Simulation of the Mechanical Properties of Snow and Mud Using Uintah

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Outline

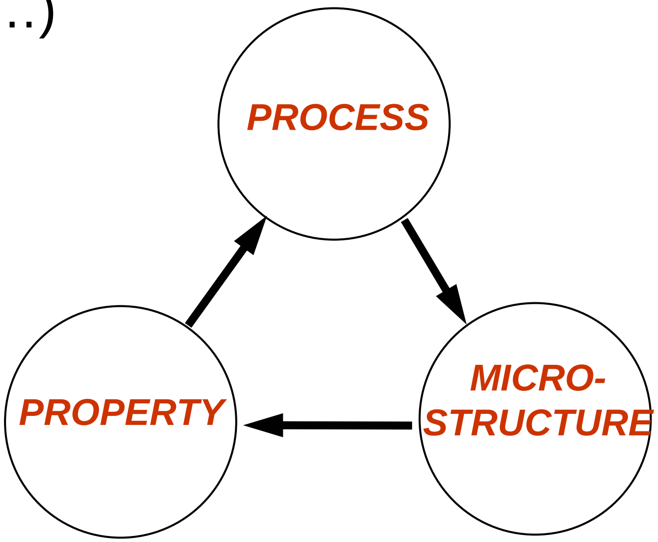
- Application and Motivation
- Mud
- Snow
- Future Work

Application: Vehicle-Snow / Mud Interaction

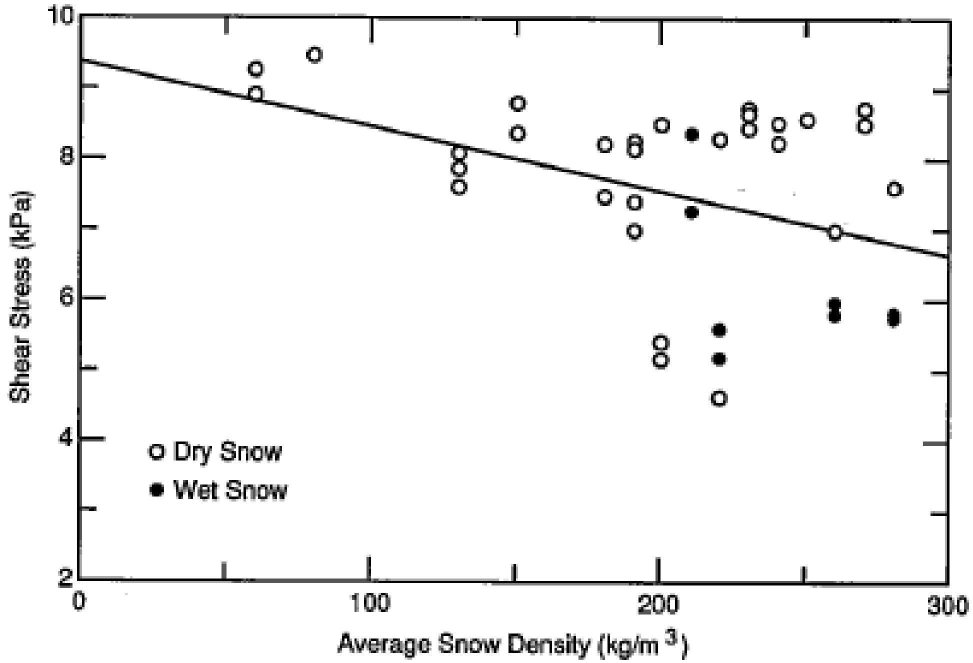
Source: Dr. Sally Shoop, CRREL

Motivation
Large Uncertainties in Material Properties of Soft Terrains

- Environmental conditions dictate terrain composition (e.g., snow metamorphism – a sintering *process*).
- Process determines *microstructure*
- Microstructure determines *properties*
  - Mechanical (elasticity, viscoplasticity, damage, fracture…)
  - Physical (thermal conductivity, permeability, dielectric constant…)



