be a factor when grid hardening strategies are being developed. For example, placing power poles with larger allowable bending moments, such as poles having a larger cross-section or manufactured using a stronger material, is a good use of resources if the site has soil that's sensitive to changes in moisture and is expected to be influenced by drought conditions. The same cannot be said for sites that are typically saturated and/or flooded. At these sites, retrofitting existing power poles with guy wires or other foundation supports would be a better use of resources because during these extreme loading events, the power pole isn't under extreme stress; rather, it's the foundation that's not up to the task.

As extreme weather events become more common, assumptions made for initial designs and retrofits must change because we've been choosing to ignore, for the sake of simplicity, the effect of factors like variations in soil moisture. Considerations like these will be critical if power companies want to ensure they can deliver power to their customers when it's most needed, such as during an ice storm.

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Looking southbound toward the Port Road bridge, showing the lowered section of the North-South Motorway in Adelaide two days after the Torrens to Torrens section opened to traffic. (Photo source: Creative Commons "North-South Motorway" by Scott Davis is licensed under CC BY 4.0.)

SOIL NAILING THIRSTY GROUND

Applying Unsaturated Soil Mechanics Theory in Practice

By Bosco Poon, Ph.D., MIEAust, CPEng NER, M.ASCE

Adelaide, South Australia's capital, is nestled on a clay plain that stretches from north to south between the Adelaide Hills and the sea. The city's semi-arid climate causes the clay above the groundwater table to remain unsaturated, with a consistency ranging from stiff to very stiff. Suction profiles in Adelaide have been studied extensively over the years, mainly in relation to residential footing design over reactive clays. The generally high suction in the area has contributed to the stability of many unsupported deep excavations in clay. Consequently, geotechnical engineers believe that applying unsaturated soil mechanics theory under suitable conditions could enable the use of lightweight retaining structures, resulting in substantial cost savings. The prerequisites for utilizing unsaturated soil strength in engineering design include:

- A groundwater table that remains permanently below the excavation depth
- Predominantly clay soils with no significant defects, such as fissuring
- Adequate site-specific determination of suction-induced shear strength

The Project

The project that's the focus of this article involved the construction of a 4-km-long section of the North-South Motorway between Torrens Road and the River Torrens, approximately 5 km northwest of Adelaide's central business district. The motorway includes a 3-km stretch of lowered roadway that reaches a maximum cutting depth of 8.9 m below the existing South Road surface. The sides of the cut are retained by permanent soil nails that provide structural reinforcement for stability.

The area of the depressed roadway features a deep Quaternary alluvial profile, with a regional groundwater table located in a gravelly aquifer at depths of 9-14 m below the surface, corresponding to the water level in the River Torrens. The soil above the aquifer, where the lowered road was constructed, consists of stiff to very stiff clays with sandy lenses, exhibiting low to medium plasticity. Below the aquifer lies a deep layer of predominantly very stiff to hard clays. Because the excavation depth is permanently above the water table, the soil nail wall design leveraged unsaturated soil strength that would be influenced by the long-term soil suction of these strata. Geotechnical investigations indicated no evidence of significant defects, such as fissuring, in the clays, so it was assumed during design that any such features, if present, were localized and limited in extent.

Figure 1. a) A trial pit of up to 8 m in depth, and b) a trench for applying water at the trial.

Soil Suction Profile and Unsaturated Soil Strength

The Department of Planning, Transport, and Infrastructure of the South Australian government examined the soil suction profiles at the project site through a soil wetting process conducted during a piled wall trial at Robert Street adjacent to the project corridor. Figure 1a shows the trial test pit that was excavated to study the stability of a vertical cut above the water table extending to depths of 8 m. Then, after construction of the piled wall, water was injected into a 1.5-m-deep soakage trench (Figure 1b) positioned 1 m behind the wall for a period of three to four weeks. In-situ total soil suction values were determined using psychrometer tests on borehole samples collected before the trial. The clays were relatively dry, with total suctions measuring up to approximately pF = 4.8. After soil wetting, the measured suction values dropped to as low as pF = 3.6, as shown in Figure 2. For design purposes, a value of pF = 3.6 was considered representative of long-term wetted soil conditions, while pF = 3.4 was adopted for worst-case scenarios, such as prolonged leakage from a broken water pipe.

The shear strength of unsaturated clay was assessed using the equation from Fredlund and Rahardjo's classic 1993 text *Unsaturated Soil Mechanics in Engineering Practice*:

$$\tau_f = c' + \sigma' \tan\phi' + (u_w) \tan\phi^b \qquad \text{Eq.1}$$

where τ_f is the shear strength, c' is the effective cohesion, ϕ' is the effective friction angle, σ_v' is the effective stress on the failure plane, u_w is the matric suction, and ϕ^b is the rate of increase in shear strength with matric suction. For practical design purposes, total suction (i.e., matric suction plus osmotic suction) was used in the equation because the osmotic pressure was significantly lower than the measured total suction, and the total and matric suction curves were nearly identical. For the fully saturated condition, the effective strength parameters, c′ and ϕ′, were derived from 33 consolidated-undrained triaxial test results. A linear regression line drawn through the data points on a p-q plot resulted in $c' = 9.5$ kPa and $\phi' = 30.7$ degrees. For design purposes, $c' = 5$ kPa and $\phi' = 30$ degrees were adopted. The ϕ^b value for the unsaturated condition was assessed using published test data of Keswick clay in Adelaide. The data show a linear relationship between shear strength and total suction. The mean value of the measured $\tan\phi^b$ was 0.15, with upper and lower bounds of 0.22 and 0.11, respectively. For design, the mean $\tan\phi^b$ value of 0.15 was adopted, corresponding to $\phi^b = 8.5$ degrees.

Figure 3 presents the plot of apparent cohesion versus total suction. It shows that the values calculated using the term $c' + u_w \tan\phi^b$ in Eq. 1 are much lower than those obtained from laboratory UU triaxial tests under cell-confining pressures varying from 40–200 kPa. In contrast, pocket penetrometer, or PP, tests on in-situ soils at the side of the trial pit, which were not subject to overburden pressures, yielded results that aligned more closely with the predictions. However, in soils with relatively high silt and fine sand content, the weak bonds between grains were easily broken during PP testing, leading to lower inferred shear strengths than predicted. For design purposes, an apparent cohesion of 40 kPa was adopted for

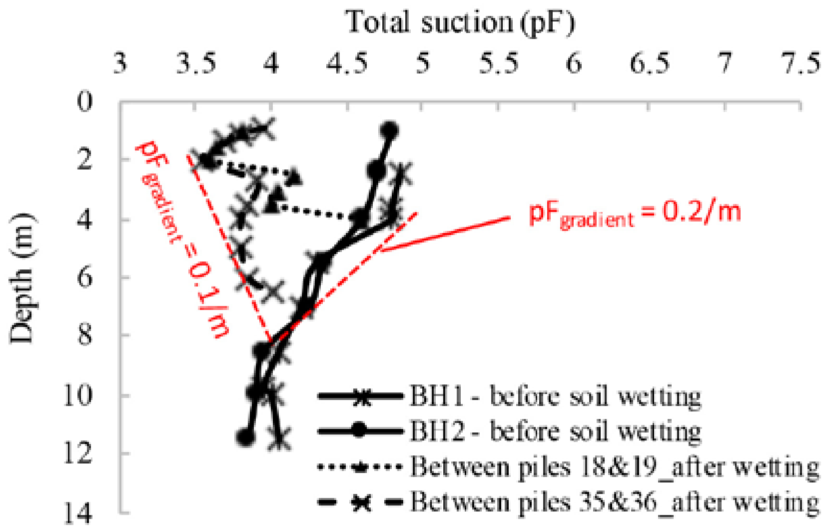

Figure 2. Total suction profile.

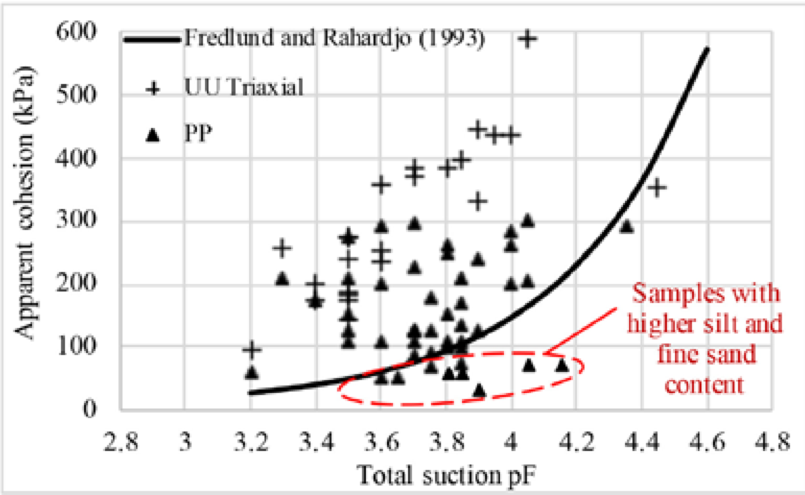

Figure 3. Apparent cohesion versus total suction.

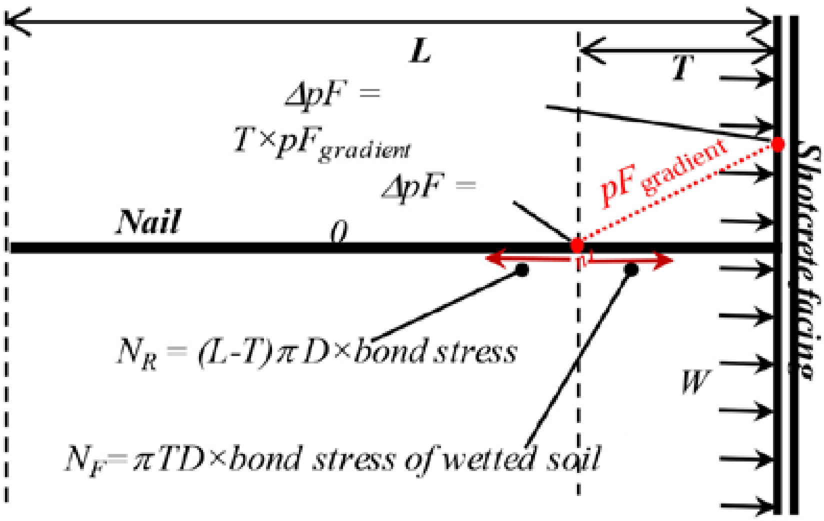

Figure 4. The nail pull-out analysis model.

long-term design, calculated using Eq. 1 for a design total suction of pF = 3.4. This was considered a conservative approach because the assessed value is generally lower than those obtained from UU triaxial and PP tests.

Swelling Pressure Behind the Wall

For soil nail wall design, swelling behind the wall face does not impact overall slope stability, but can affect the tensile forces in the nails, and the design of the nail heads and shotcrete facing. Figure 4 illustrates the adopted nail pull-out analysis model. The swelling pressure, W_p, behind a soil nail wall face depends on 1) the rate of suction change $pF_{gradient}$, and 2) the width of the swelling zone T, and can be estimated by the following site-specific equation as developed in Poon and Mitchell (2020) in the *20th ISSMGE* proceedings:

$$W_p = 3.85 \times T^2 \times pF_{gradient} \qquad \text{Eq.2}$$

Figure 5 shows the plot of W_p vs T based on Eq. 2 for a $pF_{gradient}$ of 0.1/m to 0.2/m, reflecting the worst-case scenario for $pF_{gradient}$ identified in the suction profile shown in Figure 2. CPT soundings taken after wetting at the Robert Street trial pile wall site indicated a horizontal wetting extent of typically 2-3 m behind the back of the wall face, and no more than 4 m. As shown in Figure 5, the swell pressures generated are almost always below 10 kPa for $T < 4$ m. With W_p assessed, the nail resisting force N_R required to counteract the nail swelling force, N_F, and the wall swelling load, W_F, are given by:

$$N_R = N_F + W_F \qquad \text{Eq.3}$$

$$N_R = (L - T) \times \pi \times D \times \textit{bond stress} \qquad \text{Eq.4}$$

$$N_F = \pi D \times T \times \textit{bond stress of wetted soil} \qquad \text{Eq.5}$$

$$W_F = W_p \times \textit{soil nail tributary area} \qquad \text{Eq.6}$$

The soil nail walls were faced typically with 75-mm-thick, synthetic-fiber-reinforced shotcrete that was locally thickened over nail heads and at certain mid-span locations where required. The shotcrete was designed to resist the lateral pressures associated with clay swelling and sand lenses, as well as to resist the punching effect at the nail head.

