CASE
SCHOOL OF ENGINEERING

The Coupled Hydro-thermo-mechanical Process in Soils and its Implications for Emerging Geotechnical Engineering Practice

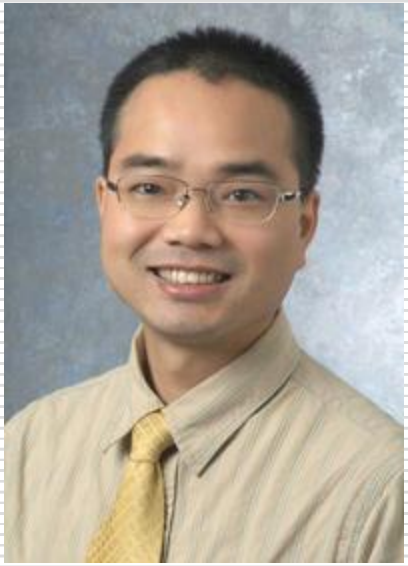
Purdue Geotechnical Society Workshop

April 19, 2013

Xiong (Bill) Yu, Ph.D., P.E.

Associate Professor, Department of Civil Engineering, Case Western Reserve University, 216-368-6247, xxy21@case.edu

About myself



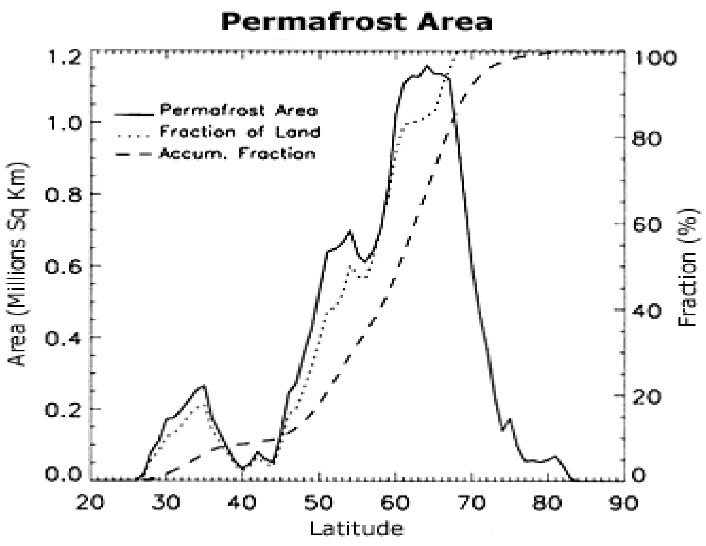
- **Purdue Graduate**
- Current program affiliation
  - Geotechnical engineering
  - Infrastructure engineering
  - EECS and other programs
- Current research focus
  - Sensor technology
  - Field instrumentation
  - Durable and multifunctional civil engineering materials
  - Sustainability
  - Energy geotechnology

Multiphysics versus Single Field

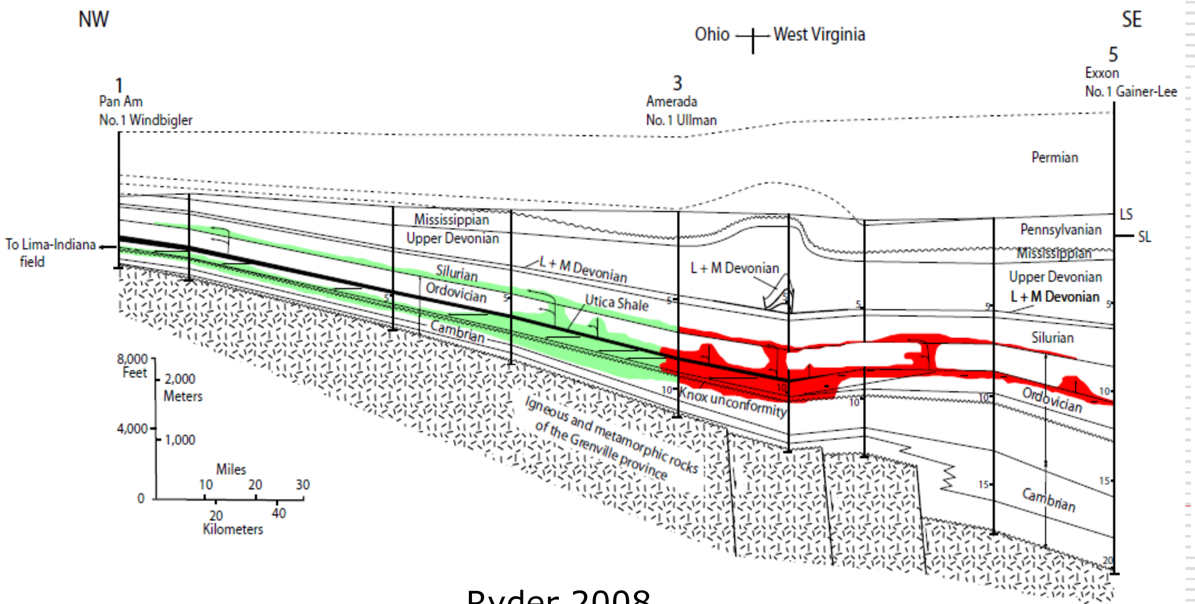
- Multiphysics stands for the coupling of multiple fields
- Common observations in soil
  - Phase change of pore water involves energy significantly alter the soil properties such as elastic modulus (hydraulic and mechanical).
  - Fluid transfer due to the temperature gradient (Philip, 1957; Cary, 1964). (Coupling between thermal and hydraulic)
  - Mechanical constraints: the mechanical field can only response partly to the other field and thus in turn affect the other field (Mechanical on thermal and hydraulic).
  - …
- We are interested to explore the common scientific basis to the multiphysics process in soils and other geomaterials

Impacts on Engineering

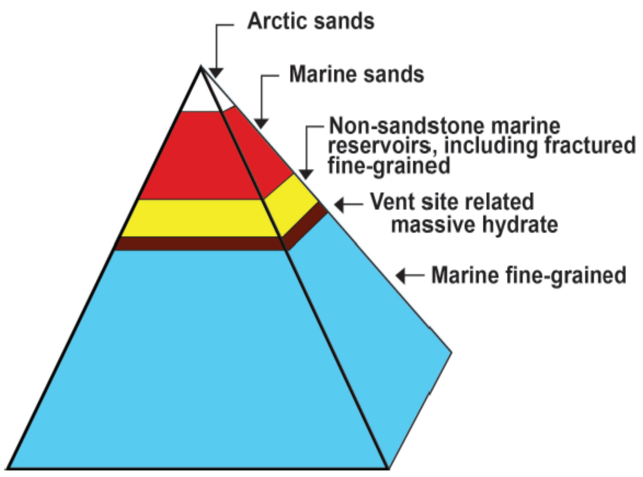
- Frozen soil covers 60% the earth surface
  - Climate effects on infrastructure
- Geothermal energy
  - Green energy source
- Gas hydrate
  - A huge potential energy source
- Unconventional gas/oil
  - Utica shale in Ohio alone contains 15 trillion cubic feet of natural gas



