Special Issue on:
Innovations in Characterizing the Mechanical and Hydrological Properties of Unsaturated Soils

Workshop Chair: John S. McCartney, PhD, PE
ASTM D.18 June Committee Week Meeting
Sheraton San Diego Hotel and Marina
San Diego, CA
June 25, 2012

Agenda - Morning

<table>
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<tr>
<th>Time</th>
<th>Description</th>
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<tr>
<td>7:30 – 9:00</td>
<td>Registration open</td>
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<tr>
<td>8:00 – 9:00</td>
<td>ASTM D18 Main Committee meeting</td>
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<tr>
<td>9:00 – 9:05</td>
<td>Welcome and overview</td>
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<tr>
<td>9:05-9:15</td>
<td>Introductions</td>
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<td>9:15 – 10:00</td>
<td>General report on papers in the ASTM Geotechnical Testing Journal Special Issues on Innovations in Characterizing the Mechanical and Hydrological Properties of Unsaturated Soils (Volume 34 Issue 5 and Volume 35 Issue 1)</td>
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<td>10:00 – 10:15</td>
<td>Coffee break</td>
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<td>10:15 – 11:45</td>
<td>Individual reports from delegates (summary of experience, key issues of interest, discussion of details from papers in the special issue, questions from delegates)</td>
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<td>11:45 – 1:00</td>
<td>Lunch (on your own)</td>
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Agenda - Afternoon

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<tr>
<td>1:00 – 2:30</td>
<td>In-depth presentations on research work in unsaturated soil mechanics (4 at 20 minutes each)</td>
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<td>2:30 – 2:45</td>
<td>Coffee break</td>
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<td>2:45 – 4:45</td>
<td>Breakout discussions on future research needs and approaches to incorporate unsaturated soils testing into practice (e.g., hydraulic properties, volume change, mechanical properties, field testing and physical modeling, elastoplastic model verification)</td>
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<td>4:45 – 5:00</td>
<td>Workshop wrap-up and closure</td>
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Brief Introduction to Unsaturated Soil Mechanics
Differences Between Saturated and Unsaturated Soils

• Saturated Soils
  – Degree of saturation is constant
  – Permeability is constant for a given void ratio
  – Effective stress = Total stress – Pore water pressure
  – Shearing behavior depends on drainage of water

• Unsaturated Soils
  – Degree of saturation is less than 1
  – Permeability varies with degree of saturation for a given void ratio
  – Effective stress depends on total stress, pore air and water pressures, and degree of saturation
  – Shearing behavior depends on drainage of water and air

Unsaturated Soil Mechanics

• Unsaturated soil mechanics is a general representation of soil behavior, saturated soil mechanics is a special case
• Generally, saturated soils have the lower shear strength than unsaturated soils (except perhaps for dry soils), and provide a worst-case design scenario
• Impact of unsaturated conditions on soil behavior are ephemeral and depend on flow processes associated with climatic interaction
• Many applications involve unsaturated soils by the nature of their situation or by design, so use of saturated soil mechanics would be incorrect or overconservative
When to Use Unsaturated Soil Mechanics?

• When designing systems which are intended to remain in unsaturated conditions, or are initially unsaturated
  – Landfill covers
  – Compacted fill
  – Nuclear waste storage

• For back-analysis of situations involving unsaturated soils
  – Explanation of rainfall-induced landslides of natural slopes
  – Collapsible or swelling soils

• For optimization of designs for local conditions
  – Retaining walls with poorly draining backfill
  – Consideration of infiltration conditions in design of embankments
  – Embankments made from Lateritic soils in tropical regions
    (unsaturated with natural cementation)

What is Needed for Unsaturated Soil Analyses?

• Constitutive relationships
  – Hydraulic properties (water retention and hydraulic conductivity)
    – *non-unique functions, not constants*
  – Relationship for effective stress
  – Hardening relationships and constitutive modeling framework to capture phenomena like swelling and collapse

• Soil-atmosphere interaction flow analysis to identify pore water pressure distributions
  – Weather data and boundary condition discretization

• Sensors and instrumentation for field monitoring
Where Do Unsaturated Soils Occur?