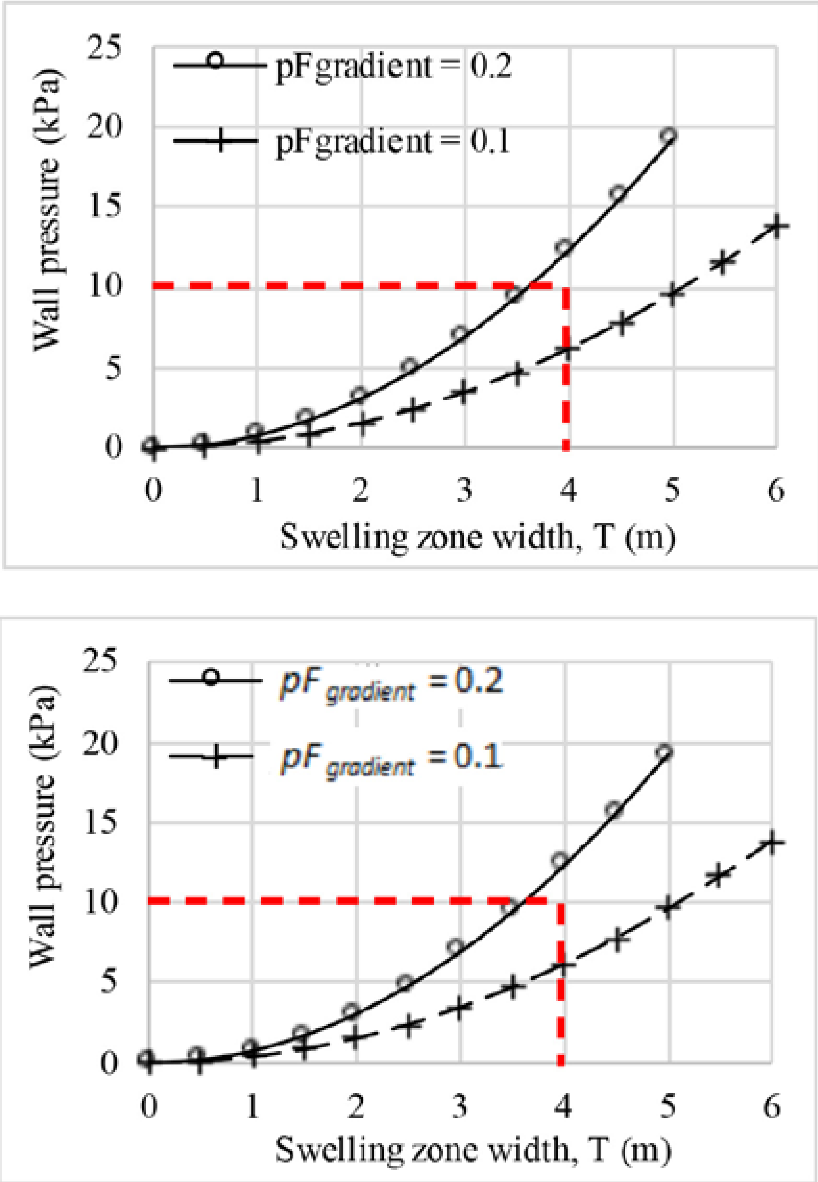

Figure 5. Assessed wall pressure versus swelling zone.

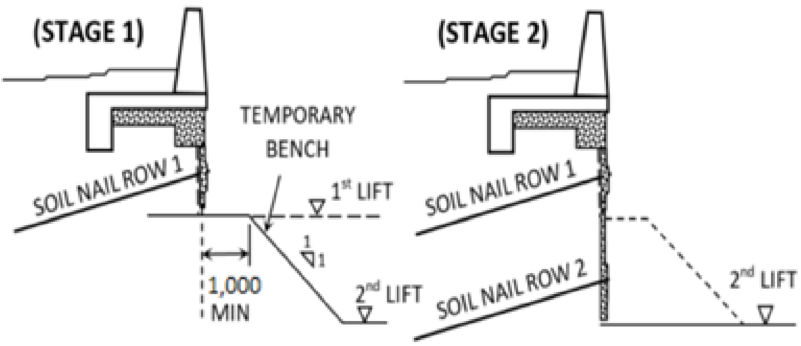

Figure 6. Observational method for soil nail wall construction.

Wall Design and Observational Method

The soil nail walls varied in height, reaching a maximum of approximately 8.9 m. They were constructed at a 1H:40V batter. The 150-mm-diameter drill holes for the soil nails were inclined at 15 degrees to the horizontal. In areas with sandy soil or softened clay where remolding issues were present along the bond zone, the diameter was increased to 200 mm.

Design of the soil nail walls considered both global and a nominal 1-m-wide local wedge surface failure modes. For an 8-m-high wall excavation in unsaturated clay, three rows of 6-m-long soil nails were required. The vertical and horizontal spacing between nails were 2.5 m and 3 m, respectively. For clay profiles with interbedded sand lenses, the nail lengths were increased to between 5 and 7 m, and the nail spacings were reduced to 1.5 m vertically and 2.1 m horizontally.

An observational method approach (Figure 6) was adopted for the soil nail wall construction. This approach entailed cutting a temporary bench in front of each excavation lift to facilitate a visual assessment of the ground conditions. The bench provided access and time for the geotechnical site representative to confirm the ground conditions and select appropriate soil nail arrangements from the predeveloped toolbox designs. These designs covered a range of possible soil profiles and unfavorable ground conditions, such as sand lenses, unsaturated fissured clay, and perched groundwater. After the final trim of the temporary bench was made for each excavation lift, the ground conditions were reinspected before the installation of soil nails and shotcrete.

Wall Movements

The soil nail walls were monitored during construction and throughout the service life using a system of inclinometers and survey markers. For wall excavations in clayey soil profiles having typically stiff to very stiff consistency, the observed wall deflection during construction was generally less than 0.25 percent of the excavation depth in clay, which was considered minimal.

Figure 7. The soil nail wall after full-depth excavation.

Sand lenses, including pockets of cohesionless sand and silty sand of varying thicknesses and depths, were encountered in the southern part of the wall alignment. These sand lenses, if left exposed for an extended period, could cause unwanted wall movements. In one case, after excavating the second lift to a depth of 5.3 m for a planned 8-m-high wall, the exposed cut face wasn't immediately covered with shotcrete due to unexpected construction delays. The resulting lost moisture from the cut face led to significant unravelling of the sandy soil and soil sloughing.

The loss of soil moisture caused wall movements at the top of the wall that exceeded design predictions, with horizontal and vertical displacements of up to 25 mm and 14 mm, respectively. Longitudinal cracks up to 7 mm wide were observed in the pavement behind the wall. The cracks were formed parallel to the road alignment at an offset of 2 to 2.5 m from the inner side of the crash barrier, which coincided with the footing heel of the barrier. Coring investigations along the length of the cracks indicated that they generally terminated at the bottom of the base course of the pavement structure, about 650 mm below pavement surface. Despite these surface cracks, the wall top deflection was measured to be 0.47 percent of the excavated depth, which remained within the 0.2 to 0.5 percent range commonly observed for wall excavation in stiff clays.

In response to the observed wall movement, a back-analysis was conducted using 2D finite element analysis in PLAXIS 2D. The analysis was used to simulate the soil unravelling at the exposed cut face in sandy soil, as well as how the shallow crack zone formed behind the footing heel of the crash barrier. The global stability of the wall was further evaluated using the c'-ϕ' reduction method in FEA, supplemented by a conventional limit equilibrium analysis employing the Morgenstern-Price method of slices. Both analyses showed that while the Factor of Safety was satisfactory for the short-term excavation to mid-wall height, the formation of tension cracks led to a FoS lower than 1.35 following full-depth excavation and under long-term wetted soil suction conditions (pF = 3.4). Additional soil nails were subsequently installed as part of the remedial design to meet the long-term stability requirement. Figure 7 shows the finished wall after full depth excavation.

Lessons Learned

The relatively deep groundwater level and predominately unsaturated and nonfissured clay ground conditions at the project site were ideal for wall design using unsaturated soil mechanics. This ground profile allowed for a lighter retaining structure, leading to significant cost savings. The wall excavation was reinforced by soil nails and a typically 75-mm-thick fiber shotcrete facing.

A key design challenge was the potential impact of swelling clay on the lateral stress and deformation on wall performance. While swelling did not affect overall slope stability, it did increase the tensile forces in the nail and influenced the design of the nail-head and shotcrete facing. It's been demonstrated that the swell pressure generated by suction change is less than 10 kPa.

Construction of the soil nail wall in unsaturated clay was not without its challenges. As demonstrated by this project, excavating through thick, clean sand lenses within the clay can lead to significant overbreak, resulting in greater wall movements than initially anticipated. To manage the soil variability and mitigate the risk of overbreak during soil nail wall construction, an OM approach should be adopted. This allows geotechnical site representatives to inspect the exposed face and select an appropriate soil nail arrangement from the design toolbox, which contains predefined designs for various possible soil profiles.

An OM approach offers a valuable strategy for addressing uncertainties in soil models and design assumptions. It allows adjustments during construction to align with observed geotechnical behavior, reducing the risk of overdesign or unforeseen issues. However, the following challenges should be carefully considered when applying the approach in future design and construction planning:

- *Need for experienced personnel:* Implementing an OM approach necessitates oversight by an experienced engineering geologist or geotechnical engineer who can accurately interpret ground conditions during wall excavations and make well-informed decisions to adopt the appropriate toolbox design.
- *Resource and time requirements:* An OM approach demands extra resources and time for tasks such as detailed site mapping during construction and real-time decision-making. These requirements must be incorporated into the construction program, as they can influence project timelines and budgets.
- *Risk of overreliance on observations:* Solely relying on observations without robust contingency plans can introduce vulnerabilities, especially if unexpected conditions arise that exceed the scope of anticipated scenarios.
- *Integration into design planning:* Effectively incorporating the observational approach requires early-stage planning to establish clear protocols, monitoring thresholds, and contingency measures. Failure to do so may lead to reactive, rather than proactive, decision-making.

The OM approach may incur higher costs compared to traditional design methods due to the additional design work and the extra resources and time needed for site mapping and decision-making during construction. However, these costs are outweighed by the significant savings achieved through optimized designs based on unsaturated soil theory, which help reduce overdesign and material wastage. GS

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FROM ALASKA TO TEXAS

Unsaturated Moisture Management Transforms Pavement Performance

By Xiong Zhang, Ph.D., P.E., M.ASCE, Nripojyoti Biswas, Ph.D., John M. Lostumbo, P.E., M.ASCE, and René Laprade, P.Eng., M.ASCE

MMG installation on Dalton Highway in Alaska.

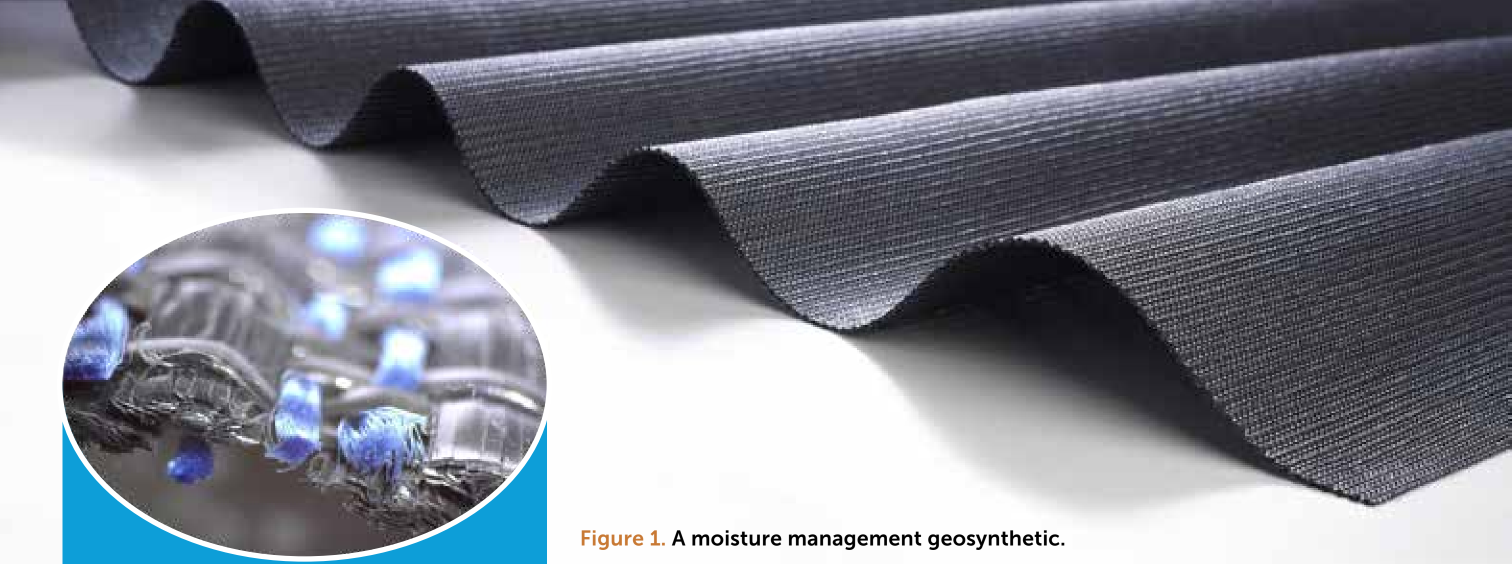

Figure 1. A moisture management geosynthetic.