Zhang et al. 1999



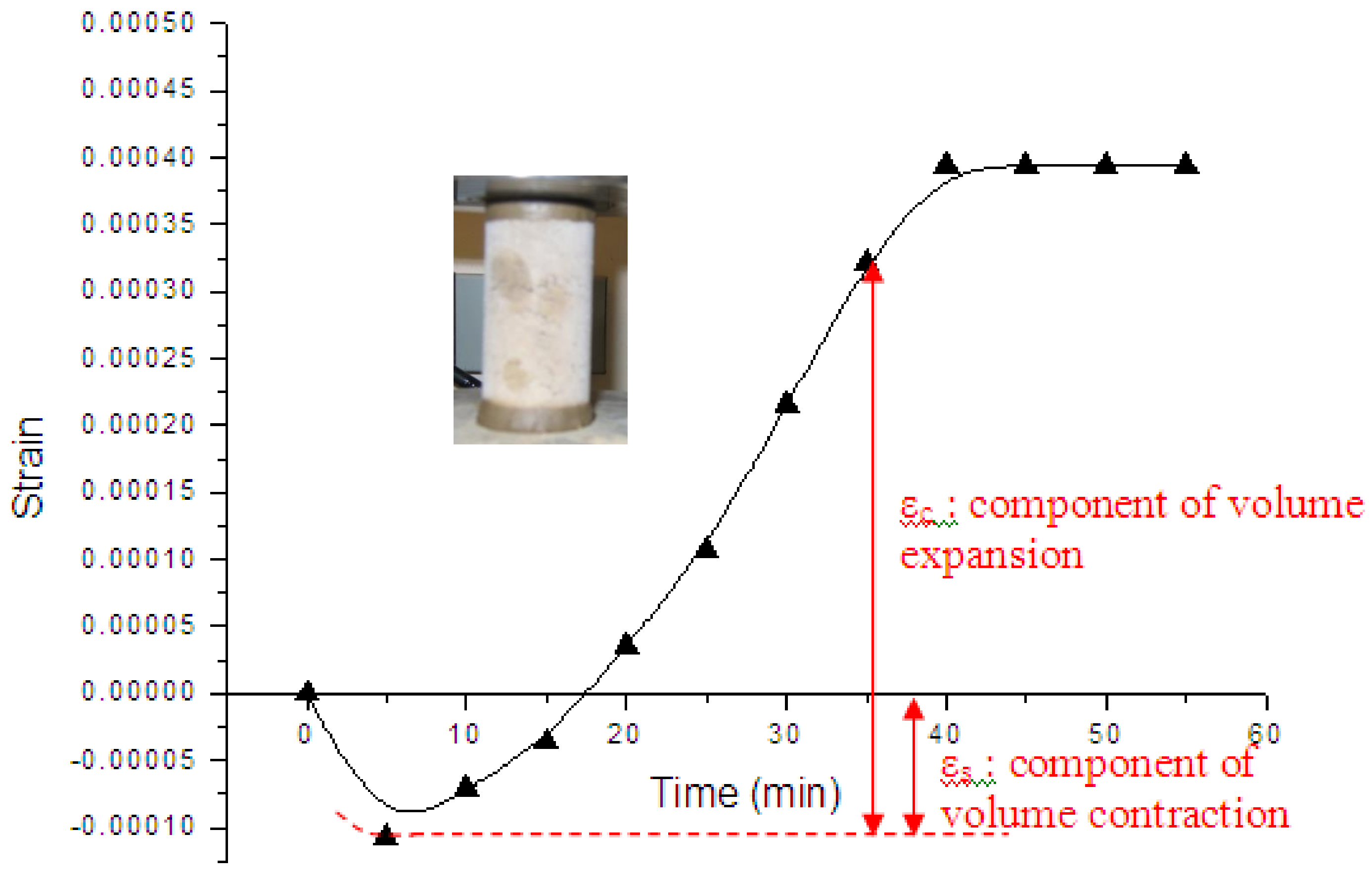
Ryder 2008



Johnson 2011

Observation 1: Thawing Soils

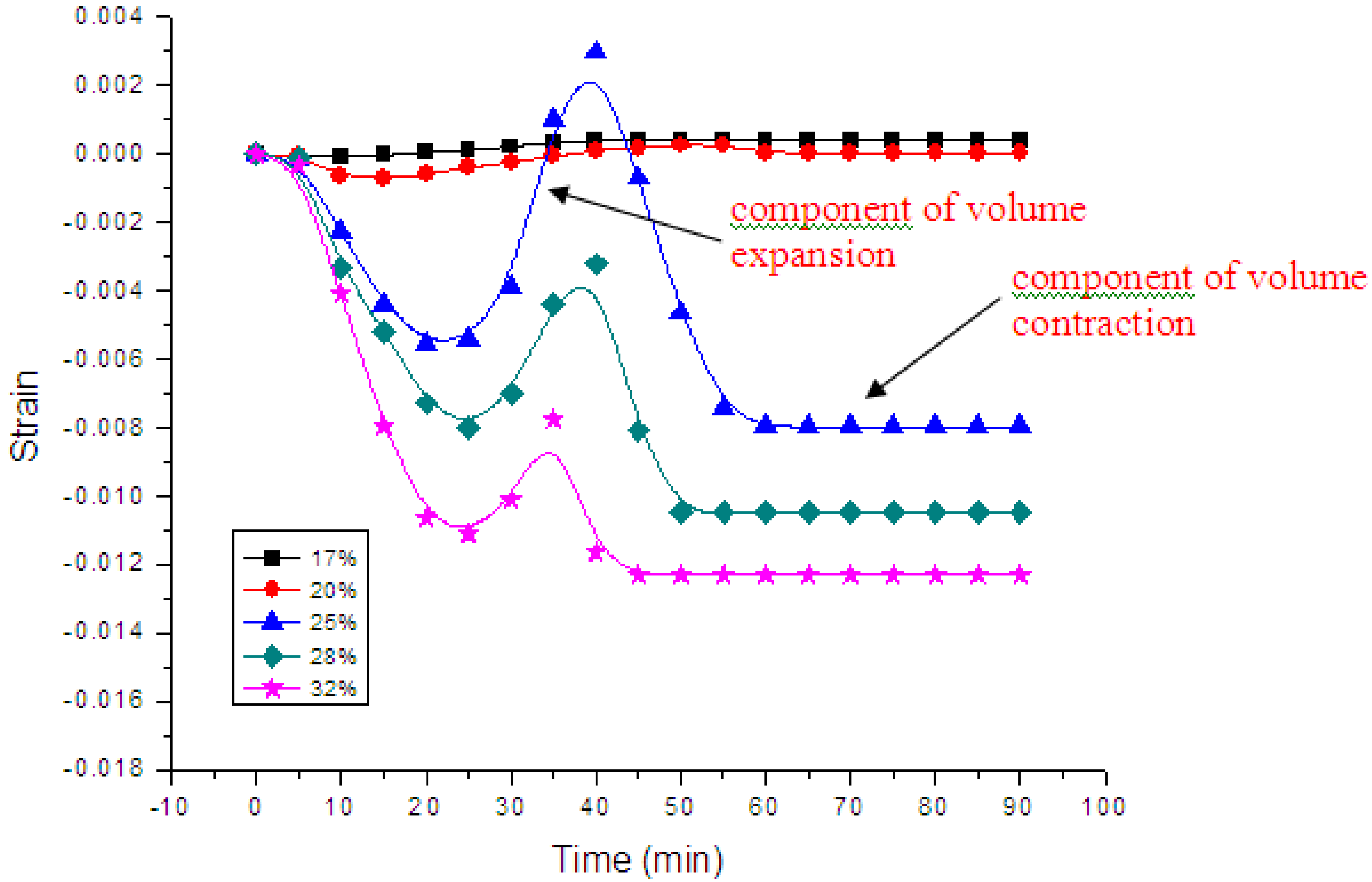
- Volume Change Behaviors in Thawing Soils



Liu Y., Yu, et al. 2009

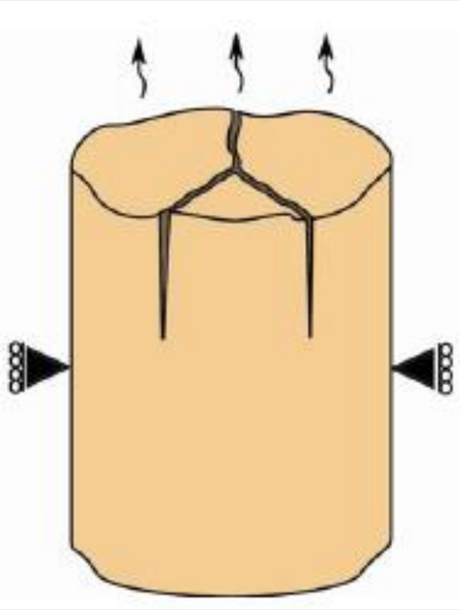
Thawing Soils: cont.

- Component of volume change



Liu Y., Yu, et al. 2009

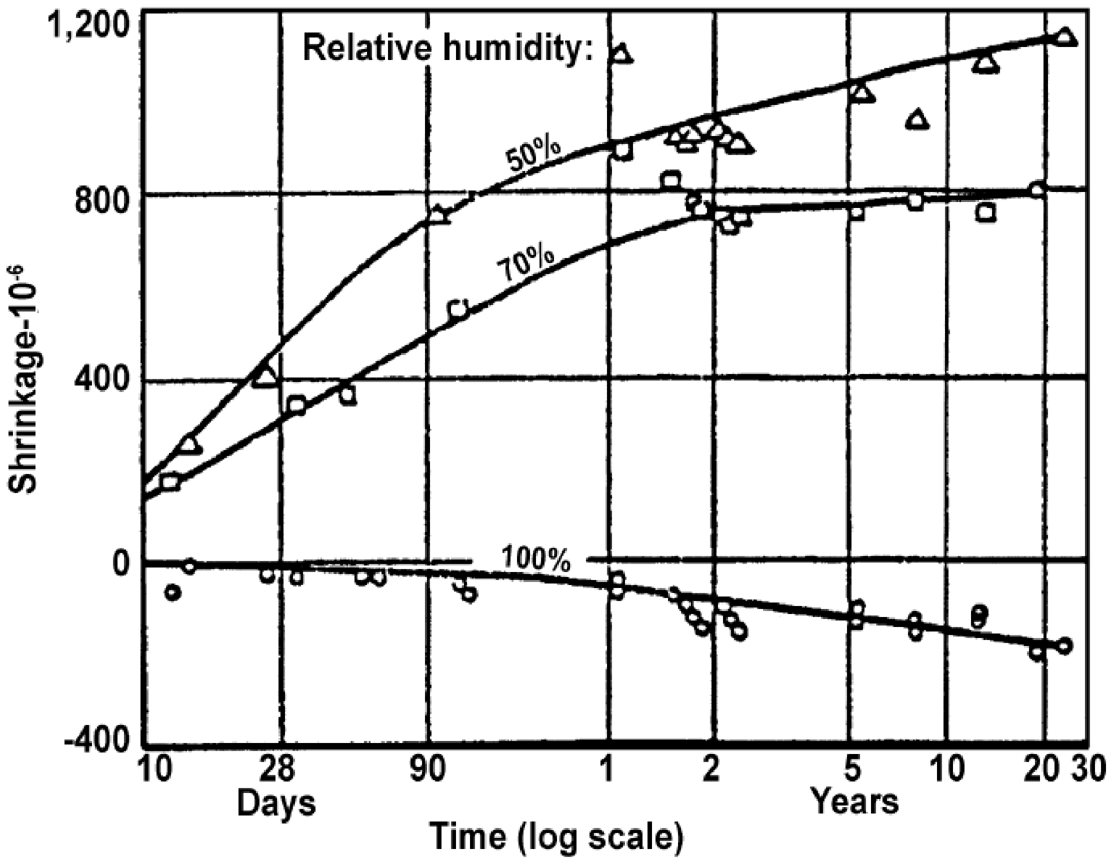
Observation 2: Desiccation Crack in Soil



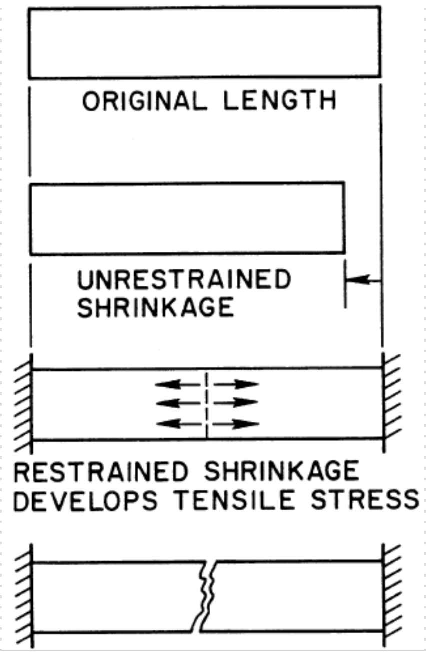
Schematic drawing modified
from internet resource

Observation 3: Plastic shrinkage of concrete

- Commonly observed in fresh concrete
- Accelerate deterioration



Relations between shrinkage and time for concretes stored at different relative humidities (Troxell, Raphael, and Davis 1958).



Shrinkage cracking mechanism (ACI 224R-01)

Examples of plastic shrinkage cracking (source Internet)

Chemically Treated Soils

- Cement treated soils
  - Cracks accelerate water infiltration into pavement base

Shrinkage Cracking Resulting from Problems with Cement-Treated Base (internet image)

Are There Common Mechanisms?

- Freezing
- Drying
- Chemical hydration

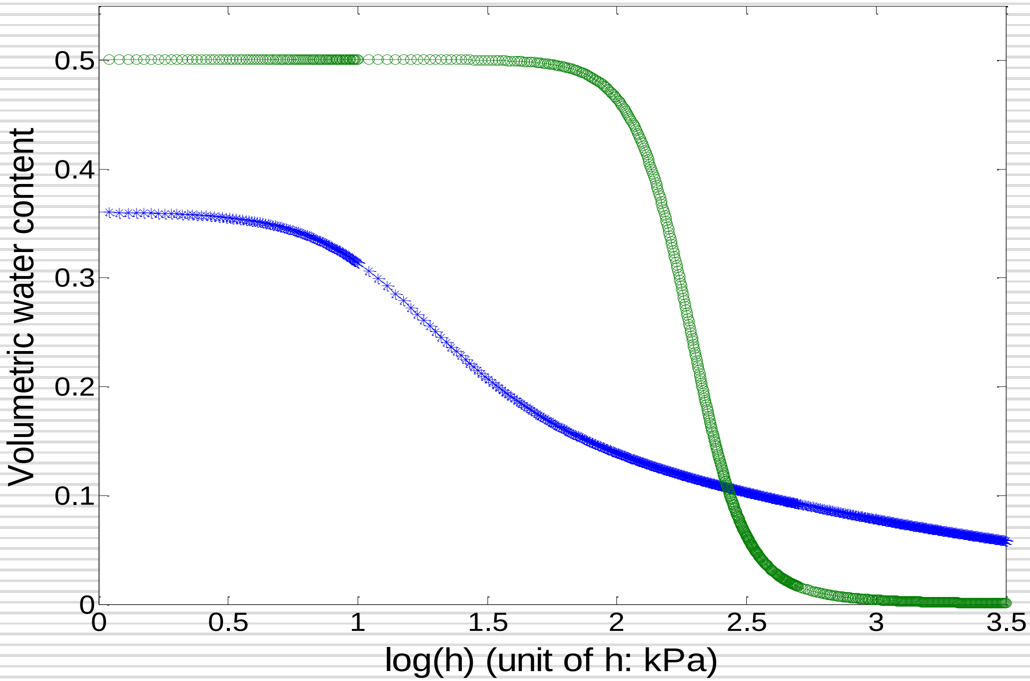
➔ These motivates us to explore the fundamental knowledge for porous materials

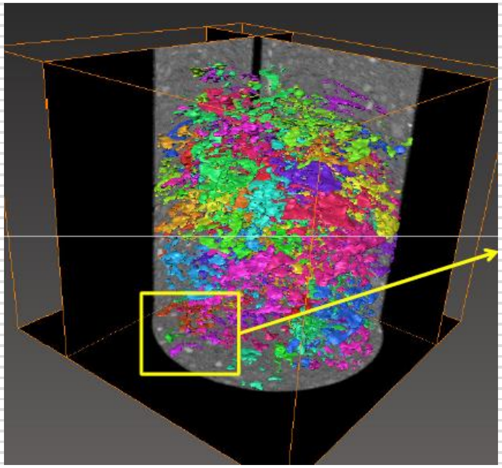


Liquid water “consumption”?