Example: Large Uncertainties in Snow Properties

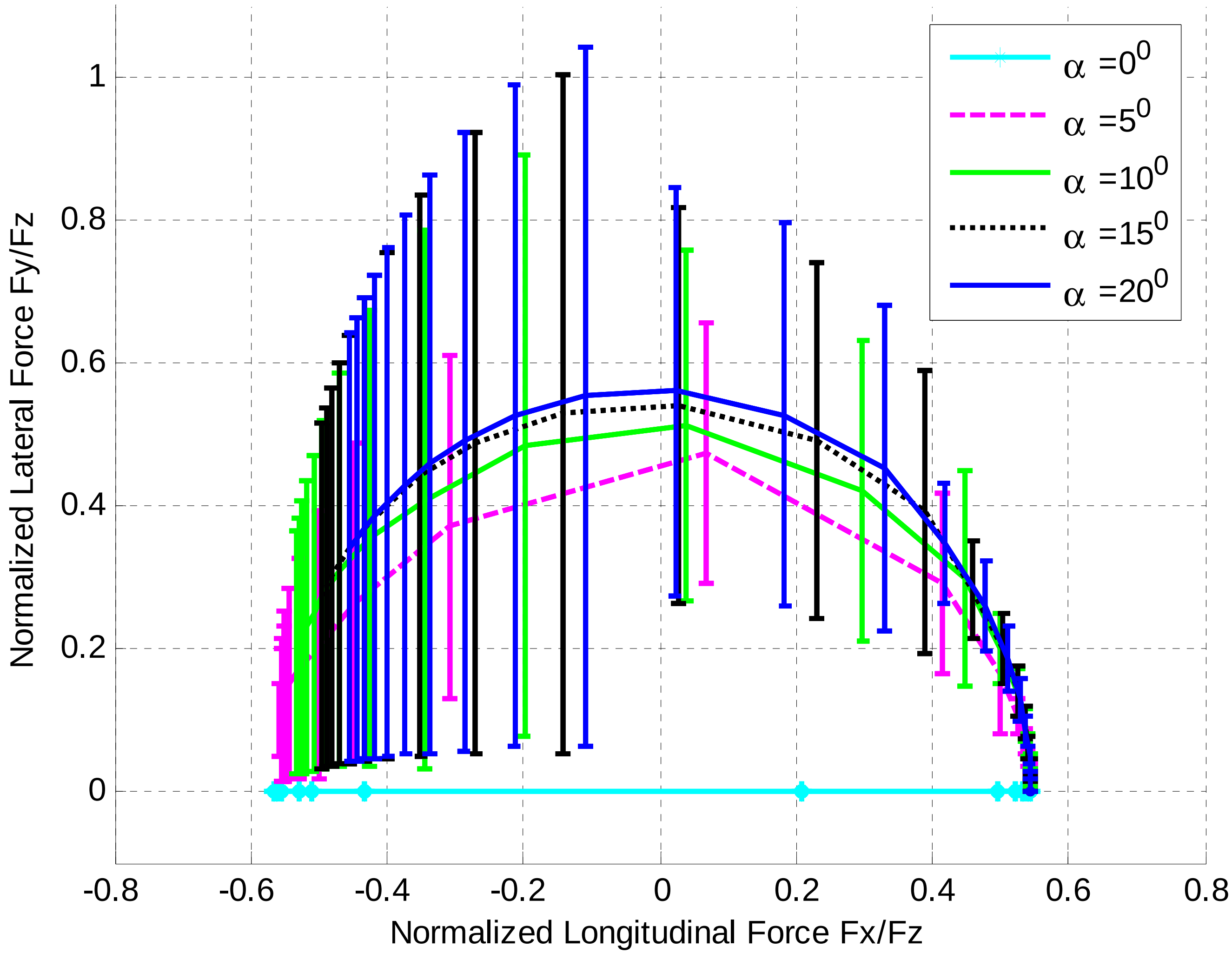


e. σ = 35.16 kPa.