While today's infrastructure is built on unsaturated soils, contemporary design methods generally presume soil is fully saturated. This premise is based on the idea that designing for saturated soil conditions results in conservative outcomes. But this isn't always the case, such as when assuming a fully saturated subgrade can lead to ineffective drainage designs in pavement structures. Coarse-grained aggregates are often used for drainage due to their high saturated permeability, but in unsaturated conditions, the permeability of these aggregates significantly decreases as air enters the relatively large voids and impedes water flow.

Excess moisture in pavements significantly reduces roadway life expectancy through several means, including stripping of asphalt (occurs when lower layers of asphalt separate from the asphalt cement, causing it to collapse), joint displacement in concrete pavements, subgrade shrinkage and swelling, and frost heave. According to the National Cooperative Highway Research Program, excess water can reduce pavement life expectancy by more than 50 percent.

A potential solution to this problem is to connect the moisture within the pavement structure to the atmosphere, thereby relying on the natural environment's ability to dehydrate the pavement. One approach is to apply a woven, high-modulus moisture management geosynthetic, or MMG. While geotechnical designers recognize that enhanced woven geotextiles provide reinforcement, separation, filtration, and stabilization, an MMG also removes water via capillary suction from within pavements and unsaturated subgrades by drawing water from the high relative humidity within a roadway toward the lower relative humidity of the atmosphere or drain. This movement of water is facilitated by carefully engineered hydrophilic and hygroscopic wicking yarns, which are woven within the high-modulus yarns of the MMG (Figure 1). By installing the MMG in the pavement as illustrated in Figure 2, the water in the pavement structure can be transported within the wicking yarns to the roadway shoulder, and vaporized to the surrounding atmosphere, which has much higher suction. The MMG generates a relatively dry zone in the pavement structure that not only improves its performance, but also helps mitigate differential settlement caused by expansive soils in Texas, pumping in pavement shoulders in Missouri, and frost heave and subsequent thaw-weakening in Alaska. To incorporate an MMG into a pavement design, a Hydraulic Improvement Factor, or HIF, is calculated and applied to the structural number of the adjacent layer in AASHTO pavement design. Examples of these benefits are described in the following case history examples.

Research Validated Full-Scale Field Performance

Mitigating Expansive Soils and Improving Recycled Material Performance in Texas

In many areas of Texas, the seasonal saturation/desaturation moisture cycles of expansive soils induce volumetric strains that can severely affect the performance of lightly loaded structures like pavements. This problem led engineers with Solmax to team up with researchers at Texas A&M University to study how MMG could be used to address and mitigate the problem of differential heaving and subgrade deterioration.

The pavement section that was selected is one of the country roads, FM 1807, that connect rural areas to market towns or distribution centers within Texas. This one, in Venus, Texas, had been subjected to repetitive rehabilitation every six months because of constant deterioration of the performance. The subgrade soils in the region are classified as high-plasticity clay, and their problematic behavior is exacerbated by high temperatures during the summer months causing shrinkage cracks on these soils. Moreover, rainfall-induced swelling, in addition to the water drained from the nearby agricultural fields, causes cyclic volumetric strains that damage the roads of this region.

Figure 3 shows the 2018 construction of one of two, 130-ft test sections along the eastbound lane of FM 1807, with help of the engineers from the Texas Department of Transportation. The first test section was constructed with recycled asphalt pavement, or RAP, in the 15-in. base layer. The second test section was built with traditional crushed stone aggregate, known as flex-base (i.e., FB) materials. Both sections were reinforced with MMG to gain the benefit of both mechanical and hydraulic stabilization between the base layer and expansive soil subgrade layer. A 2-in.-thick layer of asphalt was laid on top of the base. The westbound lane was used as a control section, having a 13-in. base of FB material and an approximately 4-in.-thick asphalt layer. The test sections were instrumented with moisture sensors, shape array accelerometers to monitor deformations, and pressure plates.

The test sections were monitored over the next two years using the embedded sensors as well as nondestructive testing. The moisture monitoring showed that the MMG was effective in laterally draining moisture through capillary action when compared with the control section. This became evident when the deformations monitored at the top of the subgrade showed minimal differential heaving and pavement rutting. Nondestructive tests were also performed using a falling-weigh deflectometer. The nondestructive tests showed that the base course constructed with RAP had a better performance in terms of higher moduli values compared to the FB section. Another interesting test observation was that the MMG section with only 2 in. of asphalt performed equal to the control section with 4 in. of asphalt.

Six years after construction, the test sections have shown minimal damage

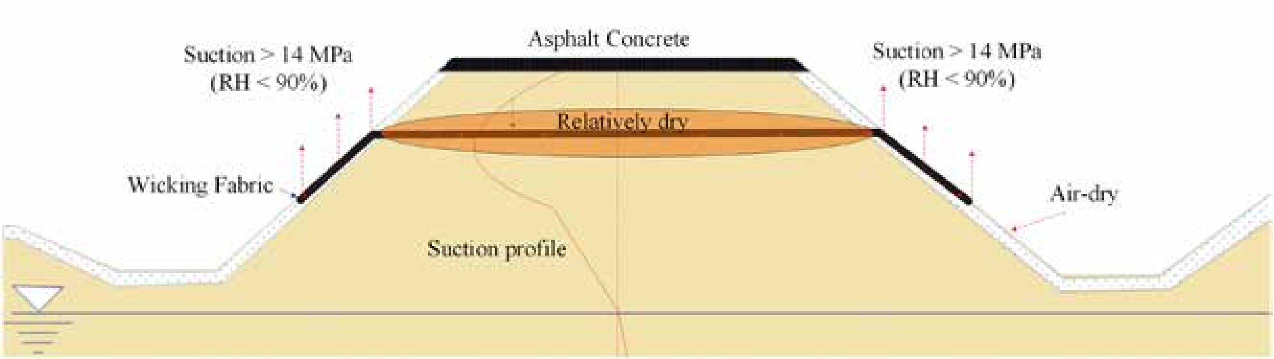

Figure 2. **Placement of MMG in a pavement section.**

Figure 3. **MMG in a reinforced section on FM 1807.**

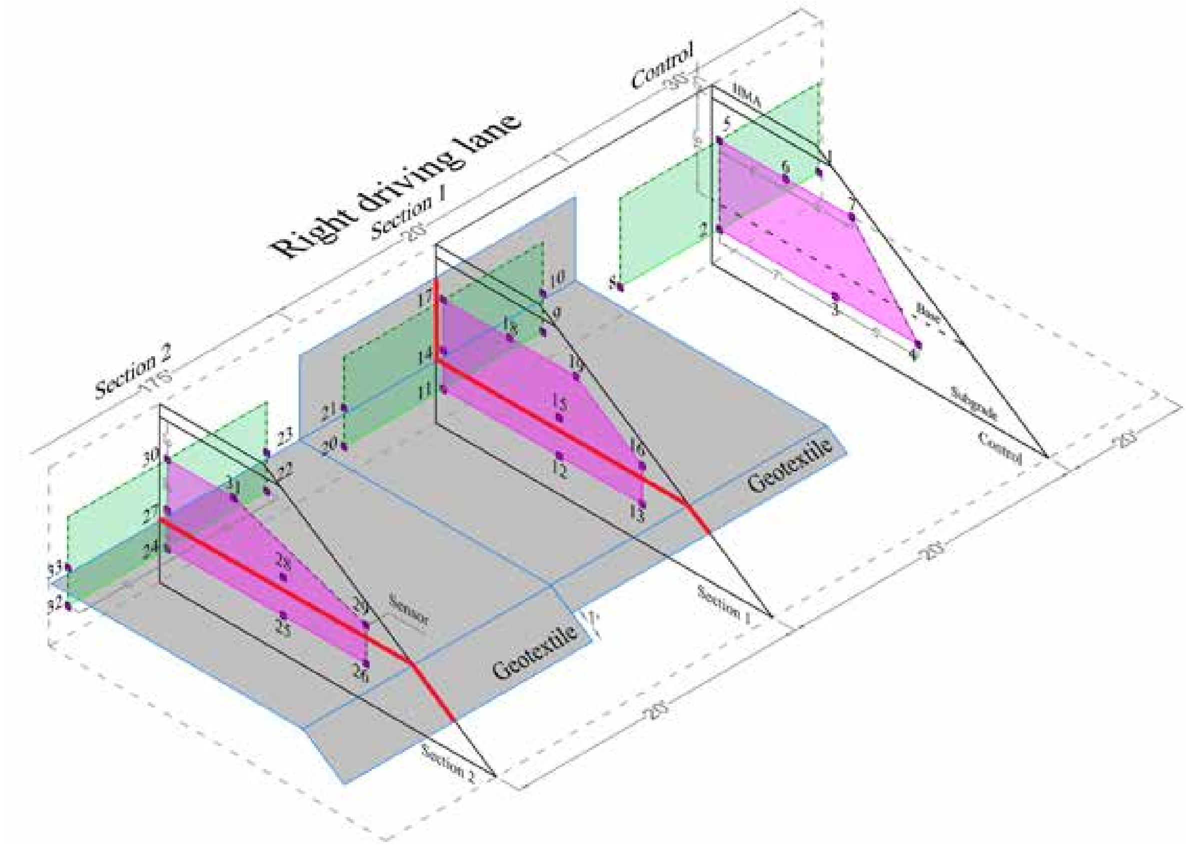

Figure 4. **The design schematic of MMG on I-44. The red line represents MMG; the pink area represents sensor bounded areas; and the red dots with numbers represent the sensor location.**

compared to the other country roads in the region. Applying MMG enhanced performance by not only providing reinforcement and lateral restraint, but also increasing the unsaturated lateral drainage of the pavement layers. Moisture reduction was observed to be greater in the base layers compared to the subgrade layer, and additionally more in the FB materials than RAP materials. The presence of the MMG had a zone of influence for reducing moisture to depths of 10 to 12 in. below the geotextile layer in the subgrade soil. This enhanced moisture reduction of unsaturated soil not only reduced volumetric strains in the subgrade, but also enhanced the layer stiffness, resulting in longer serviceability of the pavement layers. With further long-term monitoring and data interpretations, the life-cycle cost and sustainability benefit of improving unsaturated conditions with this geotextile should be realized.

Mitigating Roadway Shoulder Pumping in Missouri

Pavement failure due to pumping is a significant issue that's primarily caused by fines that migrate from subgrade soils into upper granular layers under the stress of traffic loads. This phenomenon shortens pavement life span, compromises road safety, and leads to increased maintenance costs. For pumping to occur, four conditions must be present:

- A fines-rich soil layer beneath a granular layer with larger voids and little to no fines
- Saturation of the soil with free water
- Repeated heavy axle loads that cause pavement deflection and generate excess pore water pressure
- The presence of voids and cracks that provide continuous pathways to the surface

Unfortunately, these conditions are commonly found in many pavement structures, exacerbating the problem.

Efforts to mitigate pumping have focused on addressing one or more of these conditions, and numerous studies have explored using geotextiles to reduce pumping, employing them for reinforcement, separation/filtration, and drainage. However, conventional geotextiles are limited in their ability to drain capillary water because they can only handle free gravitational water under saturated conditions. In Missouri, MMG was used to address this problem by removing excess water from the pavement shoulder. The goal was to lower the moisture content in the shoulder to prevent the generation of positive pore water pressure under traffic loads, thereby reducing the likelihood of fines being ejected through cracks and joints — a key mechanism of pumping.