Solid (Soil, Concrete, Ceramic, ...) Water Characteristic Curve (SWCC)

- Describes the change of matric suction with water
- Decided by the pore structures





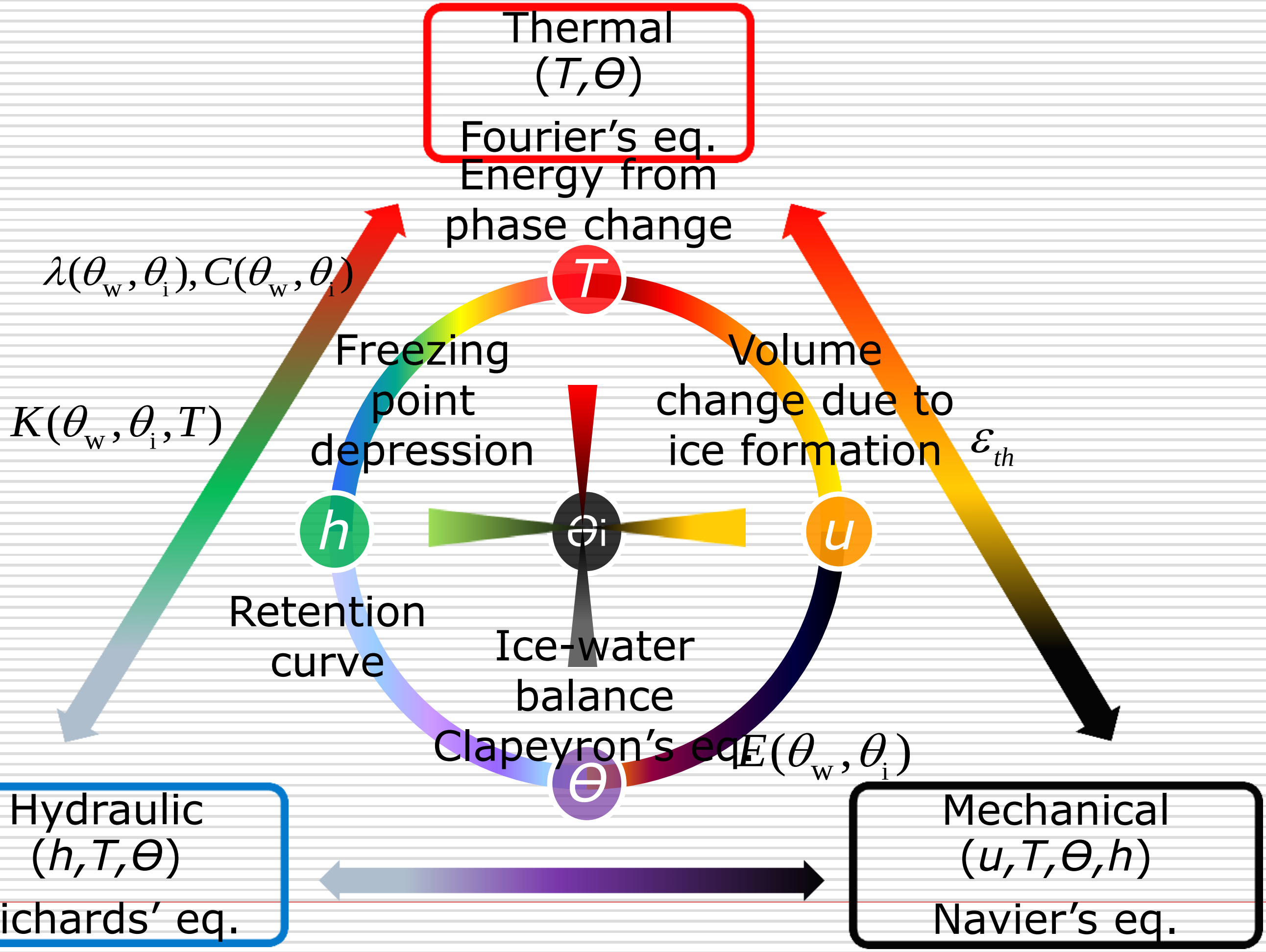
Pore space from CT scanning

Q1. Can SWCC explain the experimental observations?

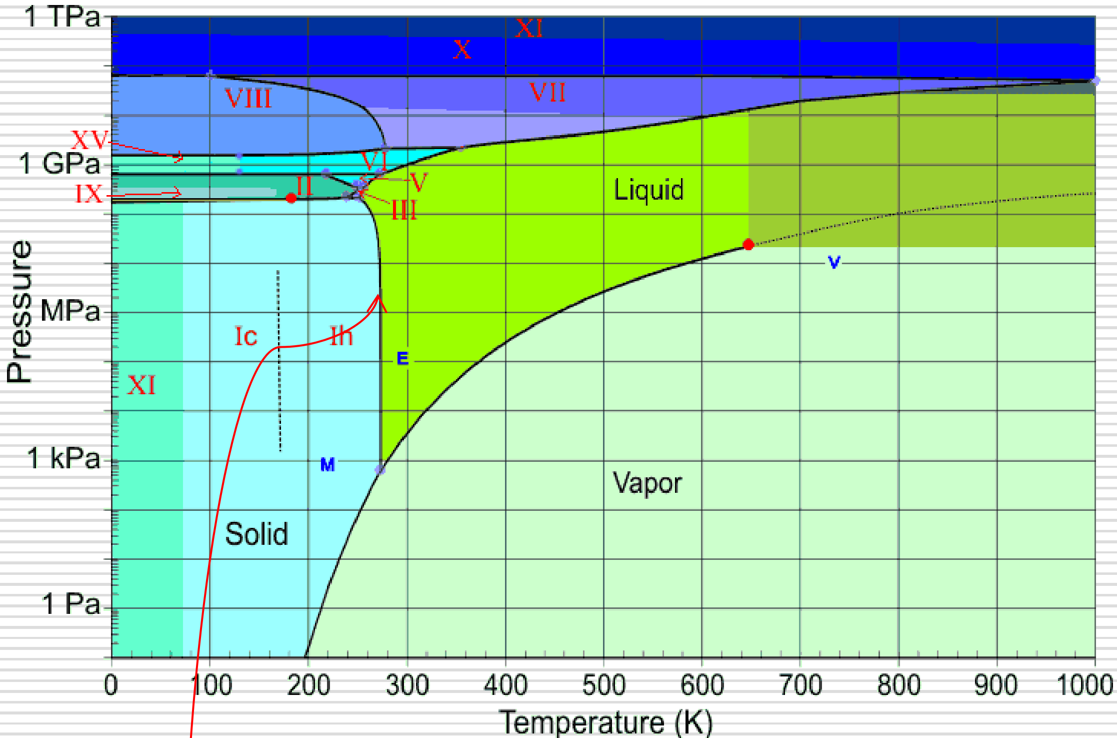
Q2. If so, how to integrate into simulation modeling?

Simulation of Freezing Soils

- A multiphysical thermo-hydro-mechanical process.



Freezing Point Depression



Three phase diagram of water
(From www1.lsbu.ac.uk)

Generalized Clapeyron equation:
(Williams and Smith, 1989)

$$\frac{dP}{dT} = \frac{L_f}{V_w T} \qquad \frac{d\theta_i}{dT} = -\frac{L_f}{gT}\frac{d\theta}{dh}$$

Approach to the Problem

- PDEs governing individual process
  - Fourier's equation, Richard's equation, Navier's equation
  - Boundary and constitutive relationships
    - Newton's low of cooling, Darcy's law, mass balance, constitutive relationships
- Experimental correlations for porous media
  - Soil water characteristic curve,
  - Hydraulic conductivity
  - Thermal conductivity
- Phase transition
  - Clapeyron's equation for water-ice balance
- Theoretical model–(PDEs-weak form)-solved numerically

➔ Can't go into details due to time constraints

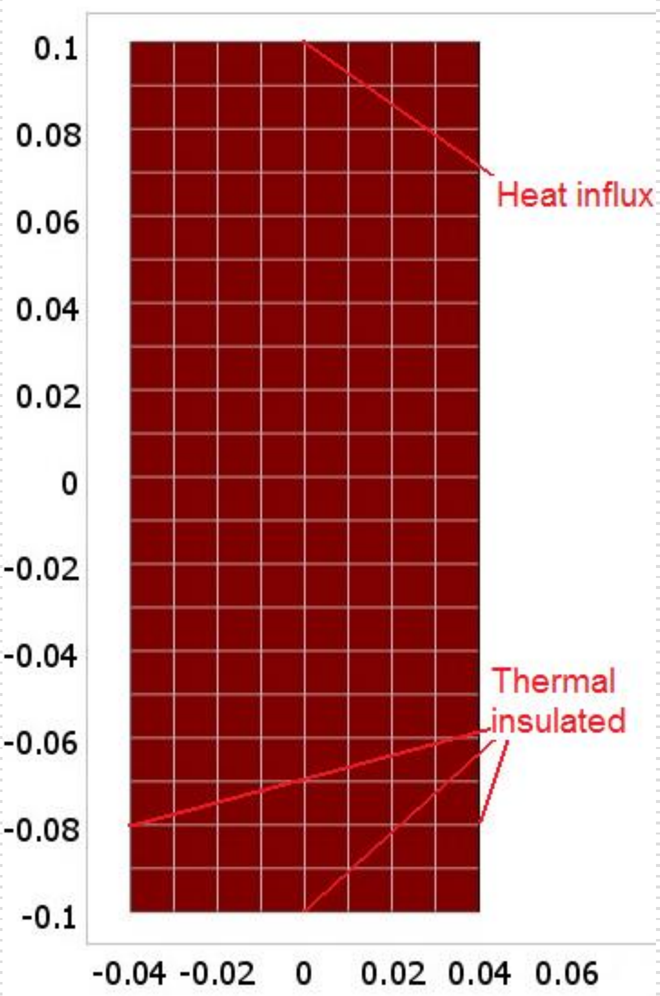
Example

Unsaturated uniform soil specimen subjected to surface freezing

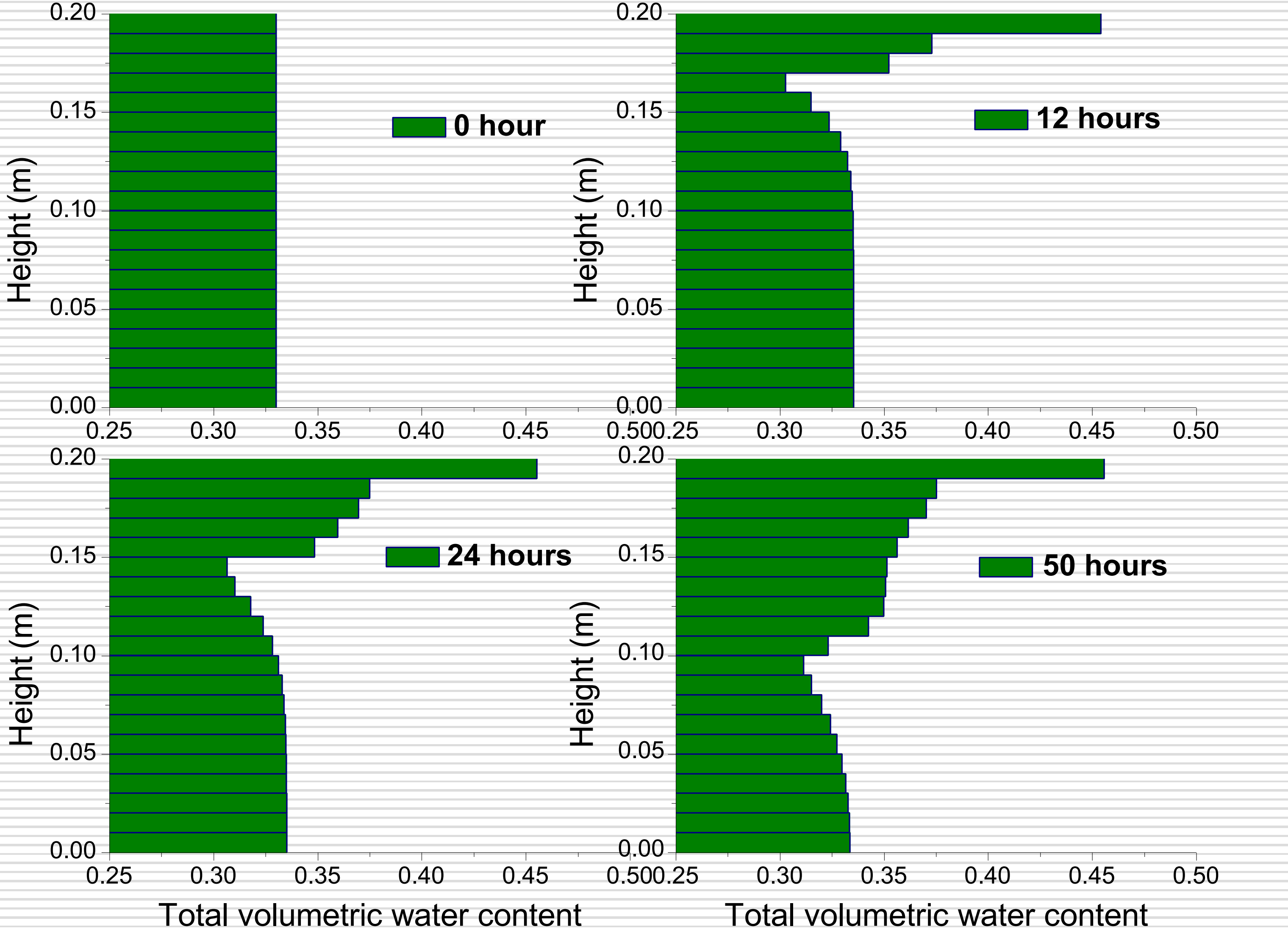
Boundary condition

$$\vec{\mathbf{n}}\cdot(K_{\mathrm{Lh}}\nabla h + K_{\mathrm{Lh}} + K_{\mathrm{LT}}\nabla T) = 0$$