Figure 6 (cont'd). Shear stress versus initial snow density for various normal loads (shear annulus).

Source: CRREL CR90-9

Example: Large Uncertainties in Tire-Snow Interaction Interfacial Forces (Li et al., 2009)



Scientific Question

How does one address the large uncertainties in the mechanical properties of soft terrains?

1. **Study the microstructure of materials**
2. **Study micro-scale properties of materials as a function of microstructure**

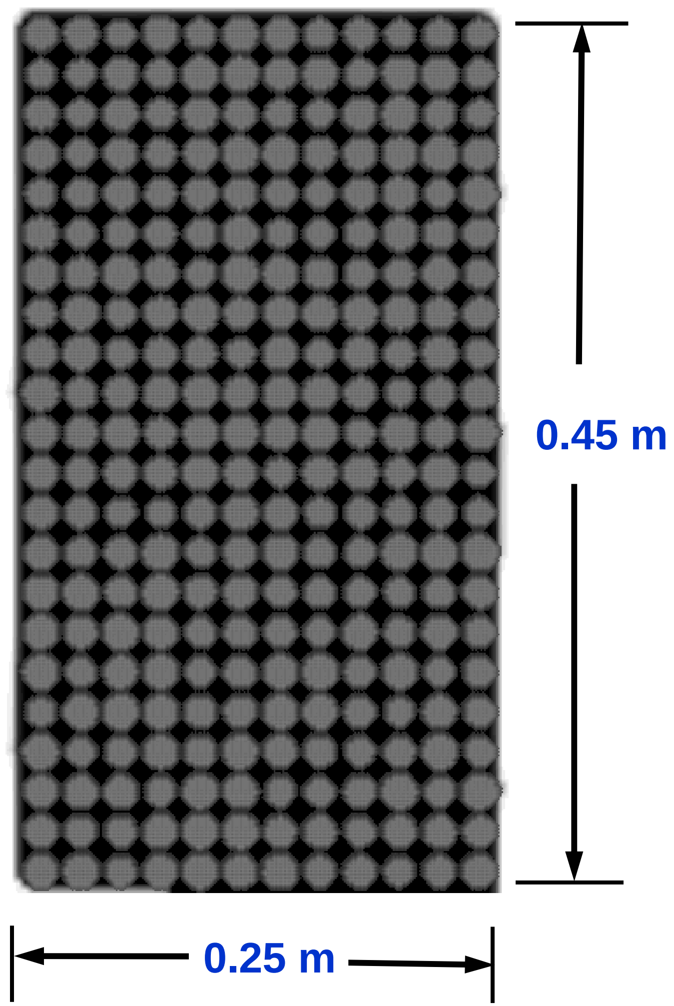
The ‘Big’ Picture

- Multiscale stochastic studies
  - Link micro-, meso- and macroscale properties
  - Link multiscale material properties to multiscale terrain topologies
  - Incorporate results into vehicle design with uncertainties
- Key technical fields
  - Stochastic geometry
  - Stochastic mechanics
  - Reliability

Why Study Mud (Saturated Soil)?

- Tire companies group snow and mud together
- Provides a baseline for
  - Unsaturated soils
  - Frozen and thawed soils

Domain of Saturated Soil
(void ratio = 0.338; depth = 0.012 m)



Modeling of Saturated Soil as a Fluid-Structure Interaction Problem – Uintah Explicit

- Soil grains modeled as circular cylinders packed in a regular array
- Radius of each grain varies randomly in [0.75 radius, radius] (radius=1 mm)
- Each soil grain is discretized into material points
- Soil grain is modeled as an elastic material
- Gaps between the soil grains are filled with interstitial water, also discretized into material points
- Plane strain deformation