- In natural soils above the water table (level ground, slopes, etc.)
- In engineered geosystems above the water table
  - Retaining walls (MSE, gravity, cantilever, etc)
  - Embankments
- In earth dams and levees
- In landfills
  - Landfill cover systems
  - Municipal solid waste
- Mine operations
- Pavements

Static Water Pressure, Volumetric Water Content, and Degree of Saturation Profiles in Unsaturated Soils

\[ \gamma_w = k_i = 0 \]
\[ k \neq 0 \]
\[ i = 0 \]
\[ dh/dz = 0 \]
\[ dh_p + dh_e = 0 \]
\[ dh_p = -dh_e \]
Natural Slopes

Pavements
Earth Dams

Mine Tailing Applications
Retaining Wall Systems

Foundations in Expansive Soils
Alternative Landfill Cover Systems

- Evapotranspirative Landfill Covers
- Capillary Barriers Covers
- Passive Methane Oxidation Biocovers

Thermally Active Geotechnical Systems or Nuclear Waste Repositories
Summary of Topics in the Geotechnical Testing Journal Special Issue

Overview of Topics

• Measurement of Suction and Water Content (6 papers)
• Soil-Water Retention Curve (SWRC) (7 papers)
• Hydraulic Conductivity Function (HCF) (5 papers)
• Strength/Stiffness of Unsaturated Soils (8 papers)
• Volume Change of Unsaturated Soils (3 papers)
• Emerging Topics (8 papers)
Overview of Topics: Emerging Topics

• Hydrophobic soils
  (2 papers)
• Consolidation of multi-phase contaminated sediments
• Oxygen consumption in mine tailing covers
• Bioreactor landfill performance tests
• Testing with transparent soils
• Thermo-hydro-mechanical testing
  (2 papers)

Papers on Measurement of Suction and Volumetric Water Content
Important Variables in Unsaturated Soils

- **Volumetric moisture content** \( \theta = \frac{V_w}{V_t} \) [m³/m³]
- **Suction** \( \psi = u_a - u_w \) [kPa]
- **Hydraulic conductivity** \( K \) [m/s]
- **Flow velocity** \( v \) [m/s]

**Darcy’s Law**

\[
v = \frac{Q}{A} = \frac{K(\psi)}{g} \frac{\partial \Phi}{\partial z}
\]

**Fluid potential**

\[
\Phi = \frac{g z}{2} + \left( \frac{v}{\rho_e} \right)^2 + \frac{u_a - u_w}{\rho_e} \approx \frac{g z - \psi}{\rho_e}
\]

**Richards’ Equation**

(Combine Darcy’s law with Continuity Equation)

\[
\frac{\partial \theta}{\partial t} = \frac{d}{dz} \left( K(\psi) \left( 1 - \frac{1}{\rho_e g} \frac{d\psi}{dz} \right) \right)
\]

Water retention curve (WRC): \( \theta = f(\psi) \)

K-function: \( K = f(\psi) \)

Haghighi, Medero, Marinho, Mercier, and Woodward

**Temperature Effects on Suction Measurement Using the Filter Paper Technique**

**Objective**: Study the thermal effects on filter paper calibration curves for suction.

**Approach**: The calibration curve of Whatman No. 42 filter paper was determined at 10, 25, and 50°C using the vapor equilibrium technique and the axis translation technique. Kaolinite tested showed lower retention capacity at higher temperatures.

![Temperature Effects on Suction](image)

\[ L_{\psi} = \frac{(a + b \times W_f + c \times T + d \times W_f \times T)}{(1 + f \times W_f + g \times T + h \times W_f \times T)} \]

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Marinho and Gomes

*The Effect of Contact on the Filter Paper Method for Measuring Soil Suction*

**Objective:** Study the effect of contact between the soil grains, pore water, and filter paper.

**Approach:** Used Whatman #42 filter paper and three porous materials with different contact conditions to investigate the influence of the equilibration time, the texture of the porous material and the degree of contact, or lack thereof.