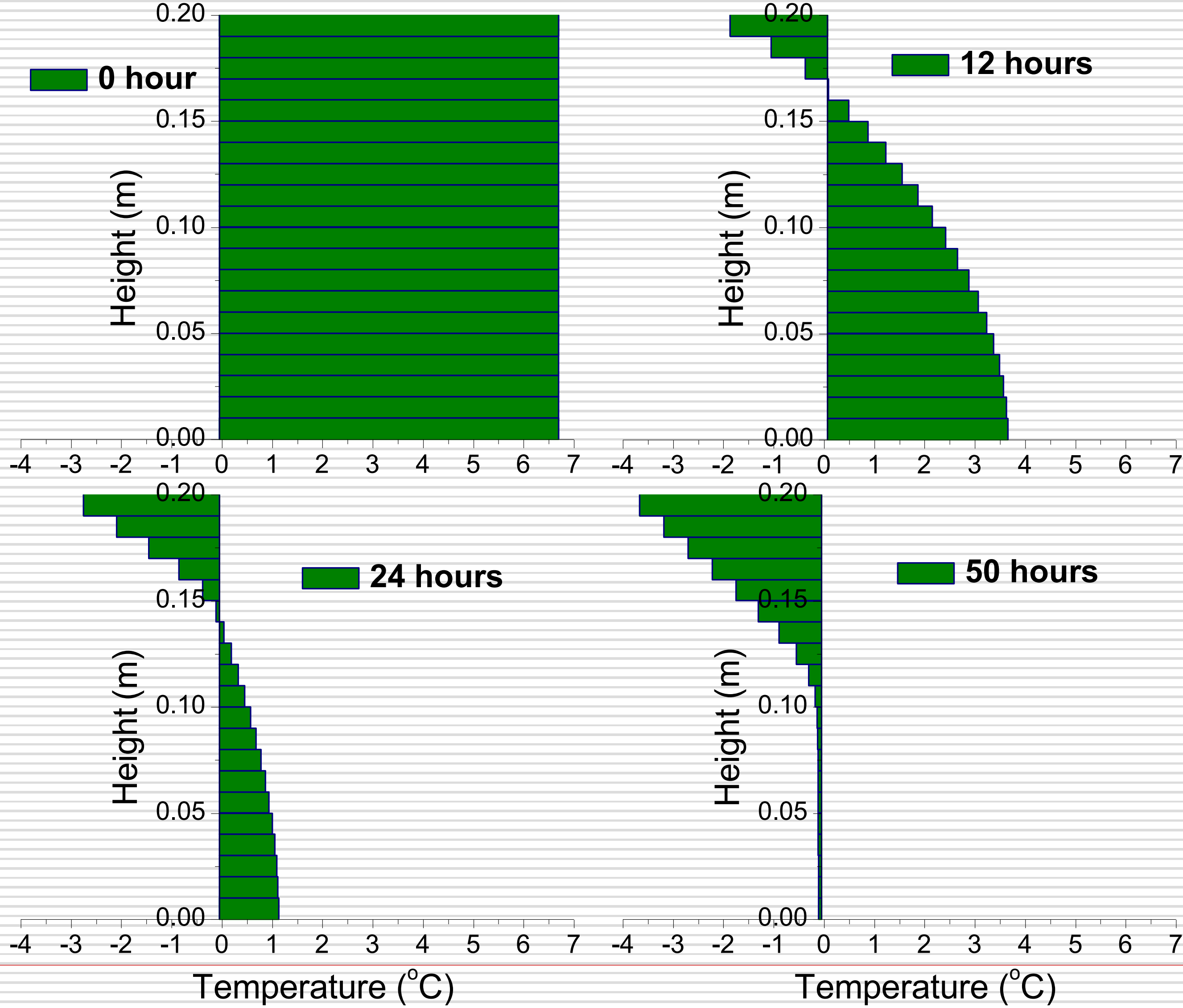
$$\vec{\mathbf{n}}\cdot(\lambda\nabla T) = \mathrm{h_c}(T_{\mathrm{emb}} - T)$$



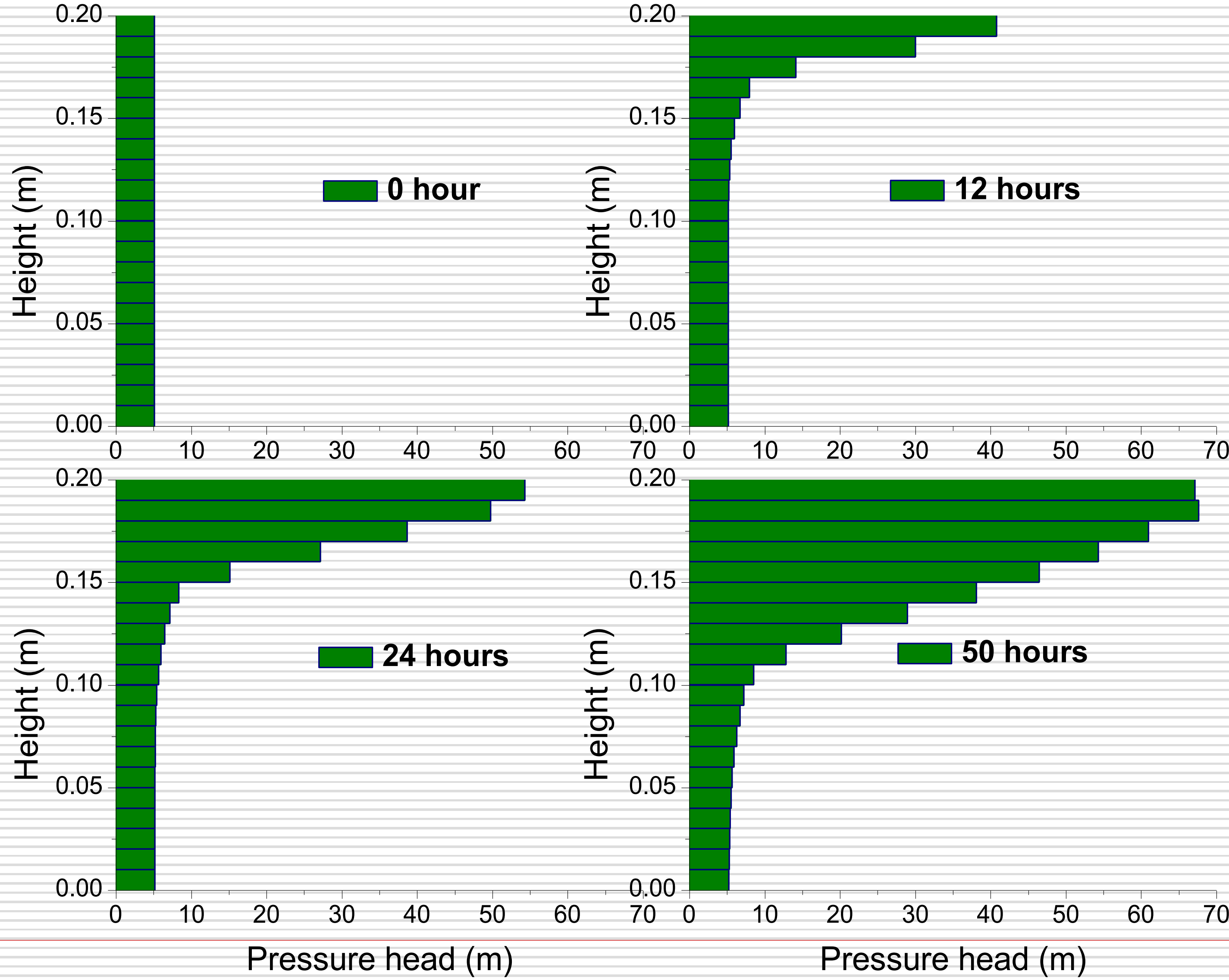
Results: thermally driven moisture migration