A 225-ft-long test section was constructed on the shoulder of I-44, with the support of the Missouri Department of Transportation and Solmax. The section was divided into three parts: a control section without treatment, and two sections using the MMG to manage water. Sensors were placed throughout the sections to monitor water content and temperature (Figure 4). The field test sections were built by excavating the existing road shoulder to expose the clayey subgrade at a depth of 18 in. In Sections 1 and 2, the MMG was installed at the interface between the subgrade and the base course. In Section 1, the MMG was installed in an L-shaped configuration with the MMG extending vertically up the side of the excavation on the roadside of the

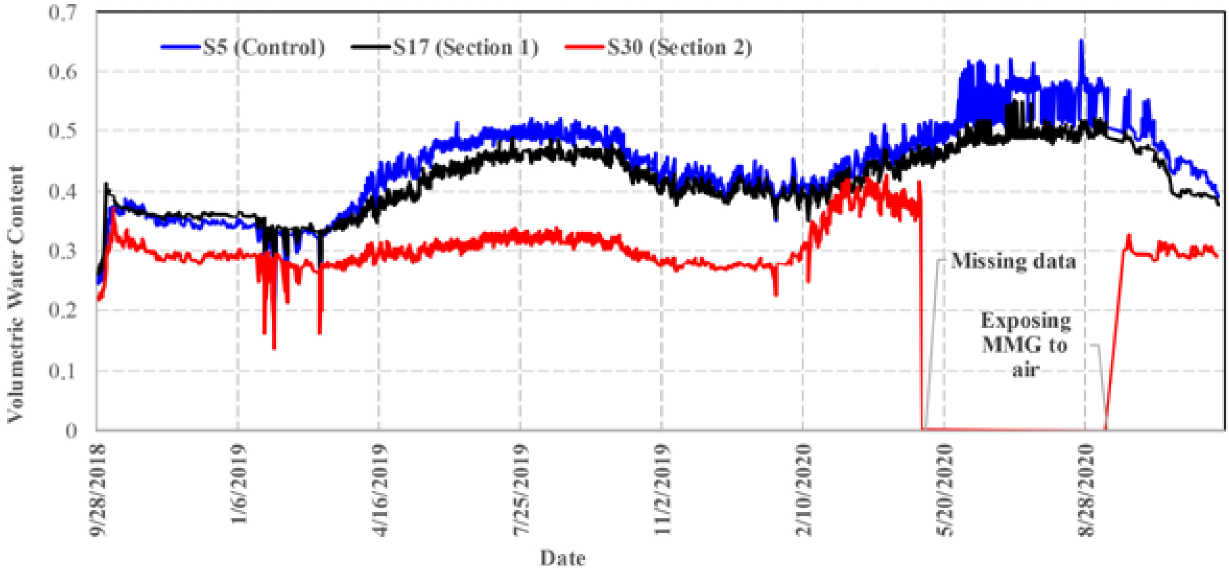

Figure 5. **Volumetric water content profiles at a depth of 8 in. below the ground surface.**

shoulder. In Section 2, the MMG was laid flat. Following the installation, a layer of base course material was compacted, and the surface was finished with a 2-in.-thick layer of hot-mix asphalt.

Figure 5 presents the volumetric water content measured at a depth of 8 in. below the ground surface at the interface between the driving lane and the shoulder, where pumping typically occurs. Throughout the monitoring period, VWC levels at all sections were consistently higher than the levels at which the base layer was initially compacted, which would typically result in pavement performance diminishing over time. However, the VWC levels in the two MMG-treated sections were lower than those in the control section. In particular, the VWC levels in Section 2 were 5-15 percent lower than those in the control section, indicating that the MMG effectively reduced moisture accumulation due to its extra horizontal length of exposure to atmosphere compared with Section 1.

Assuming that the subgrade for the control section soil was saturated and prone to pumping under its wettest conditions, the data suggest that Sections 1 and 2, and particularly Section 2, maintained a moisture content well below saturated, and possibly with negative pore water pressures. Because pumping is driven by positive pore pressure buildup, the improved sections demonstrated a significantly reduced likelihood of pumping, highlighting the effectiveness of the MMG in mitigating this problem.

Mitigating Frost Heave and Thaw-weakening in Alaska

The Dalton Highway, Alaska's main route connecting the interior to the Prudhoe Bay oilfields, is a lifeline that must remain open and safe year-round. At milepost 110.5, however, the Beaver Slide has remained a notorious problem area. At this location, the unpaved road sits on a sidehill cut, with a steep, 11-degree gradient heading north. Shallow groundwater runs down the slope and surfaces onto the road, creating soft spots, or "frost boils," especially during the spring thaw. In extreme cases, water and fines have been seen squirting from the road surface, creating treacherous driving conditions and contributing to numerous accidents.

The Alaska Department of Transportation and Public Facilities tried multiple solutions over the years, but none worked long term. One attempt involved French drains to move water out of the roadbed, but it was ineffective. Another approach involved replacing the road material with frost-resistant materials, but due to the high cost and challenge of hauling the materials to this remote area, it wasn't a viable option. Engineers subsequently began searching for a more practical and affordable solution.

In 2010, MMG was introduced to the AKDOT&PF. As previously discussed, the MMG is designed to draw out moisture from the pavement layers, even in unsaturated conditions. By reducing the water content in the soil, the permeability of the soil decreases significantly, so as winter sets in and the ground freezes, the lack of moisture supply prevents the formation of ice lenses, which are the main cause of frost heave.

The chosen test section was one of the softest spots on the highway. By the time construction was completed in August 2010, 22 pairs of moisture and temperature sensors had been placed throughout the road structure. Soil analysis revealed that the existing material was frost-susceptible, consisting of crushed rock and sand with a nonplastic fines content above 6 percent. Construction began by excavating the east lane to a depth of 3.5 ft, where the first layer of the MMG was placed. After backfilling the soil in 1-ft lifts and then compacting it, a second layer of MMG was placed at 2.5 ft below the surface. About 3 ft of the geotextile was left exposed at the east shoulder to allow for continuous drainage. The same construction process was then applied to the west lane.

Results after the installation showed significant improvements. Data collected from various sensors 1.5 ft below the road surface (Figure 6) showed that in the summers unfrozen moisture contents at all sensor locations (3, 7, 10, 14, and 17) remained well below saturation as demonstrated by sensor 22, which was installed in a ditch with saturated water content. These readings show that the MMG was effectively reducing moisture in the roadbed and eliminated frost boils at the test section. This performance has remained the case, even after 15 years of use.

The Beaver Slide case history demonstrates that MMG can offer a cost-effective

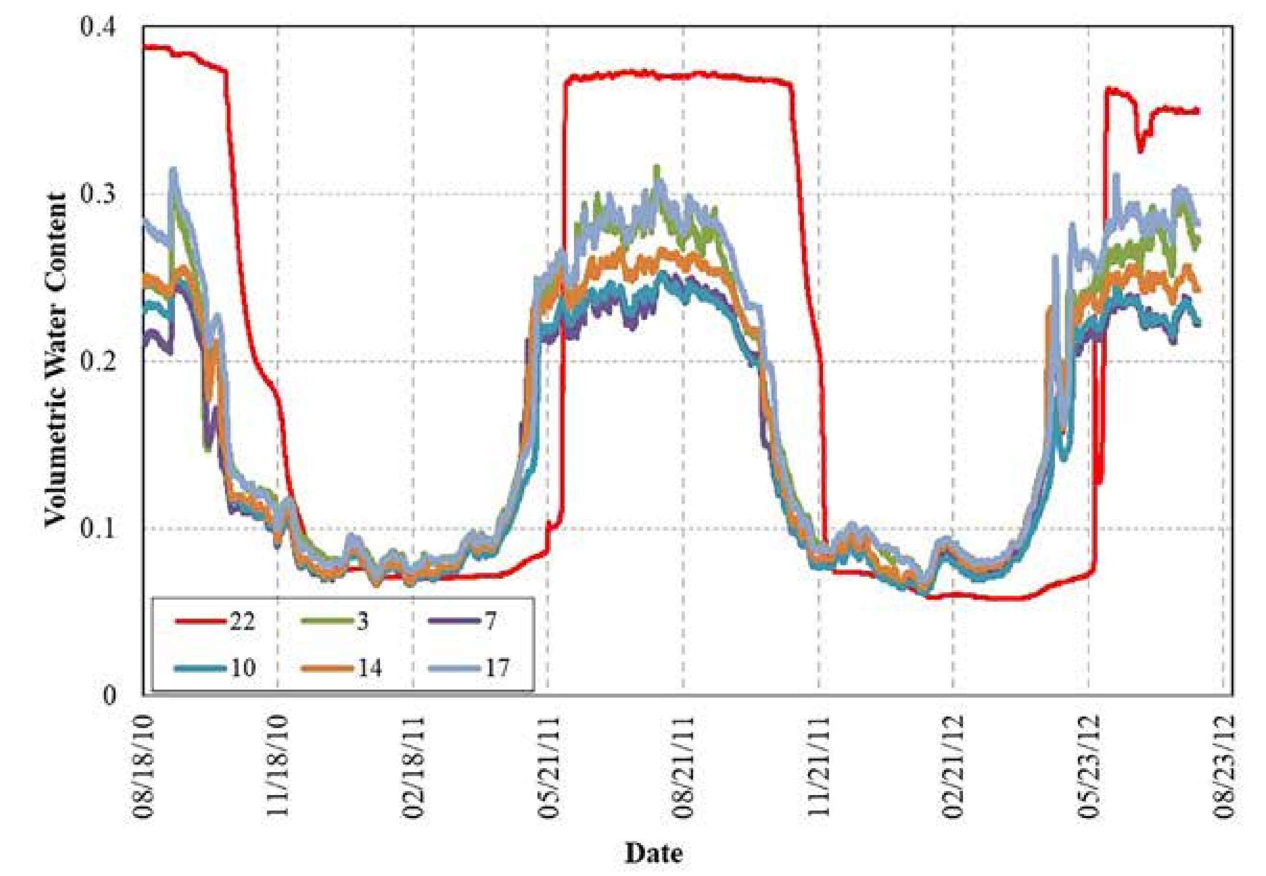

Figure 6. **Moisture content data at Dalton Highway test section (sensor 22 was in the ditch and remained saturated).**

solution to frost-related road issues, especially in regions where traditional methods are either too expensive or ineffective. The improvements to road stability and safety in another crucial section of the Dalton Highway between Mileposts 197-209 allowed the AKDOT&PF to include the MMG in a 6-mile road section. This saved the agency over $2.5 million in construction costs and $3.5 million in maintenance costs in the following five years, when compared with the traditional method of installing a shot rock material on a different section of equal length.

Managing Unsaturated Conditions in Roadways

Even for unsaturated conditions, excess moisture is a major concern for pavements. These structures typically don't drain with conventional drainage systems until they become saturated. This MMG product can effectively address such challenges by controlling moisture levels in unsaturated conditions and enhancing the overall stability of roadway infrastructure. Extensive research has validated performance in frost-susceptible conditions, expansive soils, and areas prone to pumping, but we also know that lower moisture content in pavements improves performance through increased modulus and resiliency. Roadways are often the largest cost asset of transportation agencies and the most noticeable to communities when fatigued. The MMG improves road performance, reduces maintenance, and offers a cost-effective, long-term solution to managing moisture under unsaturated conditions. GS

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Look Who's Board Certified!

Bret Lingwall, Ph.D., P.E., BC.GE, F.ASCE

BRET LINGWALL

Bret Lingwall, Ph.D., P.E., BC.GE, F.ASCE, is a geotechnical engineering team lead for the U.S. Bureau of Reclamation Technical Service Center in Denver, Colo. Previously, he served as an associate professor at the South Dakota School of Mines and Technology, and a consulting engineer. His research and practice encompass many dimensions of geotechnical, geoenvironmental, biogeotechnical, and earthquake engineering. His research interests include carbon sequestration, soil health, PFAS, mine tailings, and wildfires. His current practice focuses on large dams and risk analysis of complex geotechnical systems.

Lingwall received his bachelor's, master's, and Ph.D. degrees in civil and environmental engineering from the University of Utah. He's licensed in Utah, and serves as an associate editor of the ASCE *Journal of Geotechnical and Geoenvironmental Engineering*.

Where were you born, and where did you live for most of your childhood?

I was born in Salt Lake City, but grew up in a small town in the deserts of southern Utah amongst the red rocks, white canyons, and purple mountains of the American southwest. Coming from a small town, I learned about the importance of water resources, soil health and its implications to agriculture and forestry, and the criticality of mining to the economy.

We spent time camping and fishing, helping our neighbors tend the soil on their farms, and working the soil ourselves to grow some of our own food. One of my earliest memories is being roused from bed in the wee hours to watch the flooding from failure of the Quail Creek Dike. We spent days rock-hounding in the scour channel after that dam failure. I remember being amazed at that breach event, the consequences, and the new dam being built. That childhood really set me up for a career in geotechnical engineering!