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Tripathy, Elgabu, and Thomas

*Matric Suction Measurement of Unsaturated Soils With Null-Type Axis-Translation Technique*

**Objective:** Measured the matric suctions of compacted specimens of a low-plastic soil using the null-type axis-translation technique. The study showed that in general, the dynamically compacted specimens reached equilibrium sooner than statically compacted specimens and exhibited greater matric suctions.
Objective: Assess uncertainty when extrapolating the calibration curve to negative values of water pressure associated with a single measurement of potential in a soil.

Approach: Measured suction during a drainage SWRC test.
Puppala, Manosuthkij, Nazarian, Hoyos, Chittoori  
*In Situ Matric Suction and Moisture Content Measurements in Expansive Clay during Seasonal Fluctuations*

**Objective:** Measure suction and water content in the field using thermal conductivity sensors and time domain transmission.

Munoz-Castelblanco, Pereira, Delage, and Cui  
*The Influence of Changes in Water Content on the Electrical Resistivity of a Natural Unsaturated Loess*

**Objective:** Develop an electrical resistivity probe to monitor the change in water content of a soil specimen. The sensor is only in contact with the boundary of the specimen and is not inserted. Two theoretical models of resistivity were also used to analyze the obtained data to define the SWRC of a natural Loess.
Soil Water Retention Curve (SWRC) Papers

Constitutive Relationship
Soil Water Retention Curve (SWRC)

Relationship between suction and volumetric water content (most typical), gravimetric water content (for soils that change in volume), or degree of saturation (normalized version)

\[ \log \psi \]

Porosity, \( \theta_w = n \)

Air entry suction \( \psi_{aev} = \psi_b \)

Residual water content (adsorbed water) \( \theta_r \)

Continuous water phase

Continuous air phase
Summary of Drying Path SWRCs for Different Soils

Observations:
- Shape depends on the pore size distribution
- Fine-grained soils retain water up to higher suction magnitudes
- Many other variables which affect SWRC (hysteresis, mineralogy, compaction conditions, temperature, etc.)

Wayllace and Lu

A Transient Water Release and Imbibitions Method for Rapidly Measuring Wetting and Drying Soil Water Retention and Hydraulic Conductivity Functions

Objective: Develop an approach to evaluate outflow and inflow from a soil specimen to estimate the SWRC and hydraulic conductivity function using inverse analysis.
Nishiumura, Koseki, Fredlund, Rahardjo

Microporous Membrane Technology for Measurement of Soil-Water Characteristic Curve

Objective: A new apparatus was developed to make use of a microporous membrane for the measurement of the SWCC with matric suction of up to 25 kPa with faster equilibration time than ceramic discs.

Nowamooz and Masrouri

Soil Fabric and Soil Water Retention Curve of a Compacted Silt-Bentonites

Objective: Understand the effects of the initial dry density and the initial water content on the soil water retention curve (SWRC) of a compacted bentonite/silt mixture during a wetting and drying cycle using mercury intrusion porosimetry (MIP).
Liu, Zhang, Yu, Zhang, and Tao

A New Method for Soil Water Characteristic Curve Measurement Based on Similarities Between Soil Freezing and Drying

Objective: Develop a method to estimate the SWRC using similarity between the freezing/thawing process and drying/wetting process in soils. The soil freezing characteristic curve (SFCC) is introduced to describe the relationship between the unfrozen water content and matric suction in frozen soils. A thermo-time domain reflectometry (TDR) sensor was developed which combines both temperature sensors and conventional TDR sensor.