Volumetric total water content after 0,12,24,50 hours



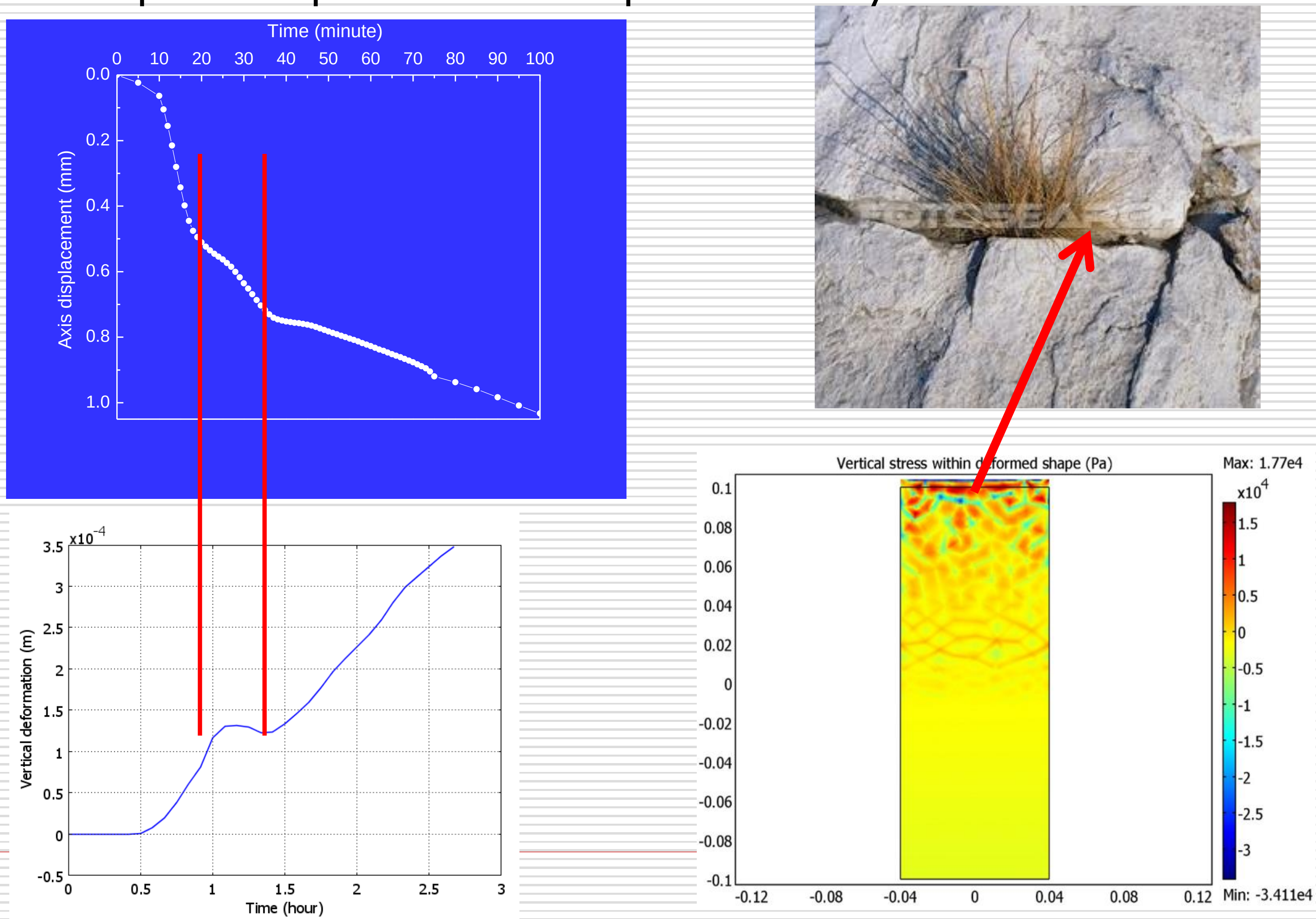
Temperature after 0,12,24,50 hours



Pore pressure head after 0,12,24 50 hours

Soil Freezing: Interesting Phenomena

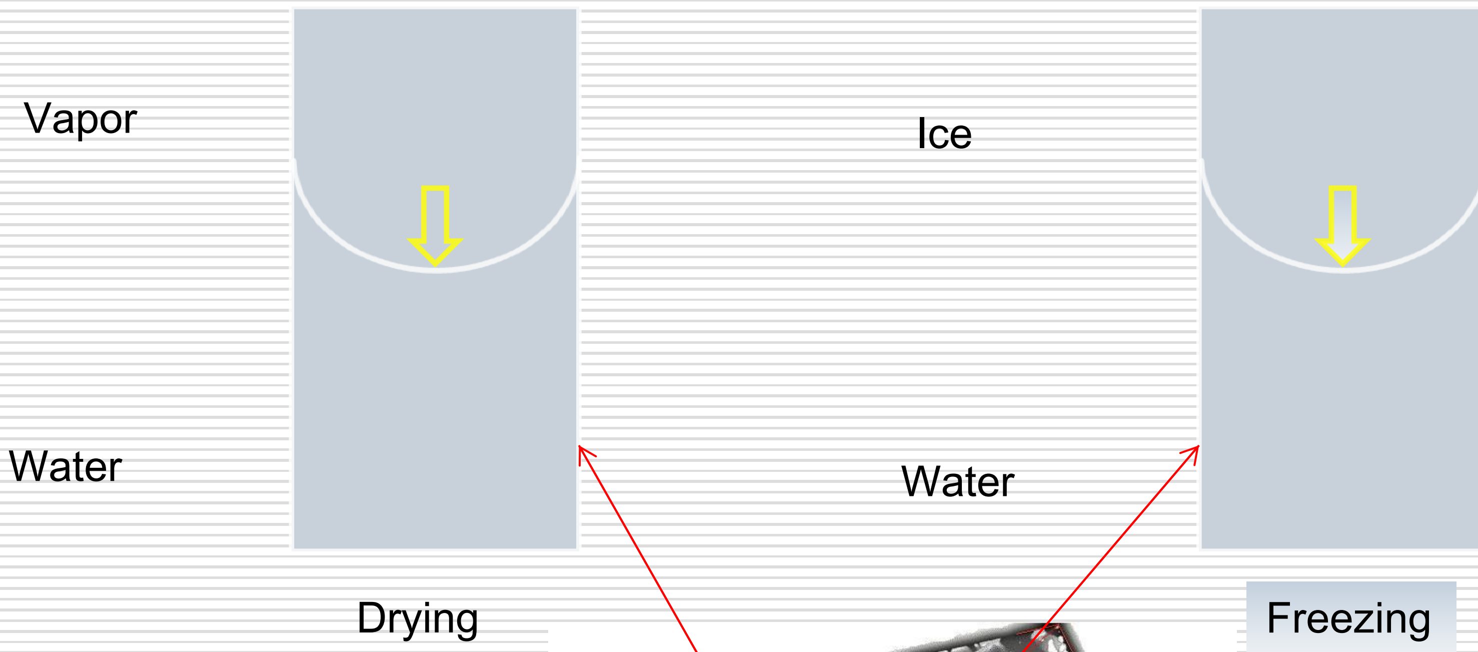
- Two important phenomena reproduced by the simulation.



Vertical deformation VS time

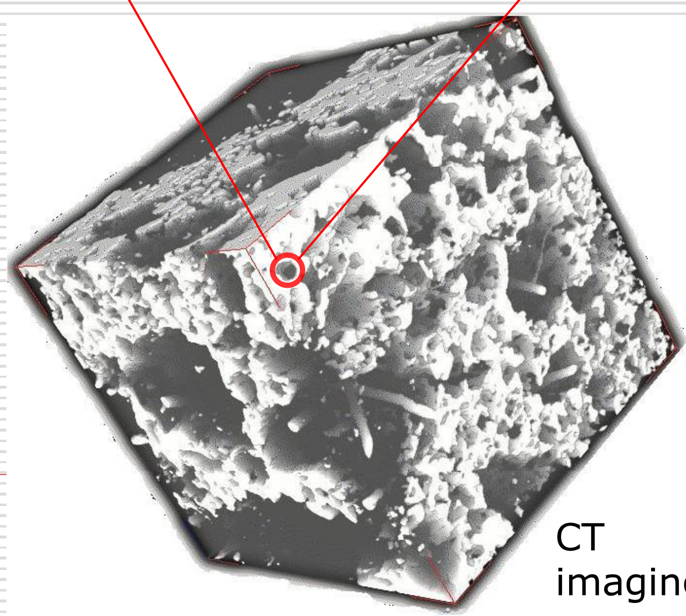
Vertical internal stress

The similarity between freezing and Drying



$$\Delta P_a - \Delta P_w = A \cdot \left(\Delta P_i - \Delta P_w \right)$$

Koopmans (1966) and
Spaans (1996)



CT
imaging

SWCC from Freezing Process?

Water content in drying process

Unfrozen water content in freezing process (measured by TDR)

$$K_a = \left(\frac{c}{v}\right)^2 = \left(\frac{L_a}{L}\right)^2$$

$$\Gamma(\%) = \frac{w_t - w_f}{w_u - w_f} \times 100\%$$

$$w = \frac{1}{b}\left[\frac{\rho_w}{\rho_d}\sqrt{K_a} - a\right]$$

$$\Gamma(\%) = \frac{\sqrt{K_{a,t}} - \sqrt{K_{a,f}}}{\sqrt{K_{a,u}} - \sqrt{K_{a,f}}} \times 100\%$$

Traditional

New method

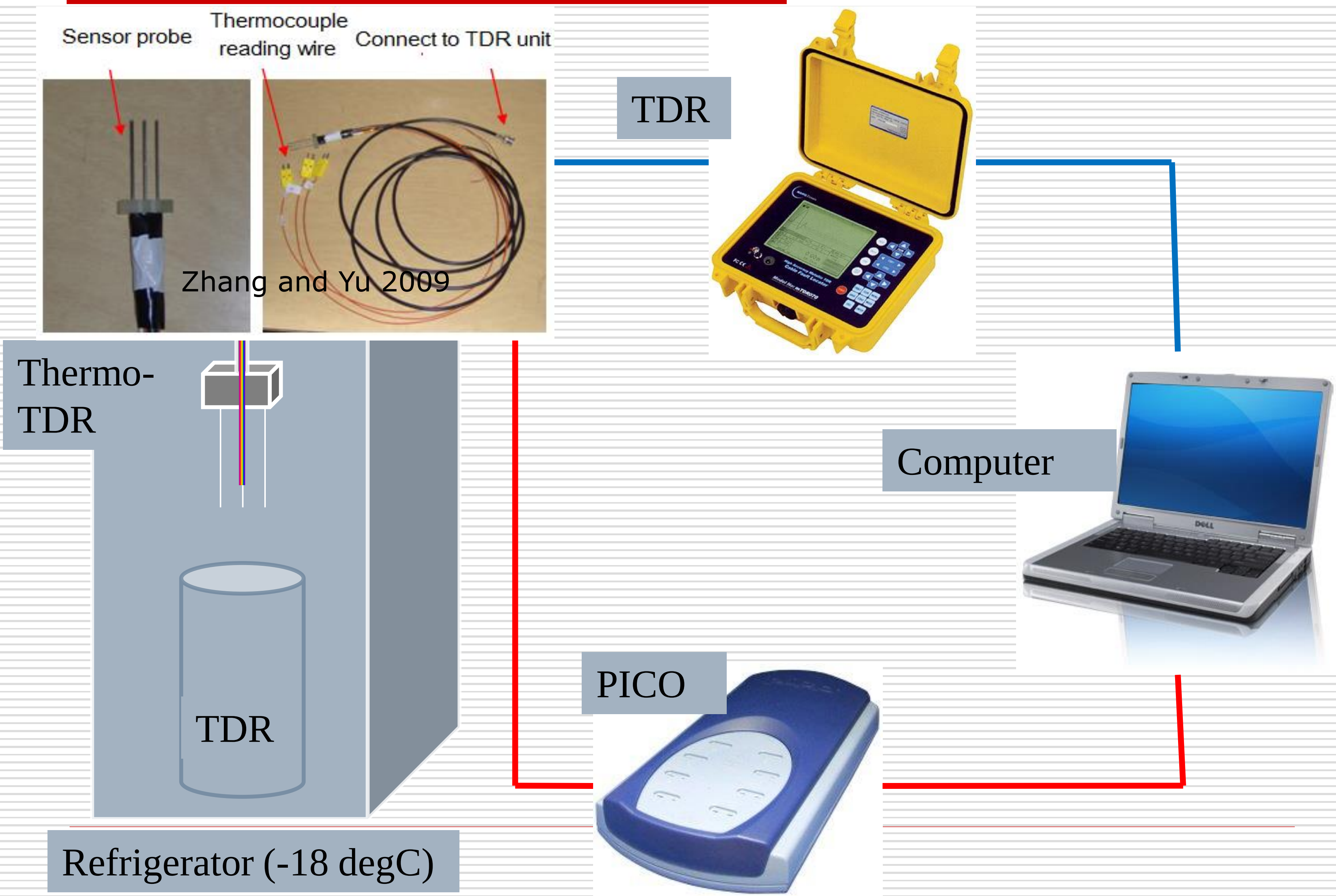
Matric suction in drying process

Temperature in freezing process (measured by thermal couples)

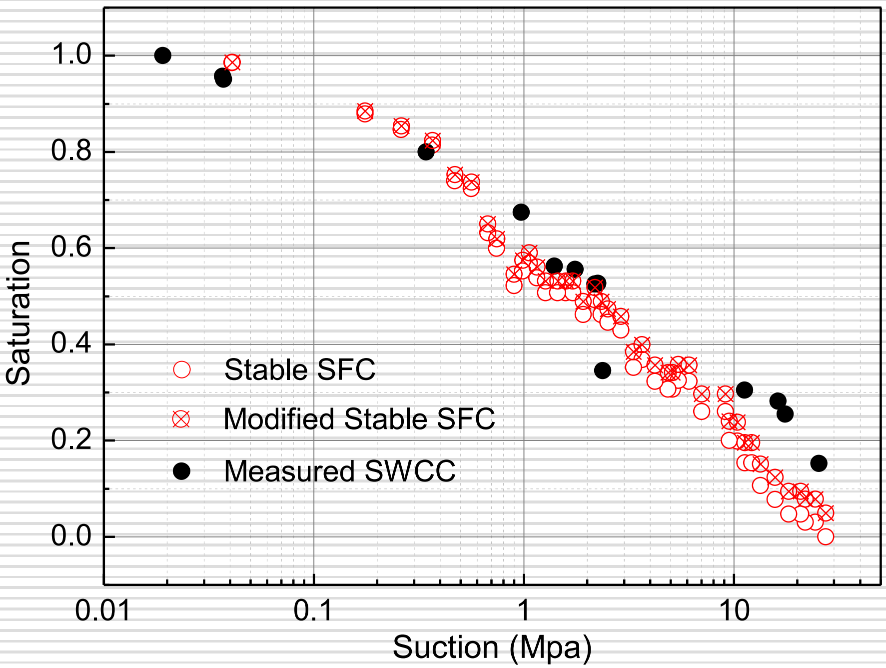
$$\psi = L_f \ln \frac{T}{273.15}$$

Clapeyron equation (Groenevelt, 1974)