When did you realize that you wanted to study civil engineering, and what led you to become a geotechnical engineer?

My maternal grandfather was an engineer. I started college as a mechanical engineer, but found I was more interested in bridges than cars. Geotechnical engineering became my passion when I worked as an intern for the City of North Salt Lake making earthwork observations. And when I took Evert Lawton's introductory soil mechanics class the next semester, I was hooked. My future was sealed when I started as an intern at Kleinfelder, working for Tracy Grover. Tracy and the many folks at that Salt Lake City office had established a culture of cooperation and optimistic enthusiasm that I found infectious. I had such great mentors that when I decided on graduate school, I could not think of anything else I wanted to do. I owe an unpayable debt to that deep bench of talent at Kleinfelder who mentored me to cement my love for this field.

What do you love about being a geotechnical engineer?

I love complexity, and geotechnical engineering is certainly complex. I love assembling a team of experts around the table to tackle the myriad problems that we face. I love that dialogue between different viewpoints allows us to constructively come to a consensus, conclusion, and path forward. I love that the problems we face, and our solutions to them, have practical consequences for the public, our communities, and to individuals. I love how geotechnical engineers interface with contractors and are actively involved in construction. Geotechnical engineers have so many fascinating opportunities to stretch themselves and truly model what it means to solve complex problems with soil and rock. Geotechnical engineering is at its worst when we mindlessly "turn the crank on the machine" and pump out a middling report after unthinking report. Geotechnical engineering is at its best when we apply our critical thinking to collaboratively attack a complex problem and use research and science as the base for our practice.

> It's much better to set up small, but bold, changes that can be low stakes if they fail, but high reward if successful.

What did you enjoy about being a professor of geotechnical engineering?

I loved it, but I eventually began missing design projects, collaborating with others on project work, and just being a practitioner. In my decade as a professor, I greatly enjoyed the research where I worked on interdisciplinary and convergent research topics, collaborating on complex problems with people from far outside geotechnics. In teaching, I soon learned that my teaching style is much more of a "guide on the side" rather than a "sage on a stage." I reconceived all my classes to be ungraded and project-based, modeled after the industry office workflows that I had used to learn during my time in industry. I enjoyed helping form and mold new geotechnical engineers, and setting them up for success in their careers. I enjoyed pushing the students to think critically, and to make connections between topics inside and outside of their base geotechnical curriculum.

What are your responsibilities with the Bureau of Reclamation?

Most directly it's "research-based practice"! Also known as evidence- or science-informed practice, it's a term borrowed from health care, and it requires a practice setting that promotes the use of knowledge, access to current scientific knowledge, and the ability of the practitioner to think critically about using the knowledge to positively affect project performance outcomes. With Reclamation, I lead technical teams that assess the state of high-hazard dams, develop correction actions, and then implement fixes if needed. I do still perform research, but my biggest responsibility is to translate research into high-level practice across my team.

What are the biggest challenges on the horizon for the profession?

Kevin Franke and I wrote an article about this in the December 2022/January 2023 issue of *GEOSTRATA*, pp 60-69. In "Making the Evidence More Impactful," we offered our thoughts about geotechnical evidence and the need for our profession to increase its research-based practice. I know I'm beginning to sound like a broken record here, but I believe it! I see too many practitioners who've never delved into the evidence after leaving college. I see too many academics who have never designed anything. The gaps between research and practice are increasing, to our detriment. Unless we correct that trajectory, it will only grow wider. Our biggest challenge is to avoid the pressures of industry low-cost commodification and academic research insulation across the profession, and to maintain the standards and legacy of research-based practice that was handed to us by our profession's pioneers. They provided us with a wonderful legacy, and the precedent of being active researchers as practitioners and being active practitioners as researchers.

What was the primary reason you pursued the AGP Geotechnical Engineer Board Certification?

It's important to me that we have a research-based practice as engineers. To me, nothing could make the statement more than to pursue board certification. There's no other means as effective that I can think of to show others that you've made that decision to have a research-based practice. A long list of publications can show dedication to research. A long client list can show dedication to industry. The benchmark of board certification is more. To me, board certification was that demonstration. That wonderfully effective synergy of research-based practice — that's the legacy of Terzaghi, Peck, Sherard, and a hundred others I cannot readily name.

What's your message to other geotechnical engineers about getting board certified?

The low-cost commodification of our industry continues to put immense pressure on engineers to reduce quality that's needed to have research-based practice. Ergo, board certification is essential to remaining profitable. The pressure is immense on students to skip graduate school and never deeply study the beautiful fundamentals of soil mechanics. Academics have immense pressure to publish and often never see an actual construction site or participate in a design. We must resist these pressures and maintain the high levels of research-based practice that are needed to be board certified. Becoming board certified is the primary way we geotechnical engineers can state that we live a research-based practice. If we are to reduce the number of foundation and earthworks failures and synergistically reduce insurance rates and fees for geotechnical engineers, we must vigilantly apply the evidence in our practice.

What's effective leadership, and what are key leadership lessons you've learned?

Effective leadership is the ability to guide and inspire a group of people to work together to achieve a common goal. Effective leaders have a variety of "soft" skills and qualities, including foresight and creativity. Effective leaders also foster an inclusive work environment and cultivate trust and collaboration by:

Example. I learned early on that "enthusiasm is caught, not taught." Leaders set the example that others will follow, whether the leader likes it or not. Leaders set a tone. That tone resonates. If a leader is concerned about the tenor or timbre of a team, they must first self-examine and reflect on the tone that they set.

Not being afraid to prune the tree. Leaders must make hard decisions for the best outcomes for the organization and its people collectively. They cannot be afraid to remove a person who's not a part of that vision. They cannot be afraid to reassign someone to a role that's a better fit despite possible hurt feelings. Leaders must look to the future just as much as they need to manage the present. To do this, leaders must know their people. A leader cannot remove or reassign the correct person if they don't really know them, their skills, their contributions, and their part of the organizational ecosystem.

Conveying an authentic sense of motivation and trust. What's the leader's true motive? Pure profit? To further their personal aims? The glory of success no matter the cost to the people? To pass the time until their next vacation? Hopefully none of these! Everyone in the organization can discern a leader's true motivations, and it's the individuals who will respond to that true motivation in their own unique way.

Not being afraid of failures and being able to move nimbly from a failure. Too much time is spent on big changes that require big investments that bring a sense of "only success is acceptable." It's much better to be nimble. And it's much better to set up small, but bold, changes that can be low stakes if they fail, but high reward if successful.

What are your personal hobbies and interests?

I sing bass in a community choir in Denver, and tenor in another. I enjoy camping, backpacking, snowshoeing, and fishing. I'm an avid gardener who loves pruning the trees and tending the soil. Cooking brings me immense joy. In reality, however, my kids participate in many activities, so much of my spare time is spent supporting them.

What are your professional goals for the next one to two years?

Reclamation has a large inventory of high-hazard dams, many of which are coming into a critical phase of their lifespans. It's an exciting time to be at Reclamation, to help keep the public safe while providing water and power to the western U.S. My goals for the next two years professionally are to immerse myself in this important work of dam safety, and develop/implement new methods for seismic assessments of dams to improve reliability and reduce uncertainties. GS

{To find out more about civil engineering certification, please visit: *asce.org/careergrowth/civil-engineering-certification*.}

New Faces in G-I

Thierno Kane, Ph.D., P.E., M.ASCE

Thierno Kane is a project engineer with five years of experience in Geosyntec's office in Oak Brook, Ill. He received his bachelor's (2012), master's (2013), and Ph.D. (2019) degrees in civil and environmental engineering from the University of Illinois at Urbana-Champaign. He's a licensed professional engineer in Illinois, and currently serves as the Illinois G-I Chapter chair. Kane's project portfolio includes waste management, litigation support, renewable energy, site development, and instrumentation and monitoring of slopes. His expertise in geotechnical engineering includes landslide movement, slope stability, field investigation, laboratory testing and analyses, and shear strength and consolidation of soils. In his current role, he's responsible for developing geotechnical solutions related to site characterization of landfills, static and seismic instability of slopes, shallow foundation design, and design of temporary and permanent retaining walls.

Born and raised in Senegal, Thierno lived one year in Thailand, two years in Hungary, and two years in Jordan, where he graduated high school. He then moved to the U.S. to begin his undergraduate studies at UIUC. In his free time, Thierno enjoys painting and drawing, exploring new cuisines, and staying active. He's also an avid traveler and has visited 25 countries so far.

What attracted you to engineering?
When you're from a developing country like Senegal, you quickly realize the importance of structures and infrastructure in all facets of people's lives. I believed becoming a civil engineer would allow me to have a direct impact on society, while still exploring my other passions. I've always enjoyed art; when my mom wanted me to sit still, she'd give me pens and paper to draw on. In school, I realized that I had a knack for numbers and developed a strong interest in math, physics, and chemistry. In my opinion, engineering is not just grounded in science and mathematics, it's also a discipline that transcends into the realm of art. It requires not only a fundamental understanding of the sciences, but also creativity and an appreciation for aesthetic design and function.

What's an exciting project you've worked on?
The Waterfront Toronto Project in Canada is one of my first and still favorite projects. I'm part of the geotechnical team for the design of a naturalized river valley, which mimics natural river valley meanders, environment, and habitat, to be constructed as part of a flood protection system for the City of Toronto, where a river valley will be constructed through an environmentally impacted site. The naturalized river valley will add 16 hectares of new parkland, promenades, and riverfront open space to the eastern waterfront, as well as 14 hectares of new aquatic habitat and wetlands to improve biodiversity and water quality, and attenuate flooding erosion. I get to provide geotechnical support and recommendations related to settlement-sensitive infrastructure. At this site, we're dealing with organic materials that are highly compressible, and while it's a park, there will be structures like foundations, roads, and a microtunnel for utilities. Total and differential settlements could cause problems that require additional maintenance. Overall, this project has been a wonderful opportunity to showcase my expertise in the characterization and behavior of soft grounds, and to add new skills in my toolbox.

What would you talk about if invited to speak at a local Chapter dinner or a regional conference?
I'd love to speak about the Waterfront Toronto Project, but I would tailor my presentation to the audience. My presentation could focus on the challenges and lessons learned from this project, or discuss using instrumentation and performance monitoring as a risk management measure for the project. For

example, we applied state-of-the-art tools to interpret field monitoring data and use that data to refine design parameters. As a result, we not only had greater confidence in the effectiveness of preloading in limiting post-construction settlements, but our reassessments helped inform and improve our understanding of the anticipated behavior of utilities following placement of permanent fill. We were also able to reduce the surcharge duration by half, which resulted in significant cost savings.

Are you involved with any G-I technical committees or local Chapters?

I'm currently the Illinois G-I-Chapter chair. I first became involved with the Chapter after attending an event in 2021. The local Chicago Chapter holds an annual lecture series, which I thought was interesting because it brought so many different geotechs together, from the contracting side, the public and private sectors, and academia. A senior principal at Geosyntec, Terry Holman, also attended the lecture and encouraged me to get involved. I joined the IL G-I-Chapter board in the fall of 2022 as the treasurer, then served as the co-chair from fall of 2023 to spring of 2024. It's been a great opportunity to meet professionals, academicians, and students throughout the Midwest region that I wouldn't have met otherwise.

Have you had mentors who've aided your professional development?

Absolutely! I've had some incredible mentors that supported me throughout my professional development. Dr. John Popovics, my behavior of materials professor, introduced me to research as an undergraduate student. By just playing with concrete in his lab, I learned I really enjoyed research. Later, during my junior/senior year, I took a course with Professor Gholamreza Mesri. After the second exam, he asked me to meet him in his office. Honestly, I thought I was in trouble, but he asked if I had plans for graduate school! While I was thinking of pursuing a master's in structures, I liked how geotechnical engineering related to almost all branches in civil engineering and enjoyed the challenges and uncertainties associated with geo. I didn't hesitate when he offered me an opportunity to pursue a Ph.D. under his supervision. Dr. Mesri has so much history with geotech, especially working with so many people who, like Dr. Peck, have contributed so much to the profession. Working with him was captivating, and being mentored by him was very fulfilling.

Geosyntec has a mentorship program that allows anyone, especially junior staff, to be mentored by seniors whose skill sets align with a mentee's interests. I cannot even begin to name all the people I genuinely see as mentors, but if I must name one, it's Jim Hansen, my supervisor. He's been (and still is) an incredible mentor and advocate for me at Geosyntec. Over the years, he's offered countless project management and writing tips, encouraged me to voice my opinions and collaborate with other offices, and pursue other nontechnical ventures. He was one of the people who encouraged me to be more active in the G-I. When I asked if I should get more involved, he said, "Oh you should definitely do it. It's good for you to get out there, give presentations, get involved in recruiting — all of it."