Stormont, Hines, O’Dowd, Kelsey, Pease

A Method to Measure the Relative Brine Release Capacity of Geologic Material

Objective: Develop a method to estimate the brine released by pumping a brine-saturated geologic unit. Provides a rapid screening test that is suitable for multiple samples and textures and avoids issues associated with brine as the pore fluid. The method involves applying a vacuum to a group of initially saturated samples in a parallel configuration.
Objective: Estimate the SWRC of granular porous media having uniform packing along a drainage path using conventionally measured parameters (grain size distribution and mass-volume relationships).

Hydraulic Conductivity Function (HCF) Papers
Hydraulic Conductivity Function (HCF)

Less pathways are available for water flow in unsaturated soils
- The water phase must flow through water channels OR displace air
- Water phase must be continuous
- Water vapor flow is captured by relative humidity gradients (Fick’s law not Darcy’s law)

\[ k = 10^{-12} \text{ to } 10^{-14} \text{ m/s} \]

Summary of HCFs for Different Soils

Observations
- Sands can have lower permeability than clays, depending on their degree of saturation
- At high suctions, clays are often still highly conductive, while sands have zero conductivity
- Similar variables which affect the SWRC affect the HCF
Moncada, de Campos, and Steger

*A Flexible Wall Permeameter for the Determination of the Water Permeability Function in Unsaturated Soils*

**Objective:** Development of a suction controlled flexible wall permeameter for the direct determination of the water permeability function in unsaturated soils using constant head or constant flow, in order to assess predictive HCF functions.

Reis, Sterck, Ribeiro, Dell’Avanzi, Saboya, Tibana, Marciano, and Sobrinho

*Determination of the Soil-Water Retention Curve and the Hydraulic Conductivity Function Using a Small Centrifuge*

**Objective:** Development of methodology to directly determine the SWRC and HCF of an unsaturated soil using a commercially available small centrifuge with a swinging type rotor assembly without inflight instrumentation.
Parks, Stewart, and McCartney

*Validation of a Centrifuge Permeameter for Investigation of Transient Infiltration and Drainage Flow Processes in Unsaturated Soils*

**Objective:** Development of a large-diameter centrifuge permeameter to evaluate the SWRC and HCF of sands under wetting and drying using embedded instrumentation and the instantaneous profile method.

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Tristancho, Caicedo, Thorel, and Obregon

*Climatic Chamber With Centrifuge to Simulate Different Weather Conditions*

**Objective:** Development of an apparatus for simulating tropical weather conditions in a geotechnical centrifuge using a climatic chamber with a centrifuge (temperature, evaporation, infiltration, etc), including development of scaling laws for these flow processes.

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 lesb.png
Mijares, Khire, and Johnson

*Field-Scale Evaluation of Lysimeters Versus Actual Earthen Covers*

**Objective:** Development and results from two uncompacted and one compacted clay field-scale landfill cover test sections to capture the differences in the hydraulic and hydrologic responses of actual covers and lysimeters in the same conditions.

**Shear Strength and Stiffness Behavior of Unsaturated Soils**
Issues in Measuring the Strength of Unsaturated Soils

- Drainage conditions
  - Constant suction (water and air are free to flow in/out)
  - Constant water content (i.e., water can’t flow in/out but air is free to flow in/out)
  - Constant volume (flow of water and air restricted)
- Rate of shearing
  - Hydraulic conductivity is lower
- Control of suction
  - Undrained loading of a soil having a given suction (and measurement of changes in suction during shear)
  - Control of suction within the testing apparatus

Direct Shear Results from Escario and Saez (1986)
Effective Stress in Unsaturated Soils

Unsaturated Soil – 1 stress state variable (Bishop 1956)

\[ \sigma' = (\sigma - u_a) + \chi (u_a - u_w) \]

- \(\sigma - u_a\) = net normal stress = \(\sigma_n\)
- \(u_a - u_w\) = matric suction
- \(\chi\) = effective stress parameter
- \(\chi\) depends on material type and degree of saturation

Unsaturated Soil – 2 stress state variables (Fredlund and Morgenstem 1977)

Two independent stress state variables can cause volume change or strength change