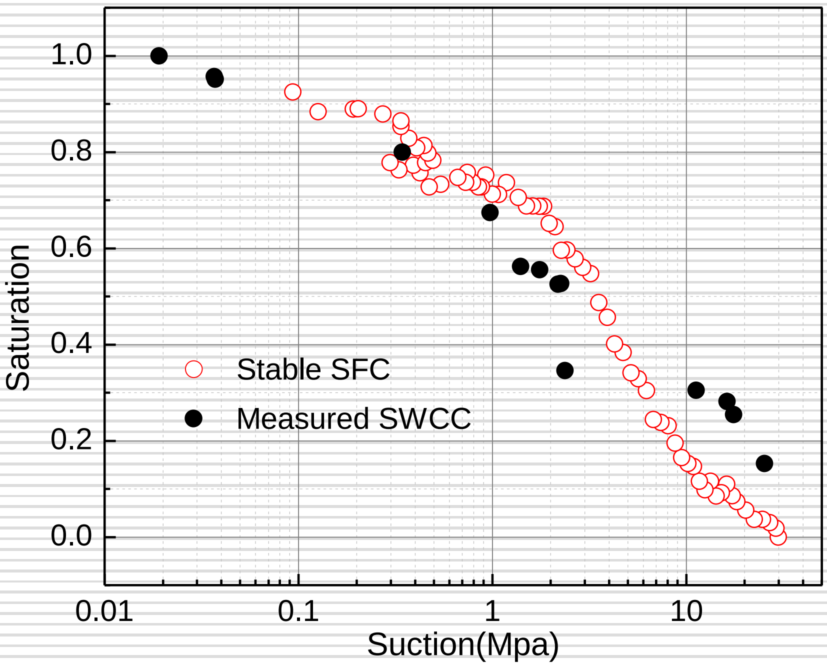
Demonstration



Example Results: 1



(a) Soil # 1, Specimen #1



(b) Soil #1, Specimen #2

Measured SFC by new method and SWCC by traditional filter paper method

Example Results: 2

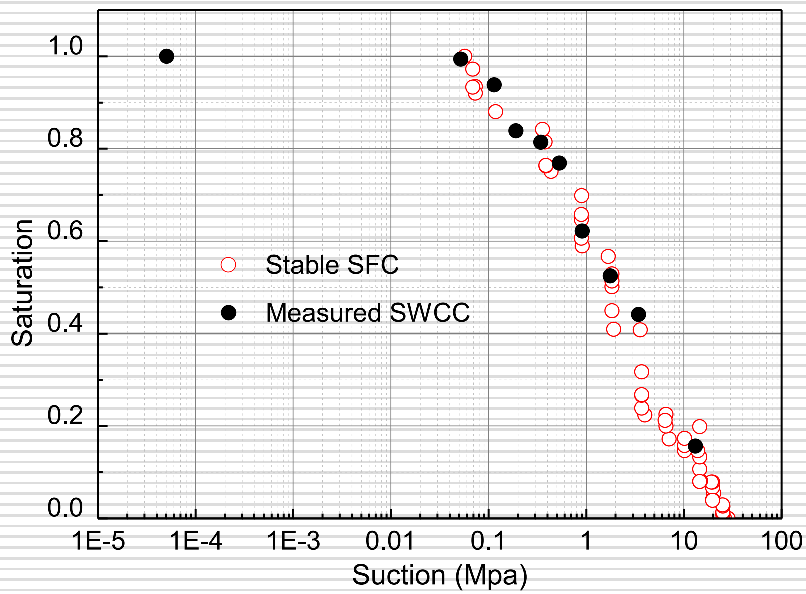
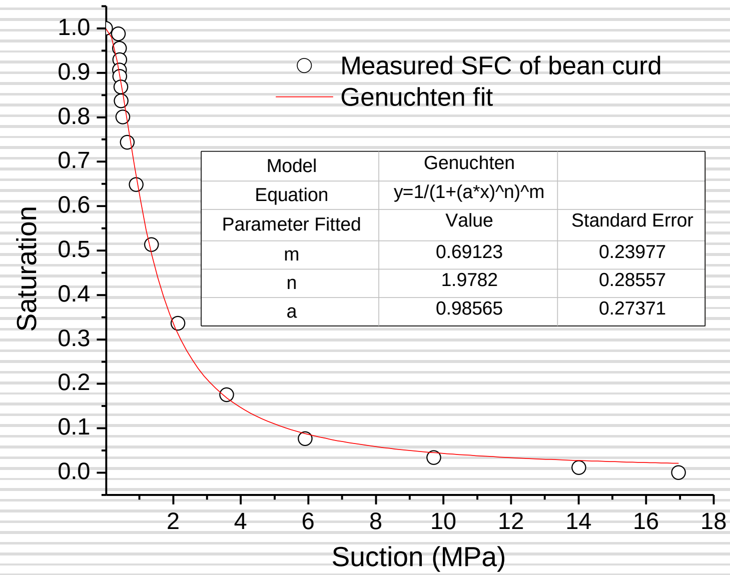


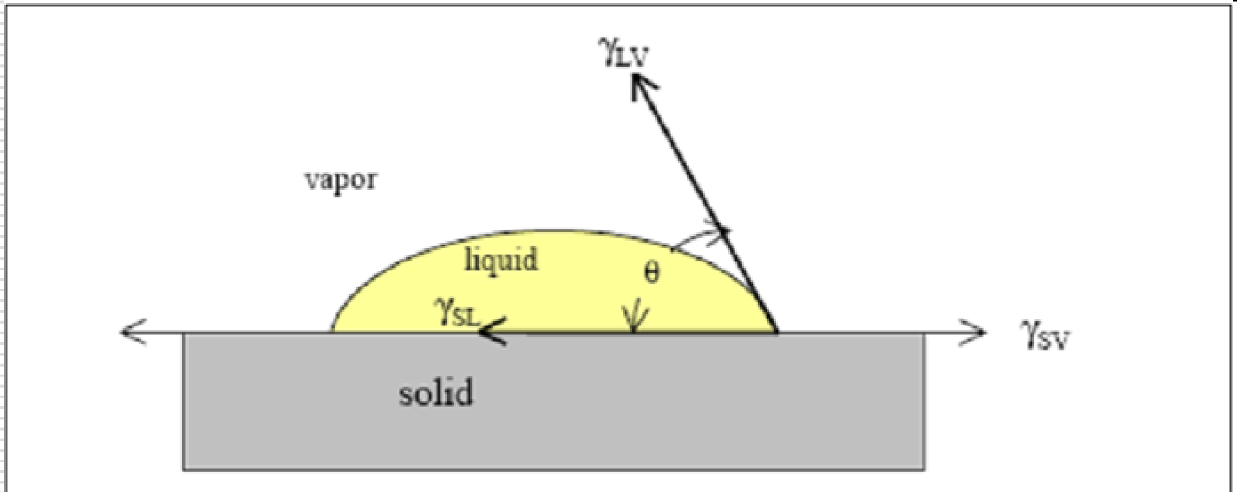
Figure 2 SFC and SWCC of soil #2



SFC of a slab of firm bean curd

Is SWCC the Ultimate Goal?

- Solid, air and liquid interface



$$\gamma_{LV}\cos\theta = \gamma_{SV} - \gamma_{SL} \qquad \text{(Young equation)}$$

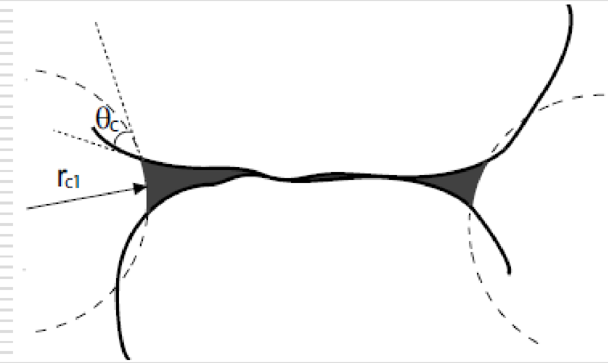
γ_{LV} = liquid-vapor interfacial tension or surface tension

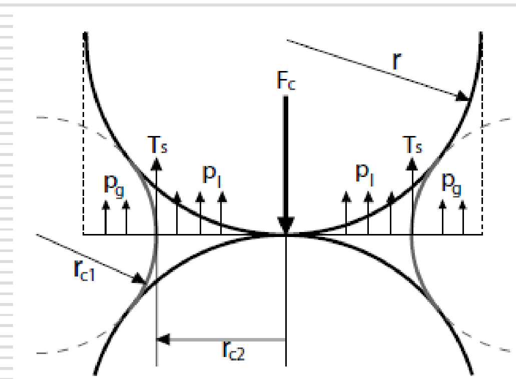
γ_{SV} = solid-vapor interfacial tension, not true surface energy

γ_{SL} = solid-liquid interfacial tension

θ = contact angle (angle liquid makes with solid surface)

Young's equation





$$p_g - p_l = T_s\left(\frac{1}{r_{c1}} + \frac{1}{r_{c2}}\right)$$

Young–Laplace equation

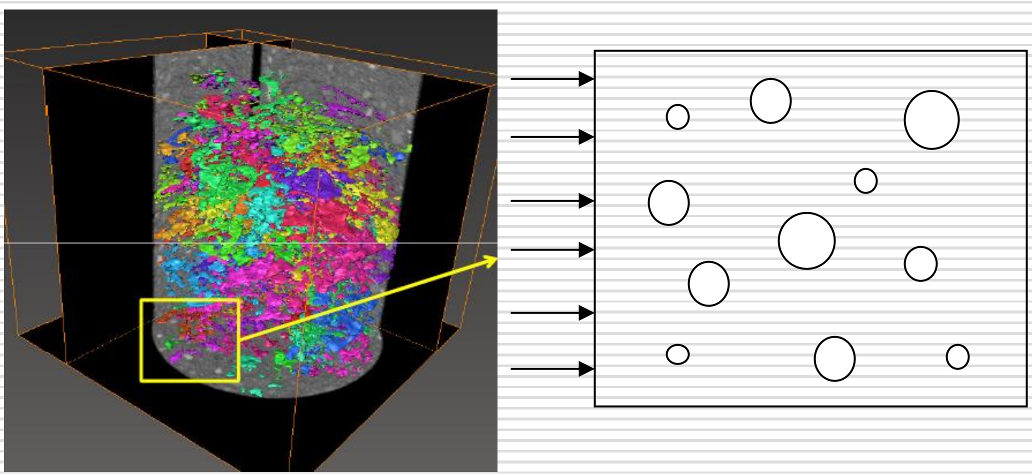
Is SWCC the Ultimate Goal? (cont.)