New Faces is an endeavor by the G-I Outreach and Engagement Committee to make readers aware of members under 40 years of age who are available to deliver engaging technical presentations to G-I Chapters and other professional groups. You can nominate a candidate for a future New Faces column via email to *ascegioec@gmail.com*, along with a brief mention of your candidate's educational background, area(s) of expertise, and employment.

What's your take on engineers as leaders?

I picture leadership as not just a set of skills; it's also about responsibility. In Professor Ana Barros' office at UIUC a couple of years ago, she asked [and I paraphrase], "Do you know what has eradicated more disease and saved more lives in human history?" When I guessed modern medicine, she said, "No, it's water infrastructure: modern day sewage systems and clean water." Living in a developed country, most people today take infrastructure for granted, but you don't know the alternative. In a developing country, many people, and especially children, die because they don't have the essentials of clean water and effective sewage systems. To me, this underscores the transformative power of engineering. It's an illustration of how engineers, through our expertise and foresight, play a crucial role in leading initiatives that profoundly improve public health and drive social progress. And it's our responsibility as leaders to bring about this change.

What's the future of civil engineering education in terms of preferred or required skills?

In the future, civil engineers will play an increasingly bigger role to address the existing challenges on Earth, and those posed with the exploration of other planets. We're experiencing rapid global urbanization, which comes with many interconnected socioeconomic and environmental challenges. For example, we're seeing limited land and resources, and more waste generation and pollution. Let's not forget the increasing effects of climate change that come with increasing natural disasters. As civil engineers, we'll be tasked to maintain and develop more resilient and sustainable structures and infrastructures to handle this increase in demand, both in terms of resources and loading conditions. Recently, the idea of venturing into space and inhabiting Mars (or other planets) is no longer just science fiction, but well within reach in a decade or two. We need students who accept that we're not constrained here; we're not tied to what's been done in the past. This uncharted territory is very exciting because such projects will require extensive surface and subsurface investigation, complex environmental studies, and the development of new tools to build and maintain structures and infrastructures in these unexplored environments. This means we'll need to better communicate our impact, adapt to our changing environment, learn to be more multidisciplinary, and get out of our comfort zones. GS

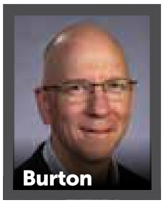
By Stacey E. Kulesza, Ph.D., P.E., M.ASCE, and
James G. Collin, Ph.D., P.E., BC.GE, F.ASCE
Outreach and Engagement Committee

Meet Our Newest Organizational Member: STV, Inc.

STV, Inc. is an infrastructure-focused professional services firm that advises, plans, designs, engineers, and delivers infrastructure that powers local economies, including transportation systems, buildings, water, and other facilities. Its CEO, Greg Kelly, leads more than 3,200 team members in more than 60 offices across North America. STV was founded in 1912 and has worked on some of the most vital infrastructure projects in our communities, such as the Purple Line Extension Project in Los Angeles and the Gateway Program in New York and New Jersey.

STV has a specialized tunneling and geotechnical team that includes geotechnical and tunneling engineers, underground structural engineers, and geologists. Based in STV offices throughout the country, including New York, New Jersey, Texas, and California, and working on various geotechnical and tunneling projects, this deep bench of experts provides specialized engineering services to STV clients nationwide. The team has rapidly expanded under the leadership of Frank Pepe, growing from a team of five to more than 50 in just three years, with additional growth on the horizon.

Advanced Construction Techniques Announces Promotion


Burton

Advanced Construction Techniques announces the promotion of Jeff Burton, P.Eng., to the new role of director, information systems & research for the ACT Group of Companies. He holds a bachelor's degree in engineering from the University of Waterloo, specializing in process control systems, and brings almost 25 years of experience, including 15 years at ACT, where he was a key contributor to the design and development of ACT's data management and monitoring systems. Burton executed and supported the implementation of progressively innovative and complex systems on projects such as the Clearwater Dam, Wolf Creek Dam, Center Hill Dam, and Rough River Dam grouting projects, as well as various projects in the mining industry. In this new role, he assumes leadership and oversight of ACT's information systems and research and development team as it continues to address the challenges faced by the deep foundations industry in the safe and effective execution of its work.

GEO-INSTITUTE ORGANIZATIONAL MEMBERS

- Advanced Construction Techniques
- Aerix Industries
- Aero Aggregates
- American Engineering Testing, Inc.
- Arcosa Lightweight
- Bechtel Corporation
- Berkel & Company Contractors, Inc.
- Braun Intertec Corporation
- Burns & McDonnell
- Condon-Johnson & Associates, Inc.
- ConeTec, Inc.
- CTL Thompson, Inc.
- Dan Brown and Associates, LLC
- D'Appolonia Engineering Div of Ground Technology, Inc.
- Dataforensics, LLC
- DBM Contractors Inc
- Densification, Inc.
- Earth Systems Pacific
- ECS Corporate Services, LLC
- Elastizell Corporation of America
- Exponent, Inc.
- Gannett Fleming TranSystems
- GEI Consultants, Inc.
- Geocomp Corporation
- Geocon Incorporated
- GeoEngineers, Inc.
- GEO-Instruments
- GEOKON, LLC
- Geopier, A Division of CMC
- Geo-Solutions
- GeoStabilization International
- Geosyntec Consultants, Inc.
- GRL Engineers Inc
- Haley & Aldrich
- Hanson Professional Services
- HNTB Corporation
- Huesker, Inc.
- Jacobs
- Jensen Drilling Company
- Keller – North America
- Kleinfelder
- Malcolm Drilling Co Inc
- Menard USA
- Nicholson Construction Company
- NTH Consultants, Ltd.
- PAGANI Geotechnical Equipment
- Rembco Geotechnical Contractors, Inc.
- Rocscience Inc.
- Schnabel
- Schnabel Engineering
- Shannon & Wilson, Inc.
- S&ME
- SME
- Solmax
- Stantec
- STV, Inc.
- Subsurface Constructors, Inc.
- Terracon
- Terra Insights
- Terra Insurance Co
- The Reinforced Earth Company
- Tolunay-Wong Engineers, Inc.
- WSP USA

Dataforensics Project Receives Award

In October 2024, **Dataforensics** received second place in the Bentley "Year in Infrastructure – Going Digital Awards" for its project with the U.S. Army Corps of Engineers called "Ground to Cloud – Enterprise Data Management Migration," in the category "Subsurface Modeling and Analysis." Dataforensics was recognized for its innovative approach to solving complex data migration and data management challenges. Bentley's Year in Infrastructure Awards are highly competitive, celebrating the world's most innovative infrastructure projects. Judges evaluated various aspects of geotechnical data collection, data management, data migration, subsurface modeling, visualization, and design solutions. The award was announced and presented at the annual award gala in Vancouver.

To learn more about this project, see the Organizational Member News on p. 79 of the December 2024/January 2025 issue of *GEOSTRATA*. Dataforensics thanks its internal project team members and, in particular, the leaders at the U.S. Army Corps of Engineers for their vision, guidance, and dedication throughout the project.

Scott Deaton, A.M.ASCE, president of Dataforensics, walks the red carpet at Bentley's "Year in Infrastructure – Going Digital Awards."

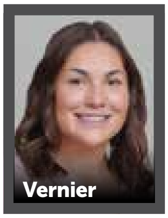
Solmax Announces New Leader

Solmax announces the appointment of Bob Gilligan as its new president and chief executive officer. Gilligan has more than 30 years of career experience spanning the industrial, utility, healthcare, and technology sectors. He's been instrumental in shaping business growth strategies, most notably as president and CEO of GE Industrial Solutions at General Electric. More recently, he has advised major private equity firms like Goldman Sachs and THL. He will also be able to draw on his experience with complex integrations as Solmax continues to consolidate its acquisitions under a single brand and culture. Gilligan has a bachelor's degree in mechanical engineering from Bucknell University and an MBA from The Wharton School of the University of Pennsylvania.

Terracon Acquires Metcalf

In October 2024, **Terracon** announced its acquisition of Metcalf Archaeological Consultants, an employee-owned firm providing environmental planning and cultural resource management services in the Rocky Mountains and the Central and Northern Great Plains. By this acquisition, Metcalf will gain significant support regionally and nationwide from Terracon's offices in Colorado, Montana, North Dakota, Utah, and Wyoming. The firms will serve clients in commercial development; energy; federal, state, and tribal agencies; transportation; telecommunication; and utilities. Metcalf will operate as Metcalf Archaeology, A Terracon Company. GS

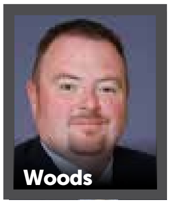
Hanson Welcomes New Specialist



Geotechnical specialist Amanda Vernier has joined **Hanson Professional Services, Inc.**, at its St. Louis office. She will conduct geotechnical field investigations focused on settlement issues, foundation design, and slide remediation. She also will perform data analysis and risk assessments, as well as prepare comprehensive reports to support project objectives.

Vernier previously served as an assistant consultant geologist for an international engineering firm in St. Louis. She received a bachelor's degree in geology from the University of Missouri and is a member of the Association of Environmental and Engineering Geologists.

Densification VP Joins AGP Board



Densification, Inc. Vice President Chris Woods, P.E., G.E., P.Eng., CEng MIEI, BC.GE, LEED^{AP} BD+C, F.ASCE, has been appointed to the Board of Trustees of the Academy of Geo-Professionals. His three-year term began on October 1, 2024. The AGP Board of Trustees administers the Board-Certified Geotechnical Engineer (BC.GE) certification program. Woods has been a BC.GE since 2013.

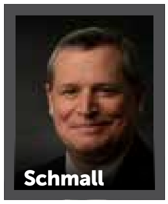
PLEASE SUBMIT company news and career achievements to *GEOSTRATA* via *geostrata@asce.org*.

COREBITS **NEWS**

G-I Members Receive Awards

On June 6, 2024, **Askar Zhussupbekov, Ph.D., M.ASCE**, received the prestigious Japanese Geotechnical Engineering Contributions Award from Junichi Koseki, president of the Japanese Geotechnical Society. Zhussupbekov is a professor in the Department Civil Engineering at L.N. Gumilyov Eurasian National University in Kazakhstan and president of the Kazakhstan Geotechnical Society. The award recognized Zhussupbekov for his many years of outstanding contributions in advancing geotechnical engineering education in Japan. His efforts have enabled 20 doctoral students from ENU to complete scientific internships in Japan and created the opportunity for Japanese professors to deliver more than 20 lectures at universities in Kazakhstan. He's also been involved with completing numerous collaborative projects, such as the geoinformation database for Astana with Kyoto University and the Japanese Geo-Research Institute.

Late in 2024, The Moles, a heavy construction industry professional organization, announced that its Outstanding Achievement – Member award for 2025 would be presented to **Paul C. Schmall, Ph.D., P.E., BC.GE, F.ASCE**. Schmall is vice president, specialty services of **Keller North America** and is known for his expertise in dewatering and tunnel grouting, and ground freezing in urban settings. He's worked on a significant number of tunnel blow-ins, underground emergency responses, and the engineering and maintenance of complex groundwater control for projects throughout the country and internationally, including the recovery and reconstruction of the World Trade Center. He was inducted into The Moles in 2002 and was its president in 2022. In 2015, Schmall was the winner of the Wallace Hayward Baker Award. He delivered the ASCE Met Section Geo-Institute Chapter's Mueser and Rutledge Memorial Lecture in 2019.



In Memoriam

Milton E. Harr, Ph.D., NAE, M.ASCE

Purdue Professor Emeritus Milton E. Harr died in Sarasota, Fla., on September 29, 2024, at the age of 98. Best known professionally for contributions to groundwater flow solutions, theoretical soil mechanics, and probabilistic modeling of particulate media and reliability analysis, he was also a soldier, family man, scientist, and an educator.

Harr was born in Chelsea, Mass., in 1925. During World War II, he served in the U.S. Navy (D-Day in Normandy) and the U.S. Marine Corps (Iwo Jima). For his service, he was awarded a Purple Heart, and Knighthood in the *Legion of Honor*, the highest French recognition for military service. He married Florence Solomon in 1945, and the couple had three children. Florence died in 2021.