Constitutive Equations for Nearly Incompressible Water

$$\sigma_{ij} = -p\delta_{ij} + 2\mu d'_{ij}$$

d'_{ij} = rate of deformation tensor

$$p = k\left[\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right]$$

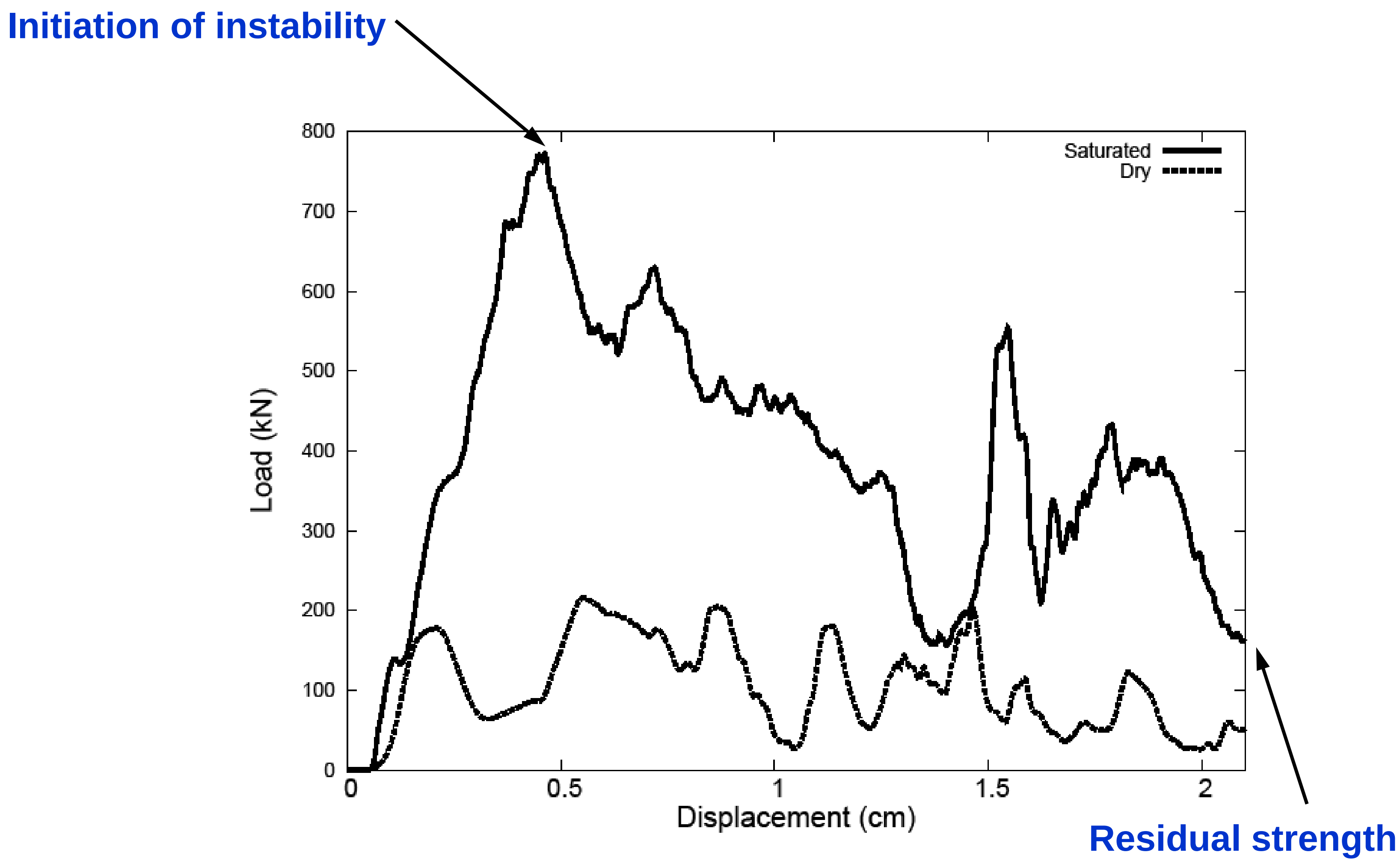
ρ_0, ρ = initial and final density