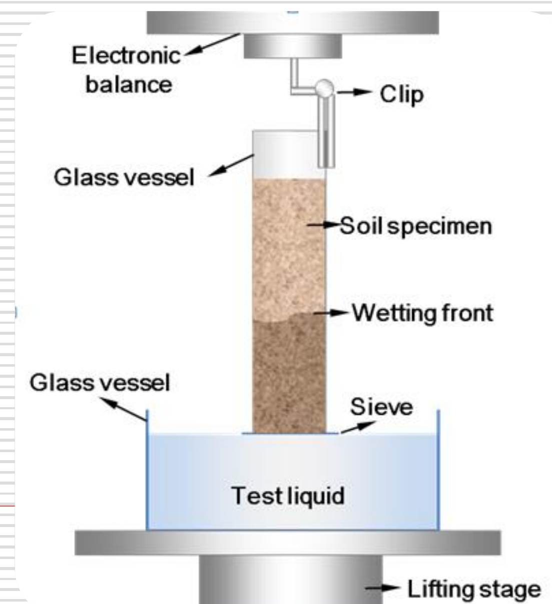
SWCC Key concept of porous geomaterials

Water Characteristic Curve

Pore-size Distribution
CT, ultrasonics

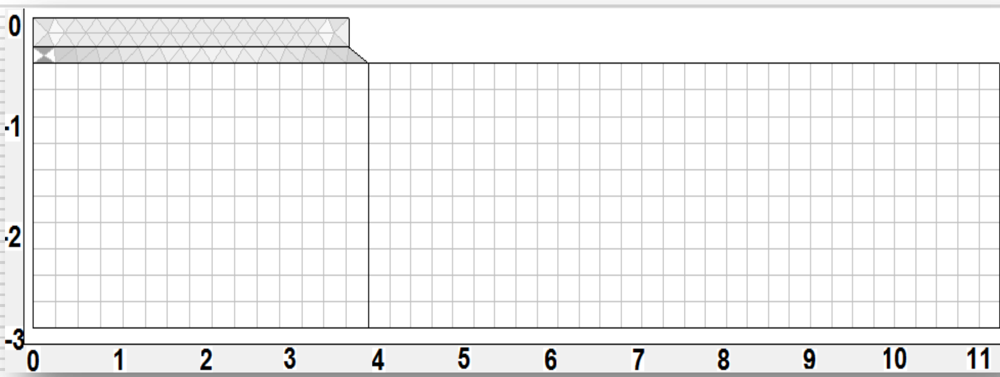
Contact Angle
Tensiometer

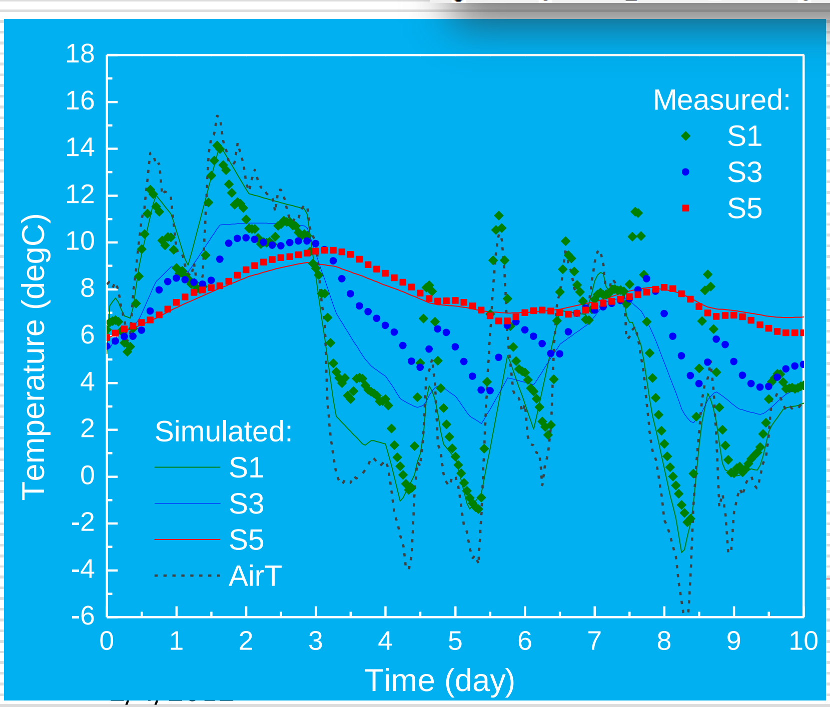


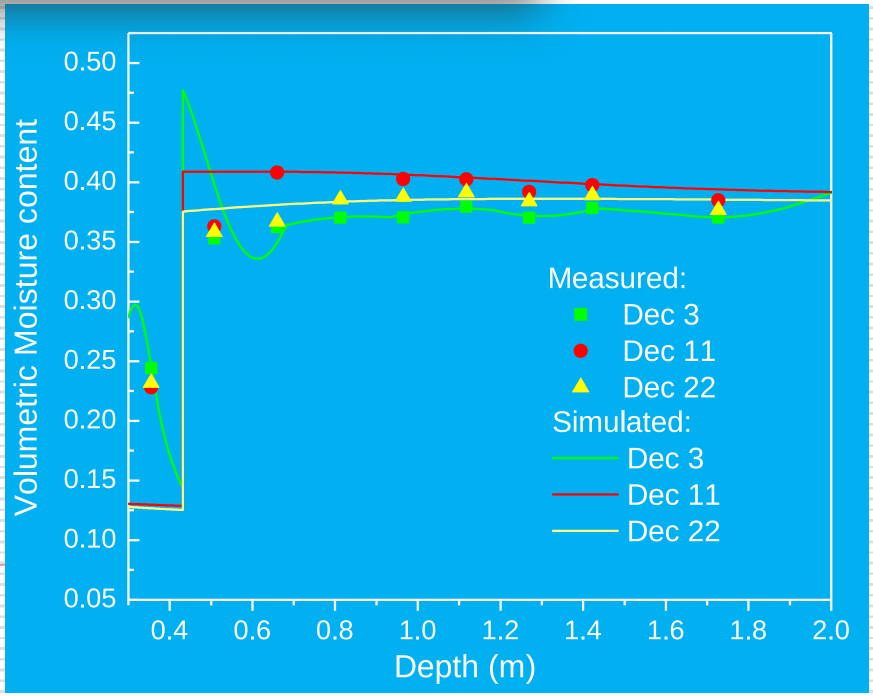


Application: Holistic Simulation of Climate Effects on Pavement

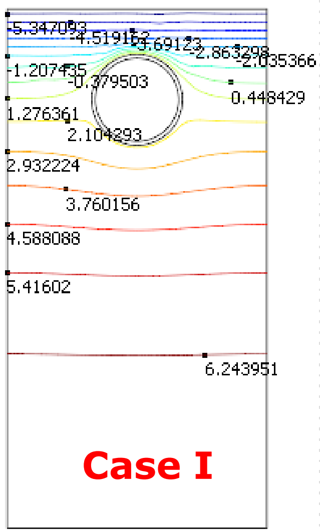
Ohio Instrumented Road: air temperature, precipitation; initial and final temperature, material properties of different layers; monitored temperature and water content by sensors

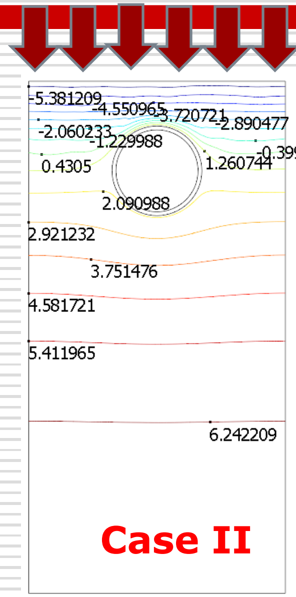


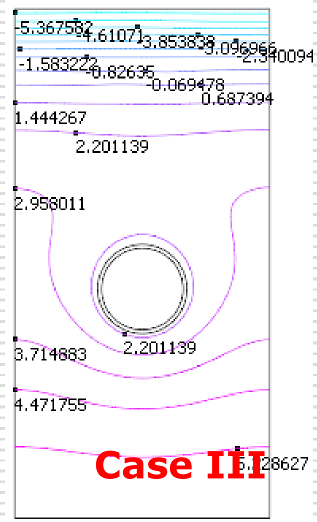


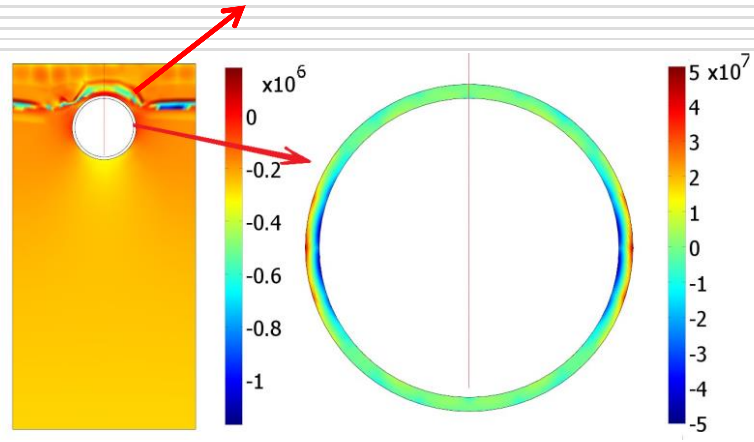


Application: Frost Effects on Pipe Fracture



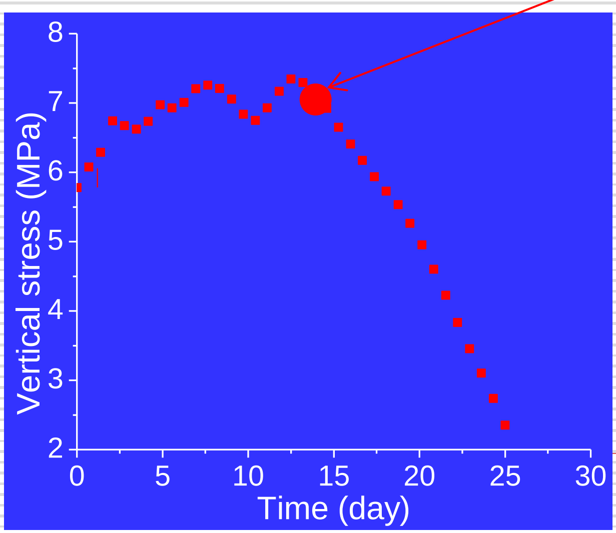




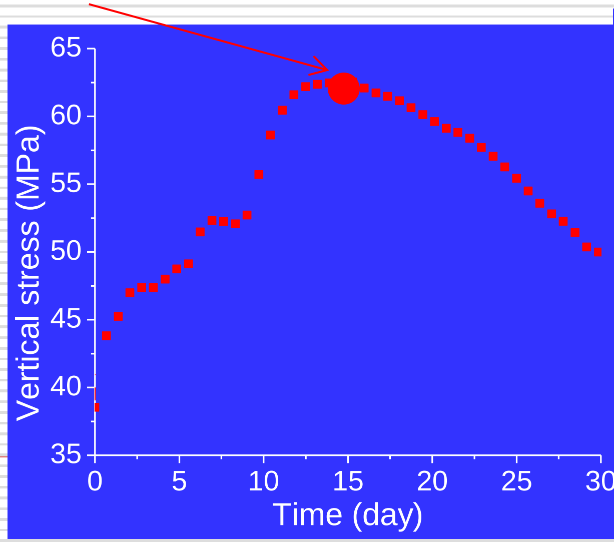


Max vertical stress VS time

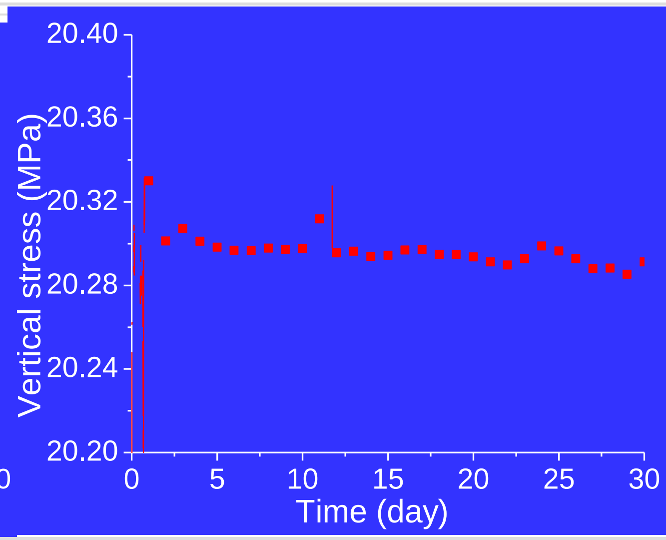
Frost front reach the crown of the pipe



Case I

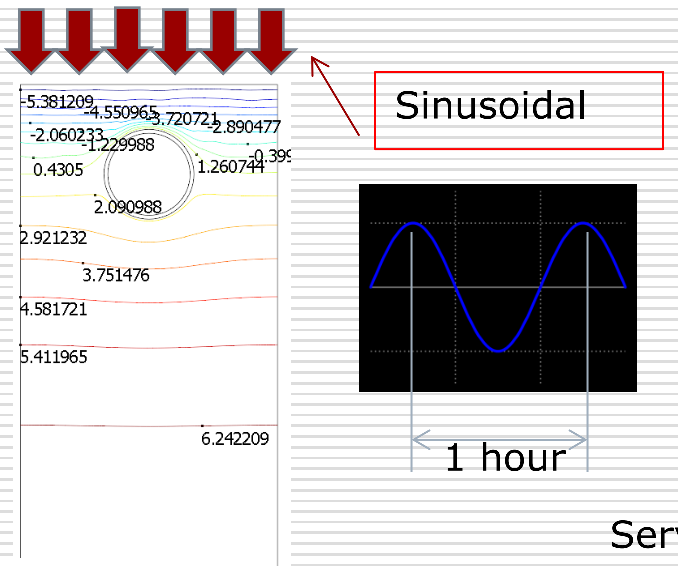


Case II

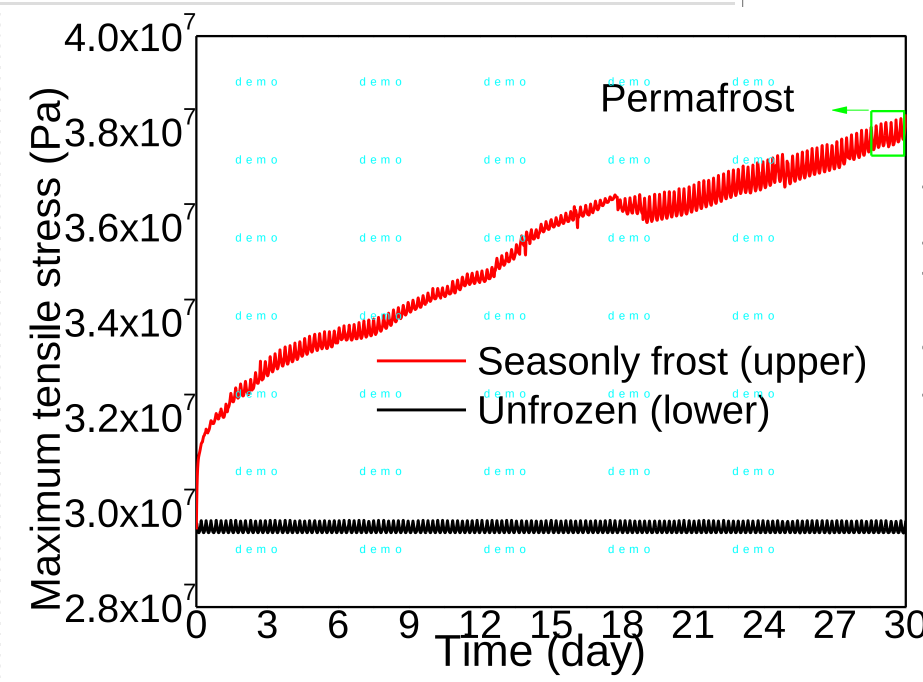


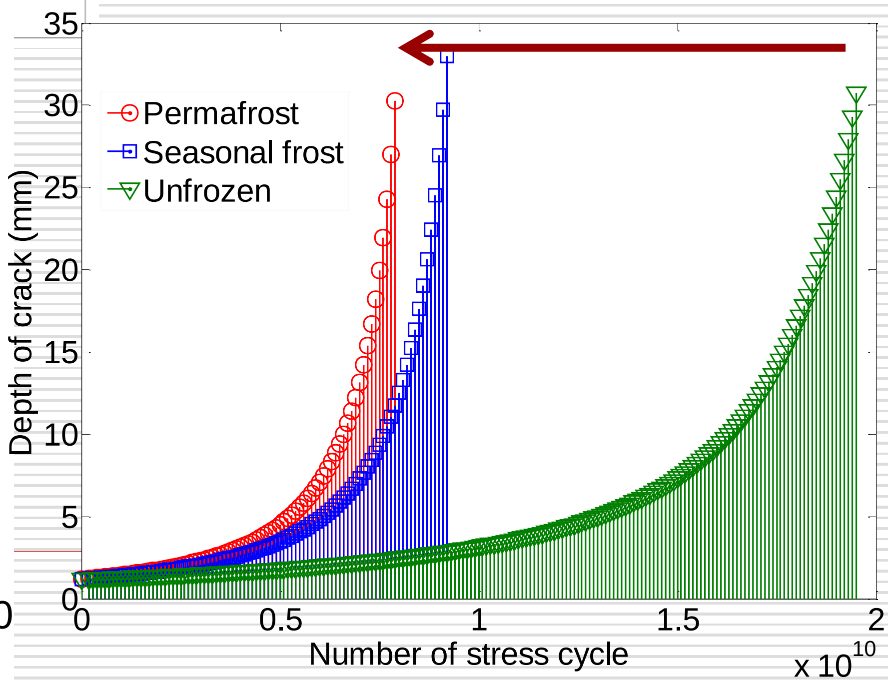
Case III

(cont.)