Harr earned a bachelor's degree in civil engineering at Northeastern University in 1949 and worked with the U.S. Bureau of Reclamation and the Massachusetts Highway Department between 1949 and 1953. He then earned a master's degree in civil engineering from Rutgers

University in 1955, and a Ph.D. degree in civil engineering under the guidance of Professor Jerry Leonards at Purdue University in 1958. He joined the Purdue University faculty in the Department of Civil Engineering and, along with Jerry Leonards and their colleagues, helped make the geotechnical program one of the very best. In 1999, Harr retired from Purdue University as emeritus professor after 43 years in the faculty.

Harr had an extensive record of involvement in professional organizations, national committees, and consulting activities around the world. He received many honors, both in the U.S. and abroad, including election to the U.S. National Academy of Engineering in 1997 for the development and dissemination of analyses of geotechnical engineering systems; an honorary doctorate from the University of Brussels, Belgium; the Alexander von Humboldt Prize; a jubilee professorship at Chalmers Technology Institute in Gothenburg, Sweden; and recognition as a distinguished engineering lecturer at many national and international universities. He also delivered the inaugural Gerald A. Leonards Lecture in 2002 at the founding meeting of the Purdue Geotechnical Society.

Harr authored four technical textbooks (*Groundwater and Seepage*, 1962; *Foundations of Theoretical Soil Mechanics*, 1966; *Mechanics of Particulate Media – A Probabilistic Approach*, 1977; and *Reliability-Based Design in Civil Engineering*, 1987) that became classics of geotechnical literature, and he authored or coauthored over 100 refereed papers. Through his textbooks and in the classroom, he introduced the profession and his students to theories and methods of solutions that had been developed by Russian and eastern European scientists between the 1930s and the 1960s, most of which had been largely ignored or were inaccessible in Western countries. To do this, Harr went so far as to learn Russian so he could read and study these sources. His presentation of these notions was always both clarifying and intuitive.

Harr had a brilliant and multifaceted mind. He was an inspiring teacher and mentor, a scholar of his field and beyond, erudite in history and the arts, and a "bon vivant" with wit. He was a gifted writer of not only engineering textbooks, but also a historical fiction novel, *The Great Affair* (2006), and a collection of short stories. He had a decisive influence on many students' and colleagues' careers and lives. Harr's long and full life as a soldier, family man, scientist, and educator was impactful to so many.

COREBITS **CHAPTERS**

Kansas City

The Kansas City G-I Chapter, in partnership with the University of Missouri - Kansas City and the University of Kansas, will hold the annual Geotechnical Engineering Conference on April 11, 2025, at the University of Kansas, Edwards Campus, in Overland Park. Additional details about the conference are available at *kcengineers.org/geo-conference.*

Mississippi Chapter

The newly formed Mississippi G-I Chapter held its inaugural meeting on Nov. 7, 2024, in Vicksburg, Miss., with more than 40 geoprofessionals in attendance. This hybrid event featured an overview of the Geo-Institute, presented by Krystina Scott, G-I's senior technical manager, and Brad Keelor, G-I director.

The Chapter plans to host monthly hybrid meetings that will be open to all, focusing on technical development and professional networking. As this issue was being prepared, an upcoming meeting was being planned for late 2024 that would include a presentation on the geology of Mississippi, followed by more detailed discussions on the local geology of the Yazoo Basin and the Mississippi River Valley. For more information, please contact *msgichapter@gmail.com.*

Alexander Reeb, Ph.D., P.E., M.ASCE, at the inaugural chapter meeting. (Photo courtesy of Brandon Cummins.)

National Capital

Curiosity, opportunity, and excitement took center stage at George Mason University on October 29, 2024, as aspiring geotechnical engineers gathered for a lively panel on professional development, organized by the National Capital G-I Chapter. The panel was very informative for students considering a career in geotechnical engineering. It was an amazing opportunity to see and connect with professionals who enjoy their work.

The event brought students face-to-face with industry leaders who shared firsthand stories of career growth, field challenges, and the daily surprises that make geotechnical engineering so rewarding. With career paths spanning government, academia, specialty construction, and design, the panel discussions showcased the wide-ranging possibilities within this amazing and rewarding field.

The panel, designed to represent different career paths within geotechnical engineering, brought together 20+ students, three professors, and professionals from government, academia, specialty construction, and design. **Burak Tanyu, Ph.D., CEng, M.ASCE,** a faculty member at GMU and academic outreach director for the NCS G-I, helped to organize the event and encouraged participation from both his graduate students and undergraduate ASCE members, creating an engaging and inclusive space for learning. Panelists included **Girmay Weldegiorgis, P.E., M.ASCE**, a geotechnical engineer from the FHWA; **Sharon Hartley, P.E., M.ASCE**, senior engineer at Geostructures and president-elect for the NCS G-I; **Adam Marolf, P.E., BC.GE, M.ASCE**, branch

A diverse group of panelists, NCS leaders, faculty, and students participated in the event.

manager at A.G.E.S., Inc. and immediate past president for the NCS G-I; and **Benjamin Stark, P.E., S.M.ASCE**, a Ph.D. candidate at GMU and secretary for the NCS G-I. The panel was moderated by **Shana Carroll, P.E., M.ASCE**, president of D.W. Kozera and board member for the NCS G-I, and offered students a valuable opportunity for networking, Q&A, and a chance to explore diverse career paths in geotechnical engineering over complimentary pizza and soda.

Panelists shared practical advice, highlighting the variety and excitement within geotechnical engineering careers. Weldegiorgis encouraged students to "be prepared to be surprised every day," underscoring the field's dynamic nature. Hartley advised students to "say YES to opportunities that are offered and ask to be involved in as many aspects of the work as possible when starting out," emphasizing a proactive approach. Marolf spoke about the importance of curiosity and building connections with co-workers, while Stark emphasized the role of fieldwork in developing communication skills. These insights showed students how geotechnical engineering offers both technical challenges and personal growth, making it a fun and rewarding career choice. GMU civil and infrastructure engineering senior Solomon Redo said, "The G-I panel was very informative for students like me considering a career in geotechnical engineering. It was an amazing opportunity to see and connect with professionals who enjoy the work that they do. I particularly enjoyed the section explaining the joys and challenges of a geotechnical career."

With the demand for civil engineers projected to grow 6 percent from 2023 to 2033, and about 22,900 job openings expected annually, workforce development in geotechnical engineering is more critical than ever, according to the Bureau of Labor Statistics. ASCE projects that a shortage of skilled professionals remains, with demand outpacing supply in many regions. Moreover, diversity is a key focus, as women still comprise only 15-20 percent of the civil engineering profession (American Profession Guide). Additionally, according to ASCE, as of 2020, African American/Black civil engineers comprised 6 percent of the workforce, up from 3.6 percent in 2016, while Asian American representation increased from 10.4 percent to 12.2 percent. Hispanic/Latinx representation, however, decreased slightly, from 10.4 percent to 8.4 percent. Events like this panel are essential, not only to inspire and prepare the next generation of geotechnical engineers, but also to show students the value of a diverse workforce. Seeing professionals on the panel with backgrounds like their own sends a powerful message — that geotechnical engineering is an inclusive field with opportunities for everyone to contribute to its dynamic future.

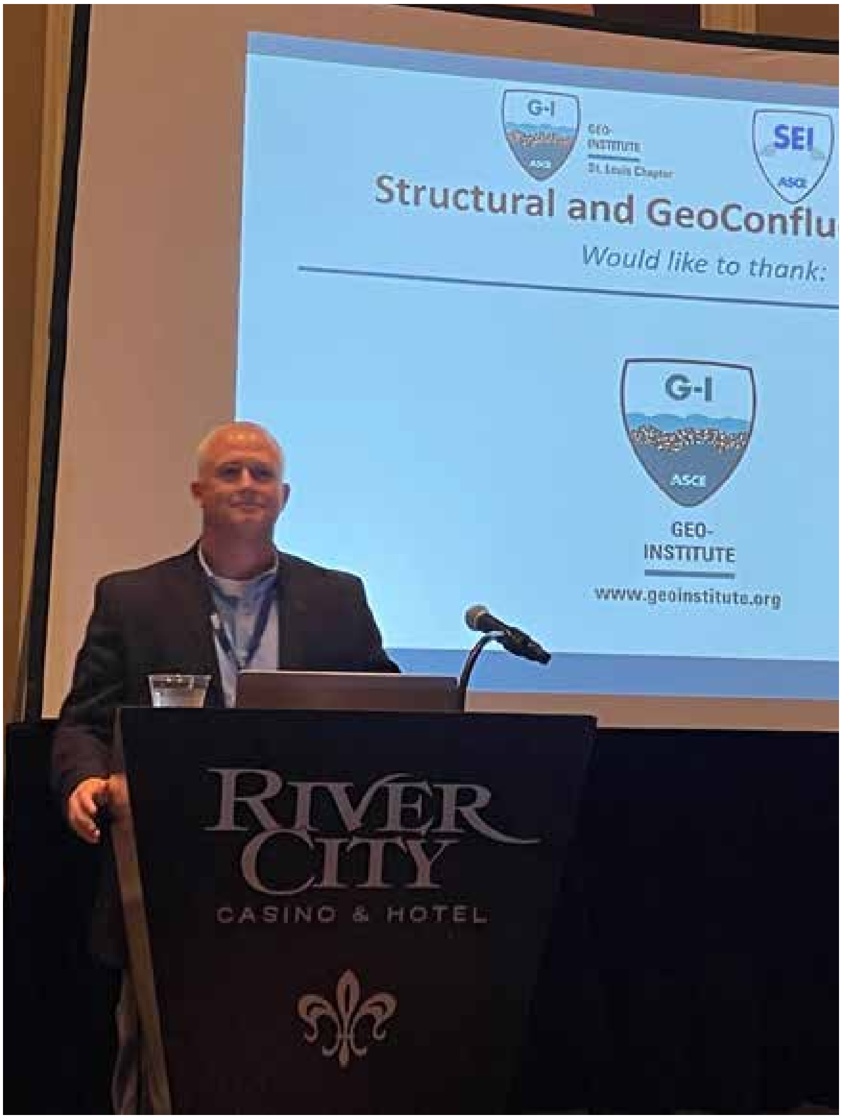
St. Louis Chapter

On November 6, 2024, the St. Louis G-I and SEI Chapters hosted the ninth iteration of the annual Structural and GeoConfluence. The full-day event showcased technical topics and case histories presented by local and national experts. The conference welcomed engineers, construction professionals, and students, with approximately 170 individuals in attendance.

Jeff Hill, P.E., and event host **Lyle Simonton, P.E., M.ASCE**, longtime Chapter members, began the conference by highlighting various events and scholarship opportunities that the G-I and SEI offer. During the sessions, participants heard from keynote speakers who covered a range of topics at the intersection of geotechnical and structural engineering. More than 20 students from nearby universities were in attendance.

Several of the presentations were project case studies within the private and public sectors, including local and international projects. There was a presentation on contracting and claims, and a discussion about the future outlook of geotechnical engineering and how it might utilize machine learning and AI. Attendees were also able to network with the numerous exhibitors who contributed to the success of the conference.

The St. Louis G-I Chapter is excited to announce that its conference will take place again in November 2025!



Event host Lyle Simonton, P.E., M.ASCE, speaks to participants.

Virginia Chapter

Since 2012, the GeoVirginia Committee of the Virginia G-I Chapter hosts a geotechnical conference every 18 months. The current home of the GeoVirginia Conference is the Smithfield Center in Smithfield, Va., along the beautiful Pagan River. The goal for every conference is to provide a "Lessons Learned in Geotechnical Engineering" experience that covers a wide range of geotechnical topics. Topics can include the development of new technologies, case studies, and current project site involvements.

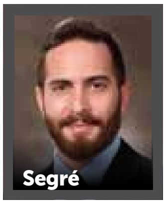
The Chapter is pleased to announce that the 2025 GeoVirginia Conference dates are scheduled from March 17-19, 2025. To learn more about the 2025 GeoVirginia Conference speaker list, visit *geovirginia.org*. Also, please note that short courses from past conferences older than one year are now freely accessible to the public. Explore the archive for valuable learning resources at *geovirginia.org/specialty-short-courses*.

▶ **PLEASE SUBMIT** Chapter news to *GEOSTRATA* via *geostrata@asce.org*.

Technical Activities Update

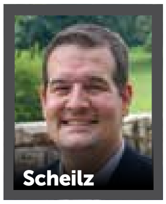
Local Involvement Committee

The G-I chapters in ASCE Regions 5, 6, 7, and 9 have new representatives. **George Segré, P.E., M.ASCE**, **Seth D. Scheilz, P.E., M.ASCE**, and **Hamid Karimpour, Ph.D., P.E., G.E., P. Eng, M.ASCE**, are the new members of the Local Involvement Committee.