k, γ = material constants

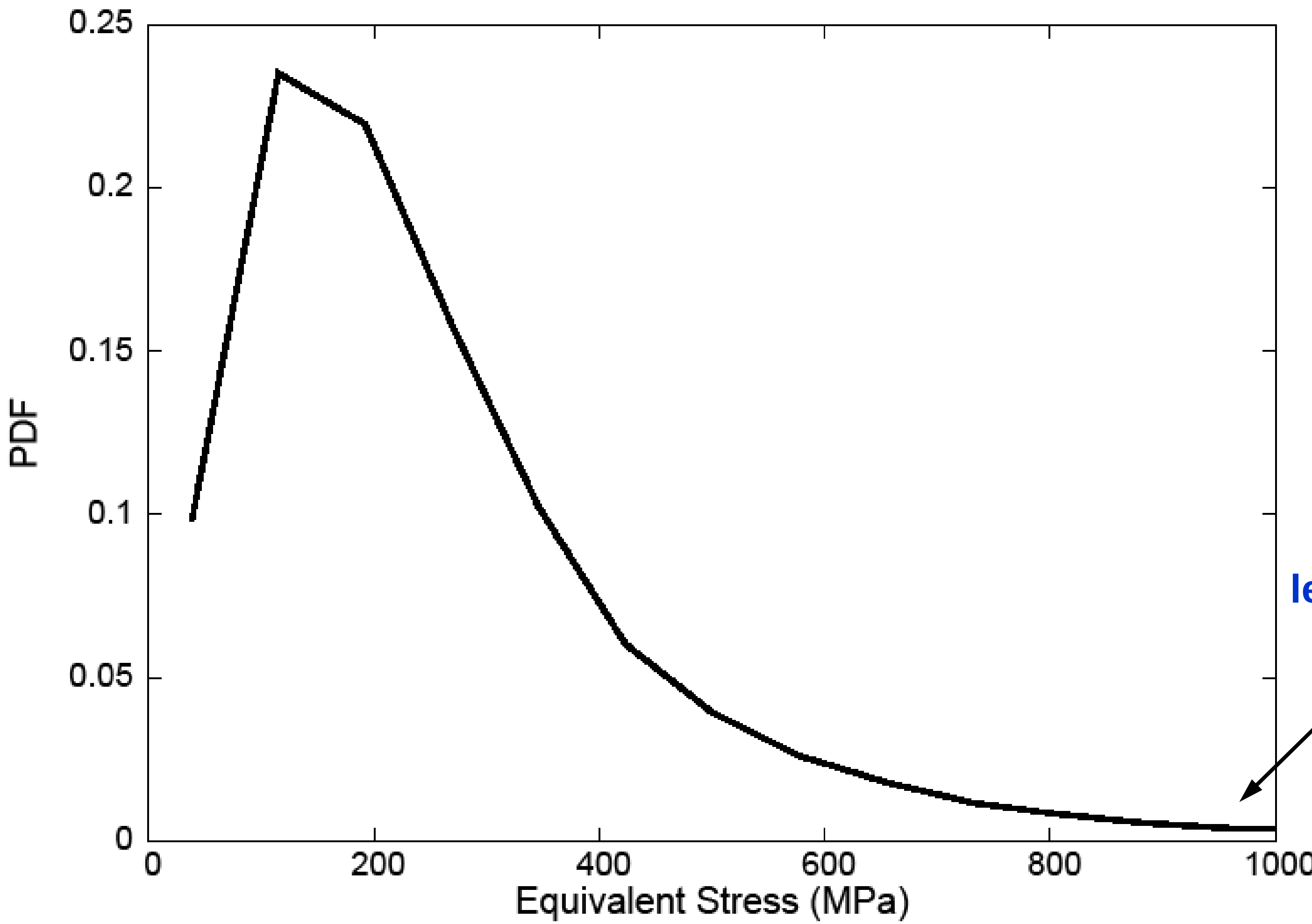
Material Properties

Solid:		
	Density	2,000 [kg/m^3]
	Bulk modulus	39.585 [GPa]
	Shear modulus	18.27 [GPa]
	Friction coefficient	0.5
Water:		
	Density	1,000 [kg/m^3]
	μ	0.001 [Pa-sec]
	γ	7
	k	2.2 [GPa]