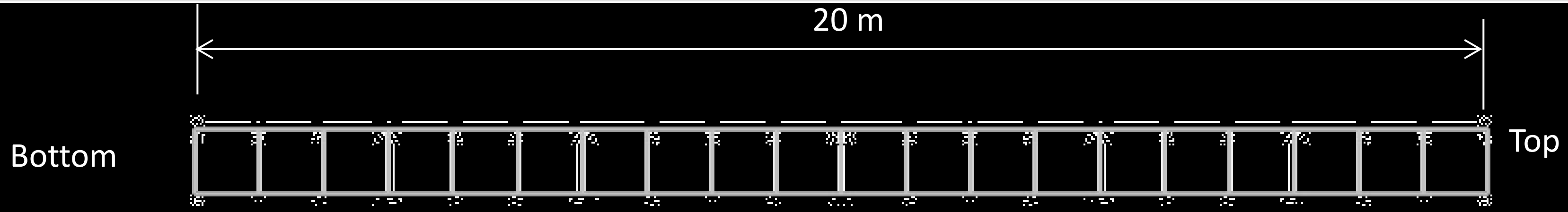
Service life decreases

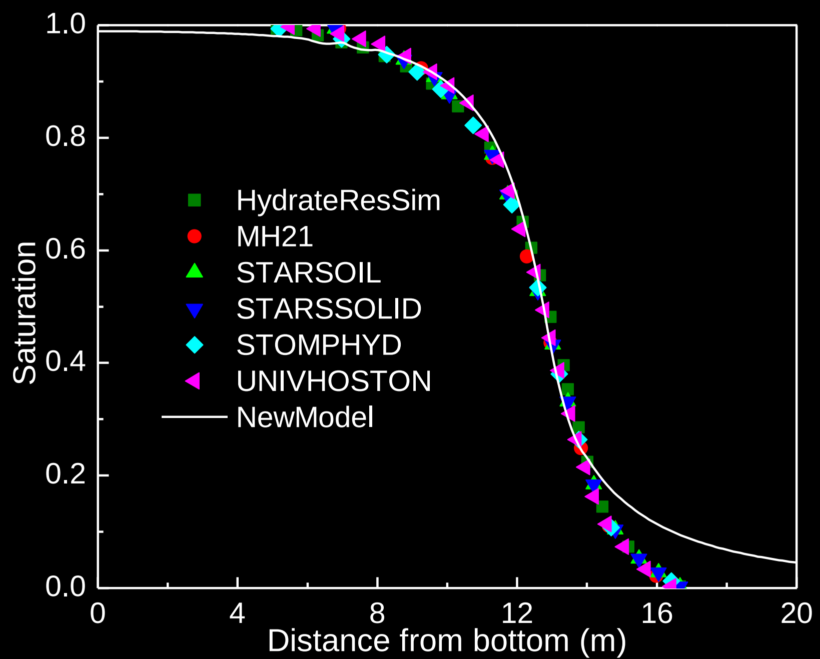




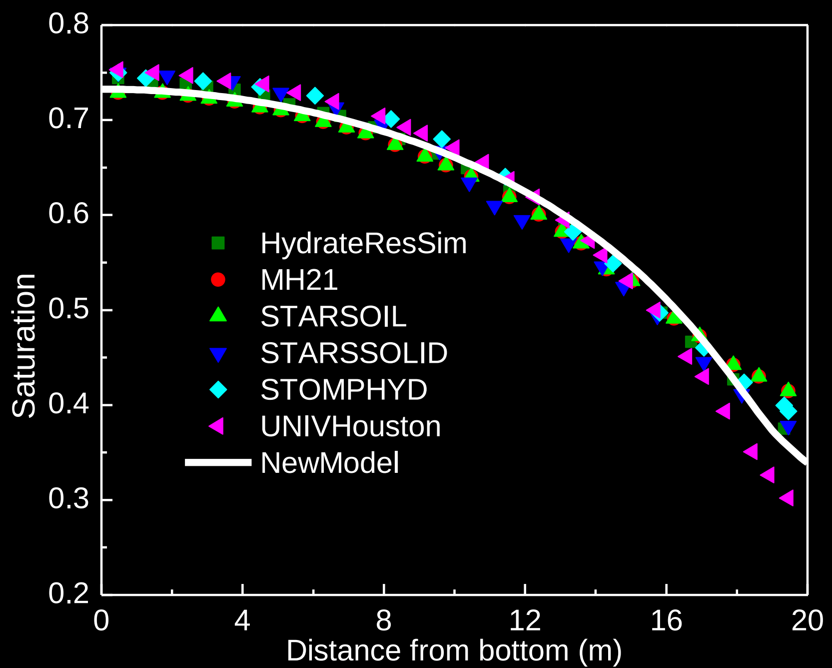
Application: Methane Hydrate Exploration and Geohazards

NETL Gas Hydrate Simulation Comparison Program: Problem 1

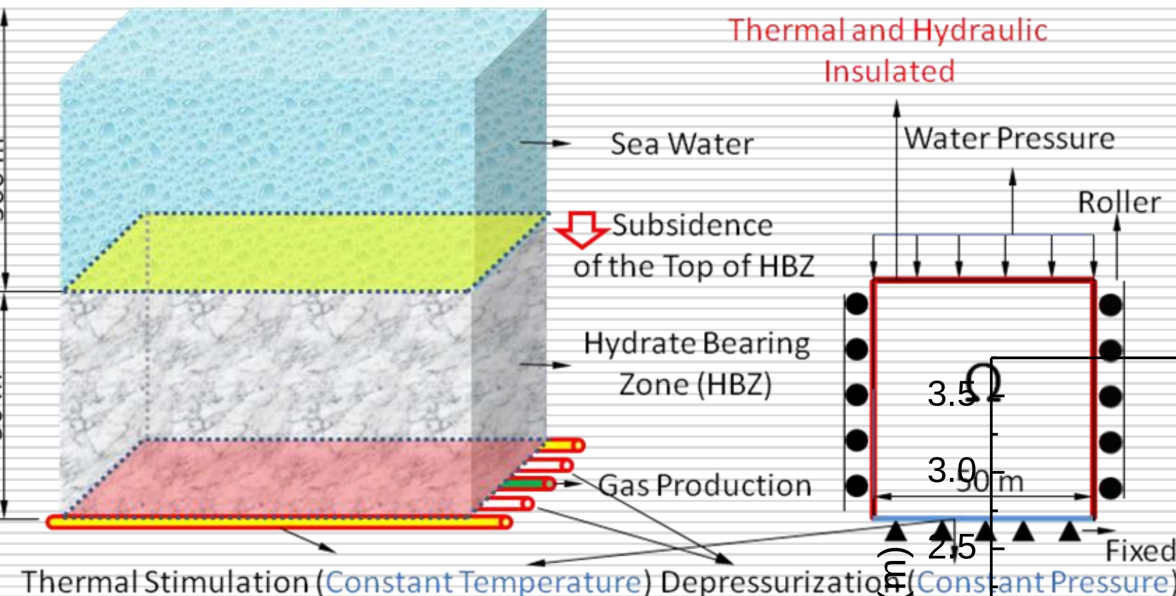


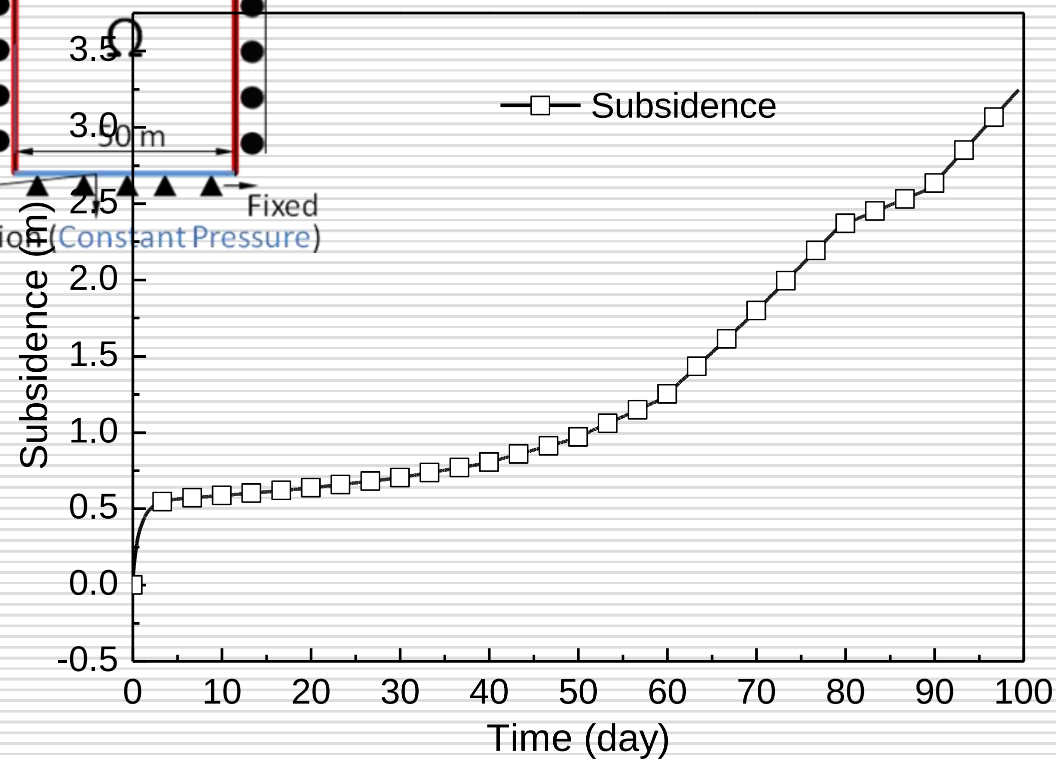


1 Day



100 Day





Liu and Yu 2012

Summary

- Multiphysics process in soils
  - An emerging frontier in soil mechanics
  - A “unified” theory might be possible
  - Improving engineering design could result from understanding and simulating the fundamentals
  - We are continuing to explore into the fundamentals as well as many exciting applications

It is a team effort

Acknowledgements

- Funding Agencies

  National Science Foundation, The Ohio Department of Transportation/FHWA, TRB, Minnesota Department of Transportation, Cleveland Water Department, Industry sponsors (GRL/PDI, WPC Inc., Durham Geo Enterprises, MWH Inc., DLZ Ohio Inc., etc)

- Graduate Students

  Past: Xinbao Yu (UT Arlington), Bin Zhang (Mike Baker), Yan Liu (GRL)

  Current: Zhen Liu, Junliang Tao, Ye Sun, Chih-Chien Kung, Guangxi Wu, Jianying Hu, Quan Gao

- Undergraduate Researchers

  Pete Simko, John Holman, Yuan Gao, Andrew Bittleman, Pete Simko, Cassandra McFadden, Paul Mangola, Jingsi Lang, Donald Cartwright, Alex Potter-weight, Randall Beck, Vanessa Penner,Peter Frank, Ben Ma, Rebecca Ciciretti, Joseph Brenner, Javanni Gonzalez, Vanessa Penner, Grant Mott, et al.)

- Department engineer Jim Berrila

Thank you