Advances and Open Problems in Soil Modeling

MAGIC: Machine-Ground Interaction Consortium, Madison, WI
May 12, 2015

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The Trouble with Unsaturated Soils...

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Precipitation-induced landslides
The effective stress framework

dry or saturated sand
\[ S = 0 \text{ or } S = 1.0 \]

\[ \sigma' = \sigma - u_w \]

"Effective Stress"

Stress state variable

Shear Strength

\[ \tau = c' + \sigma' \tan \phi' \]

Volume Change

\[ \Delta e = \frac{C_c H}{1 + e_0} \log \left( \frac{\sigma'_f}{\sigma'_i} \right) \]
The problem(s) with unsaturated soils...

Partially saturated sand

\[ 0 < S < 1.0 \]

Outstanding Issues:

Defining effective stress...
Coupling of stress/strain/flow...
Nonlinearity...
Hysteresis...
Atmospheric interactions...

**MICROSTRUCTURE IS THE KEY!**
Fluid and solid microstructure dominate macroscopic soil behavior....

- Hydraulic conductivity
- Thermal conductivity
- Dielectric response
- Stiffness
- Shear strength
- Tensile strength

(S = 0.17)  (S = 0.70)

General Research Philosophy:
- Macroscopic properties such as fluid pressure and saturation are insufficient
- Need to “get inside” the REV and consider granular and fluid microstructure

Focus of discussion for today:
- Microstructural imaging using μXCT
- Particle-scale mechanical (pull-apart) testing
Unsaturated soil research: from the atomic scale to the field scale...
(Image: A. Gens)
Particle-scale mechanical testing (pull-apart tests)

![Diagram of particle-scale mechanical testing](image)

- R = 3mm
- 5 μl DI water drop
Menisci formation, isopropanol washed, $R = 0.8$ mm, $V = 0.5$ μl and $v = 1.27$ mm/min
Liquid volume effect (DI water)

- Maximum Measured Force (N)
  - V=1.0 ul #1
  - V=0.5 ul #1
  - V=0.2 ul #1
  - V=1.0 ul #2
  - V=0.5 ul #2
  - V=0.2 ul #2
  - V=1.0 ul #3
  - V=0.5 ul #3
  - V=0.2 ul #3

- DI water volume (μl)
  - V=1.0 ul
  - V=0.5 ul
  - V=0.2 ul

- Maximum Measured Force (N)
  - (R = 0.8 mm, v = 1.27 mm/min and # number of trials)

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(R = 0.8 mm, v = 1.27 mm/min and # number of trials)
(v is the separation velocity, isopropanol washed beads – R = 3 mm, V= 5μl)
Effect of separation velocity on rupture strain:

\[ \varepsilon_a = \frac{D_f}{2R} \]

where;
\( \varepsilon_a = \) Strain at failure
\( D_f = \) Separation distance at failure

*Each point represents a separate test*
Comparison with theory

Isopropanol washed,
R = 0.8 mm, V = 0.5 μl and v = 1.27 mm/min

Measured force V=0.2 μl
Pitois et al. (2000) V=0.2 μl
Lu and Likos (2004) V=0.2 μl

Measured force V=0.5 μl
Pitois et al. (2000) V=0.5 μl
Lu and Likos (2004) V=0.5 μl

Measured force V=1.0 μl
Pitois et al. (2000) V=1.0 μl
Lu and Likos (2004) V=1.0 μl
Multiphase Microstructural Imaging

- X-Ray microfocus computed tomography (µCT)
  - Synchrotron XCT (GSECARS), Argonne National Laboratory
  - Industrial X-Ray FLASH CT (Washington State University)
- CsCl-doped water
- Voxel sizes: 10 µm - 15 µm
- Microstructure features
  - Grain size distribution
  - Pore shape and size distribution
  - Solid, liquid, and gas surface areas
  - Particle contact coordination number
  - Filled and unfilled pores
• Bead sizes: 0.5 mm – 1.2 mm
• Column size: 18.6 mm (ID)

\[ S = \frac{A_W}{A_v} \]

\[ n = \frac{A_v}{A_t} \]
Dry Sand

$S = 0.17$

$S = 0.40$

$S = 0.70$

$S = 0.80$

![Graph showing matric suction vs. saturation for dry sand](image)
Image-based quantification:

- Saturation, $S$
- Air-water surface area, $A_{aw}$

$S = 0.17$
$A_{aw} = 128 \text{ cm}^{-1}$

$S = 0.70$
$A_{aw} = 37 \text{ cm}^{-1}$
Tomography to Simulation

- Transition from CT image to simulation domain
- Fluid flow, heat flow, geomechanics
- Challenges: resolving contacts!

Image-based Simulation → μCT imaging → Segmentation & Analysis → 3DXRCT → Level set → Watershed → Density threshold

Andrade et al. (2012)
Further Reading


Acknowledgments

- **NSF CMMI 0968768**: Pore-scale modeling of capillary stress in unsaturated soil

- **NSF CMMI 0856276**: Imaging and modeling the microstructure of unsaturated soils for improved prediction of macroscale response

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