- \(\sigma - u_a\) and \(u_a - u_w\)
- Different set of constitutive laws for unsaturated soils

Burrage, Anderson, Pando, Ogunro, Cottingham

*A Cost Effective Triaxial Test Method for Unsaturated Soils*

**Objective**: Develop a test method to measure the shear strength of unsaturated soils using standard triaxial equipment with minor, low-cost modifications. The method is based on using the axis translation technique in a standard triaxial testing apparatus with a base pedestal slightly modified to accommodate a high-air-entry ceramic disk.
Khosravi, Alsherif, Lynch and McCartney

*Multistage Triaxial Testing to Estimate Effective Stress Relationships for Unsaturated Compacted Soils*

**Objective:** Perform multistage, drained triaxial tests on compacted soils under unsaturated conditions to estimate soil-specific relationships between mean effective stress and matric suction.

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Khoury and Miller

*Influence of Hydraulic Hysteresis on the Shear Strength of Unsaturated Soils and Interfaces*

**Objective:** This paper describes an investigation of the influence of hydraulic hysteresis during drying and wetting on the shearing response of unsaturated silty cohesionless soil alone and in contact with a rough steel counterface using a specially designed direct shear apparatus.
Hoyos, Velosa, Puppala

*A Servo/Suction-Controlled Ring Shear Apparatus for Unsaturated Soils: Development, Performance, and Preliminary Results*

**Objective:** This paper introduces a fully servo/suction-controlled ring shear apparatus that has been made suitable for testing unsaturated soils at large deformations via axis-translation technique. Because large strains are imposed, multi-stage testing can be used.

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Merchan, Romero, and Vaunat

*An Adapted Ring Shear Apparatus for Testing Partly Saturated Soils in the High Suction Range*

**Objective:** A commercial ring shear apparatus (Bromhead type) was instrumented and adapted to control total suction in a wide range by using vapor transfer technique.
Nyunt, Leong, Rahardjo

*Strength and Small-Strain Stiffness Characteristics of Unsaturated Sand*

**Objective:** Experiments were performed to investigate the effects of initial matric suction and net confining pressure on the small-strain stiffness and shear strength of reconstituted unsaturated sand. A series of constant water content tests was carried out using a modified triaxial apparatus equipped with local displacement transducers and bender elements.

Biglari, Jafari, Shafiee, Mancuso, and d’Onofrio

*Shear Modulus and Damping Ratio of Unsaturated Kaolin Measured by New Suction-Controlled Cyclic Triaxial Device*

**Objective:** A new cyclic triaxial test implemented with the axis translation technique is used to study the impact of suction on the shear modulus and damping relationships.
Ghayoomi and McCartney

Measurement of Small-Strain Shear Moduli of Partially Saturated Sand During Infiltration in a Geotechnical Centrifuge

Objective: Bender elements were used to measure the shear modulus of an unsaturated sand layer in a geotechnical centrifuge. Suction was controlled using steady-state infiltration and effective stress was estimated using $\chi = \frac{S_e}{\gamma}$.

Hydromechanical Behavior of Soils: Swelling and Collapse of Unsaturated Soils
Elkady, Houston, and Houston

*Static and Dynamic Behavior of Hydro-Collapsible Soils*

**Objective:** This study focuses on the evaluation of the shear strength and volume change of collapsible soils subjected to static and dynamic shear loading under a range of confining pressures and wetting conditions which ranged from "as-prepared" to soaked to backpressure saturated.

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Singhal, S. Houston, and W.N. Houston

*Effects of Testing Procedures on the Laboratory Determination of Swell Pressure of Expansive Soils*

**Objective:** This study focuses on the effects of apparatus compressibility and applied initial net normal stress on the measured swell pressure of expansive soils, with emphasis on intact specimens.
Objective: A novel image based technique has been developed to measure strains of soil specimens subjected to wetting-drying by using vapor equilibrium with closed-loop ventilation, with strains measured using a digital SLR camera.