George Segré, P.E., M.ASCE, serves as the Region 5 representative to the LIC. Born and raised in Puerto Rico, he moved to New York to obtain his bachelor's and master's degrees in civil engineering from Syracuse University. He then moved to New Orleans to begin his career as a practicing engineer. Segré has 11 years of engineering experience in the Gulf Coast area and is currently a senior engineer for the New Orleans branch of Terracon Consultants, Inc. Like a typical engineer, he enjoys making spreadsheets to compete with the best of them, learning Python, reading, music, and spending time with his wife and dogs.

Segré is a founding member and past chair of the Louisiana chapter of the G-I. In addition, he's a member of the Earth Retaining Structures technical committee and the Embankments, Dams, and Slopes technical committee. His general duties at work include proposal writing, analysis, and report writing. He's also involved with the Central Engineering group at Terracon and assists in developing web applications to automate workflows and analyses. His typical jobs range from small commercial retail to large industrial facilities, levee permitting works, coastal restoration, solar farms, and even data centers.



Seth D. Scheilz, P.E., M.ASCE, will represent ASCE's Region 7. A licensed professional engineer with more than 16 years of engineering experience, Scheilz holds a master's degree from the Lyles School of Civil and Construction Engineering at Purdue University and a bachelor's degree from the University of Missouri. He's a senior geotechnical engineer at Braun Intertec in Kansas City, where he solves challenging geotechnical engineering problems for clients in the commercial, industrial and governmental sectors. He's past president of the ASCE Kansas City G-I Chapter and the Chapter's current conference chair, responsible for planning the 2025 Annual Geotechnical Conference. Additionally, he's a member of the G-I's Engineering Geology and Site Characterization technical committee. He's excited to support the five G-I Chapters located in Region 7 and to promote our profession. Outside of his engineering career, Scheilz enjoys spending time with his wife, Sarah, playing golf, and traveling.

Hamid Karimpour, Ph.D., P.E., G.E., P.Eng, M.ASCE, has been appointed to oversee ASCE Region 9 in California. Karimpour is a senior associate and senior geotechnical engineer at Stantec Consulting Services Inc. and has been a member of ASCE since 2007.

From 2020 to 2024, Karimpour served in various leadership roles, including secretary/treasurer, vice chair, and chair of the G-I San Diego Chapter. He also served as co-chair and chair of the Calgary Geotechnical Society under the Canadian Geotechnical Society from 2017 to 2019.

Karimpour earned his Ph.D. in geotechnical engineering from the Catholic University of America in Washington, D.C. With more than 20 years of experience in geotechnical engineering, he has extensive expertise in site characterization, the development of in-situ and laboratory testing programs, slope stability analysis, numerical modeling, soil-structure interaction, pipeline geohazard management (including geohazard identification, classification, mitigation, and monitoring), geotechnical instrumentation, ground improvement, and fundamental soil behavior.

Throughout his career, Karimpour has worked on various aspects of projects, ranging from feasibility studies and planning to design and construction across different sectors, including energy/power, water/wastewater, transportation, mining, and residential, commercial, and industrial developments.

The staff and Board of Governors of the Geo-Institute would like to express their heartfelt gratitude to the following past representatives: **Jeremy Varner, P.E., M.ASCE**, past chair, **Steve Sterling, P.E., M.ASCE**, **Lyle Simonton, P.E., M.ASCE**, **Taki Chrysovergis, P.E., G.E, M.ASCE**, and **Jeff Rodgers, P.E., P.G., M.ASCE**. Your mentorship and leadership in representing G-I Chapters and ASCE Sections embody the core values of both the Geo-Institute and ASCE. Thank you for your service.

Technical Committees

COMMITTEE	COMMITTEE CHAIR	EMAIL ADDRESS
Computational Geotechnics	Dean Harris, P.E., M.ASCE	*Dean.Harris@jacobs.com*
Deep Foundations	Rozbeh B. Moghaddam, Ph.D., P.E., M.ASCE	*rbm@rbm-inc.com*
Earth Retaining Structures	Joel Dellaria, Ph.D., P.E., S.E., M.ASCE	*jbdellaria@keller-na.com*
Earthquake Engineering and Soil Dynamics	Kevin Franke, Ph.D., P.E., BC.GE, F.ASCE	*kevin.franke@hdrinc.com*
Embankments, Dams, and Slopes	Christopher L. Meehan, Ph.D., P.E., F.ASCE	*cmeehan@udel.edu*
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Geophysical Engineering	Chris M. Wood, Ph.D., A.M.ASCE	*cmwood@uark.edu*
Geosynthetics	Ben A. Leshchinsky, Ph.D., P.E., M.ASCE	*ben.leshchinsky@oregonstate.edu*
Geotechnics of Soil Erosion	John Rice, Ph.D., A.M.ASCE	*jdrice@engineering.usu.edu*
Grouting	Adam Paisley	*apaisley@schnabel-eng.com*
Pavements	Halil Ceylan, Ph.D., A.M.ASCE	*hceylan@iastate.edu*
Risk Assessment and Management	Zenon Medina-Cetina, Ph.D., A.M.ASCE	*zmedina@civil.tamu.edu*
Rock Mechanics	Kam Ng, Ph.D., P.E., M.ASCE	*kng1@uwyo.edu*
Shallow Foundations	Xiong Zhang, Ph.D., A.M.ASCE	*zhangxi@mst.edu*
Soil Improvement	Armin Stuedlein, Ph.D., P.E., F.ASCE	*Armin.Stuedlein@oregonstate.edu*
Soil Properties and Modeling	Giuseppe Buscarnera, Ph.D., M.ASCE	*g-buscarnera@northwestern.edu*
Sustainability in Geotechnical Engineering	Ranjiv Gupta, Ph.D., P.E., M.ASCE	*rgupta2@fmi.com*
Underground Engineering and Construction	Debra F. Laefer, Ph.D., M.ASCE	*debra.laefer@nyu.edu*
Unsaturated Soils	John S. McCartney, Ph.D., P.E., F.ASCE	*mccartney@ucsd.edu*

ASCE **EDUCATION and CAREERS**

ASCE/G-I Co-Sponsored Online Live Webinars

All posted webinars offer professional development hours (PDHs) as indicated.

Embankment Fills and their Interaction with Structures and Subsurface Utilities
(.4 CEU/4 PDH)
February 5, 2025 | 11:30 am - 4:00 pm ET

Investigation, Analysis, and Remediation of Building Failures
(1.4 CEU/14 PDH)
March 3-4, 2025 | 9:00 AM - 5:00 PM ET

Design of Anchors, Embedments, and Foundations to Resist Horizontal and Vertical Forces
(1.4 CEU/14 PDH)
June 26-27, 2025 | 9:00 am - 5:00 pm ET

ASCE/G-I Seminars

All posted seminars offer continuing education units (CEUs).

No seminars at this time. Check back later!

On-Demand Learning

On-demand learning opportunities offer continuing education units (CEUs). Recorded from ASCE's most popular live webinars or in-person seminars, these courses allow you to hear the instructor's lecture, see the presentation, and listen in on questions from the audience.

For more information about webinars, seminars, guided online courses and on-demand learning, visit the ASCE Continuing Education website: asce.org/continuing_education.

Guided Online Courses

ASCE Guided Online Courses are now on-demand, online, instructor-led programs in which you move through a 6- or 12-week learning experience at your own pace. The Guided Online Course content includes video lectures, interactive exercises, case studies, and weekly discussion topics to help you master the course material. Unlimited, 24/7 accessibility to weekly modules. Complete coursework at the time and pace that's most convenient for you, using your own devices. Courses offer continuing education units (CEUs).

Design and Installation of Buried Pipes
(2.4 CEU/24 PDH)

Geotechnical Design of Port Facilities
(2.4 CEU/24 PDH)

Permeable Pavements: Design, Construction, and Maintenance
(2.4 CEU/24 PDH)

Seismic Analysis of Building Structures
(2.4 CEU/24 PDH)

Seismic Design and Detailing of Steel and Concrete Buildings
(2.4 CEU/24 PDH)

Seismic Loads
(2.4 CEU/24 PDH)

Internships Available
Are you looking for an internship? Explore the positions listed on the ASCE website to help you obtain the experience you need to further your career path. New opportunities are added all the time, so start your search today: *careers.asce.org/jobs?keywords=internship*

GEOSTRATA

COMING IN APRIL/MAY 2025

Geo-history & 25th Anniversary Issue

Celebrating a Quarter Century of Publication
By James L. Withiam

Our Roots: Terzaghi's Principles of Soil Mechanics: II – Compressive Strength of Clay
By Michael Bennett

As I See It: When It Comes to Resilience, Speed Saves
By Scott A. Anderson

As I See It: Climate Change – Are You Dealing With It?
By Lawrence H. Roth

As I See It: Walking with Legends
By John H. Schmertmann

Building Ruth's House
By Michael Bennett

A Highway Relic Turned Into a Geo Playground
By Brian Brenner

A ChatGPT Interview with Karl Terzaghi
By Enrique Farfan

Arthur Casagrande's Canadian Connection
By Heinrich K. Heinz, M.A.J. (Fred) Matich, and Doug VanDine

Terzaghi on Terzaghi
By Sergei Terzaghi

Lessons Learned from GeoLegends: Jerry A. DiMaggio
By Hiramani Chimauriya and Siamak Yoosefi

INDUSTRY **CALENDAR**

2025

73rd Minnesota Geotechnical Engineering Conference
Feb. 21, 2025
Minneapolis, Minn.
mgs-gi.com/events/2025-conference

Geotechnical Frontiers 2025
March 2-5, 2025
Louisville, Ky.
geotechnicalfrontiers.com

GeoVirginia Conference NEW!
March 17-19, 2025
Smithfield, Va.
GeoVirginia.org

Iowa G-I Chapter and Iowa ASCE Annual Conference NEW!
March 27, 2025
Ames, Iowa
regcytes.extension.iastate.edu/asce-geotechnical

Structures Congress 2025
April 9-11, 2025
Phoenix, Ariz.
structurescongress.org

Kansas City G-I Chapter Annual Conference NEW!
April 11, 2025
Overland Park, Kan.
kcengineers.org/geo-institute

Geoprofessional Business Association Spring Conference
April 24-26, 2025
Savannah, Ga.
geoprofessional.org/event/gba-2025-spring-conference

Seattle Chapter Spring Seminar
May 16-17, 2025
Seattle, Wash.
seattlegeotech.org

2025 World Environmental and Water Resources Congress
May 17-21, 2025
Anchorage, Alaska
ewricongress.org

PORTS 2025
June 1-4, 2025
Providence, R.I.
portsconference.org

50th Annual Conference on Deep Foundations
Oct. 20-23, 2025
Nashville, Tenn.
dfi-events.org/dfi50

Geo-Extreme 2025
Nov. 2-5, 2025
Long Beach, Calif.
2025.geo-extreme.org

2026

Geo-Congress 2026
March 2-5, 2026
Salt Lake City, Utah

Geoprofessional Business Association Spring Conference
April 23-25, 2026
Phoenix, Ariz.
geoprofessional.org/event/gba-2026-spring-conference

For more ASCE conference information: *asce.org/conferences*

// GeoPoem

Vadose Zone

By Mary Nodine, P.E., M.ASCE

When air occupies
some space
Within the voids of
upper soil,
Considering its impacts
Is a monumental task.
For the flow of water now
Will depend on saturation.
And to understand the stress state,
We must know the matric suction,
In addition to the total stress and water pressure too.
This puzzling uncertainty joins the soil's tendency
To change in volume differently
Based on composition and initial state of stress.
All this complication makes it
Just a bit too easy to ignore nuanced behavior
Of these complex soil systems of solids, fluid, air.
But doing so can lead to conservative designs, or worse,
Results that might not capture some critical behavior
When it comes to permeability, settlement, or strength.
Below the water table, where effective stress is simply pore water pressure taken
From the soil's total stress, consolidating as predicted by a log-time fitting method,
Fluid flowing freely through each and every void, drained shear strength distilled
Into a single friction angle. Reassuring calculations make the engineering simpler,
But our infrastructure benefits when designers make the effort to consider
interaction of the soil, air, and water in the complex, omnipresent vadose zone. GS

MARY NODINE, P.E., M.ASCE, is a geotechnical poet and geotechnical engineer on the Federal Highway Administration Resource Center's Stuctures, Geotechnical and Hydraulic Engineering Team. She can be reached at *mary.nodine@dot.gov*.

GEOSTRATA FEBRUARY/MARCH 2025