Emerging Topics in Unsaturated Soils
Cleall, Singh, and Thomas

*Non-isothermal moisture movement in unsaturated kaolin: An experimental and theoretical investigation*

**Objective:** Non isothermal moisture movement in unsaturated kaolin is investigated using a thermo-hydraulic cell is used to apply thermal and hydraulic gradients to confined specimens in a number of thermal gradient, thermal-hydraulic gradient, and isothermal-hydraulic tests. Vapor transfer is empirically quantified, and its theoretical representation considered.

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Uchaipichat, Khalili, and Zargarbashi

*A Temperature Controlled Triaxial Apparatus for Testing Unsaturated Soils*

**Objective:** This paper describes a modified Bishop–Wesley triaxial apparatus for testing unsaturated soils at elevated temperatures.
Erten, Gilbert, El Mohtar and Reible

*Development of a Laboratory Procedure to Evaluate the Consolidation Potential of Soft Contaminated Sediments*

**Objective**: Develop a triaxial test to evaluate the consolidation of soft soils containing a non-aqueous phase liquid.

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Byun, Tran, Yun, and Lee

*Strength and Stiffness Characteristics of Unsaturated Hydrophobic Granular Media*

**Objective**: This study evaluates the shear strength and stiffness of hydrophilic and hydrophobic soils using direct shear tests. Hydrophobicity may occur in natural slopes due to wildfires.
Kim, Kim, Lee, and Yun

*Thermal and Electrical Response of Unsaturated Hydrophilic and Hydrophobic Granular Materials*

**Objective:** This study presents methods to prepare water-repellent soils and to evaluate the evolution of thermal and electrical properties of unsaturated wettable (hydrophilic) and water-repellent (hydrophobic) soils.

Peters, Siemens, and Take

*Characterization of Transparent Soil for Unsaturated Applications*

**Objective:** This study involves the development of an alternative method which aims to combine the use of digital image analysis with a transparent soil to avoid the ambiguity of traditional boundary image measurements of moisture content in column experiments.
Dagenais, Mbonimpa, Bussiere, and Aubertin

A Modified Oxygen Consumption Test to Evaluate Gas Flux through Oxygen Barrier Cover Systems

Objective: The evaluation of an oxygen barrier cover performance is an integral part of many reclamation programs that aim at limiting acid mine drainage (AMD) production from sulphide tailings. This paper focuses on the development of a modified testing and interpretation method based on the oxygen consumption (OC) test, which is commonly used to determine oxidation rates of uncovered tailings.

Mukherjee and Khire

Instrumented large scale subsurface liquid injection model for bioreactor landfills

Objective: In order to simulate hydraulic scenarios to improve understanding of leachate recirculation systems for landfills, an 86 cm long by 30 cm wide by 56 cm tall unsaturated flow physical model was designed and fabricated. Water was injected at different rates in continuous and on/off modes to achieve transient and steady-state conditions.
Final Comments

- Experimental unsaturated soil mechanics has a long history since the early part of the 20th century, but has seen many improvements in experimental setups, techniques, and sensors
- Significant time requirements for unsaturated soil testing often cannot be avoided
- Many experimental approaches available, many with different suction ranges suitable to different soil types
- Best approach mimics flow process in problem being studied
- Approaches to predict the hydraulic properties of unsaturated soils work well in some scenarios but not in others – it is best to use predictions for preliminary guidance but confirm results with experiments
- Many variables can impact the properties of soils including soil-specific issues (mineralogy, gradation, stress history, anisotropy) as well as setting-specific issues (temperature, pore fluid chemistry)

Final Comments

- There are still different philosophies as to how to integrate the hydraulic and mechanical aspects of unsaturated soils
- The best philosophy from an engineering perspective is the one that works well to solve a specific problem (not all problems)
- A unified framework with saturated soils is possible with advancements in definition of a single-value effective stress, but elasto-plastic hardening mechanisms specific to unsaturated soils need to be considered
- Education and outreach will help improve implementation into practice