Load-Displacement Curves of Saturated and Dry Soils under Unconfined Compression – 6.18 m/s

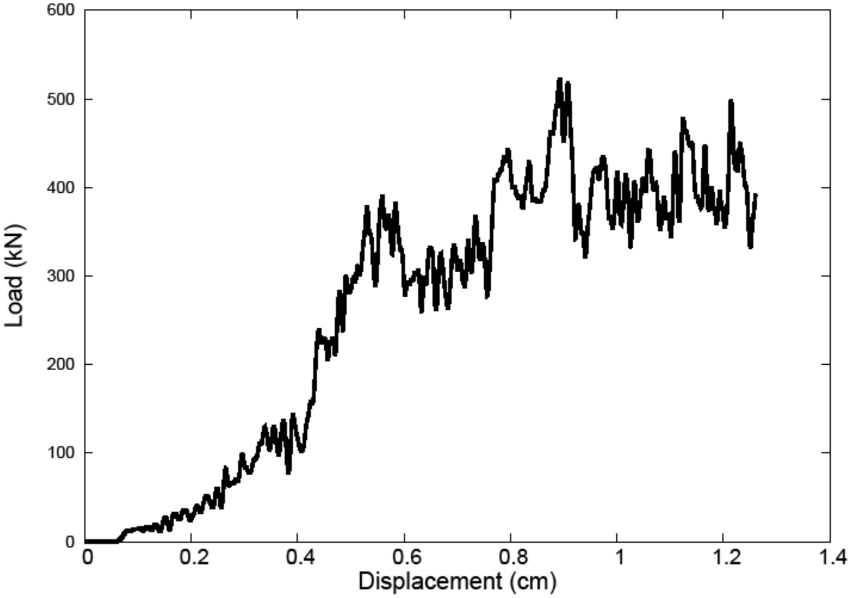


PDF of Equivalent Stress Near Peak Stress

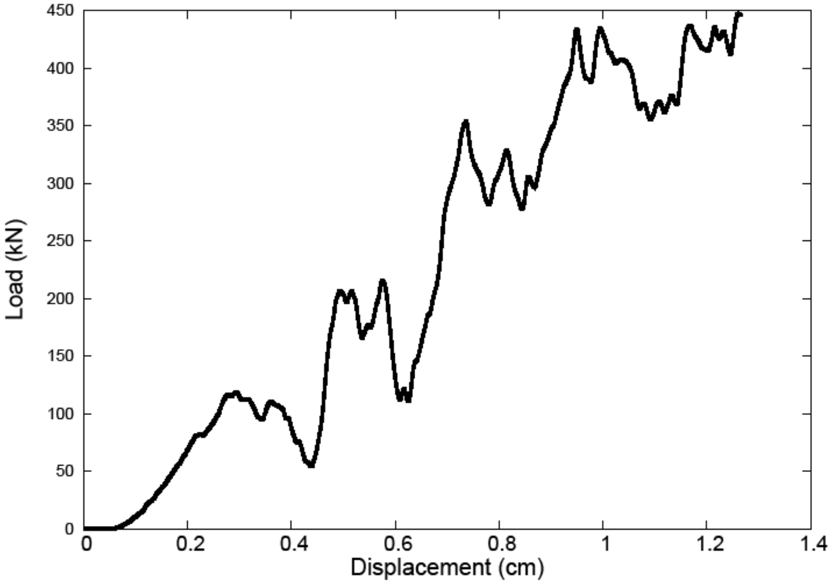


High stress will lead to fracture of soil grains

Load-Displacement Curves of Indentation Tests
Indenter Width 3.125 cm



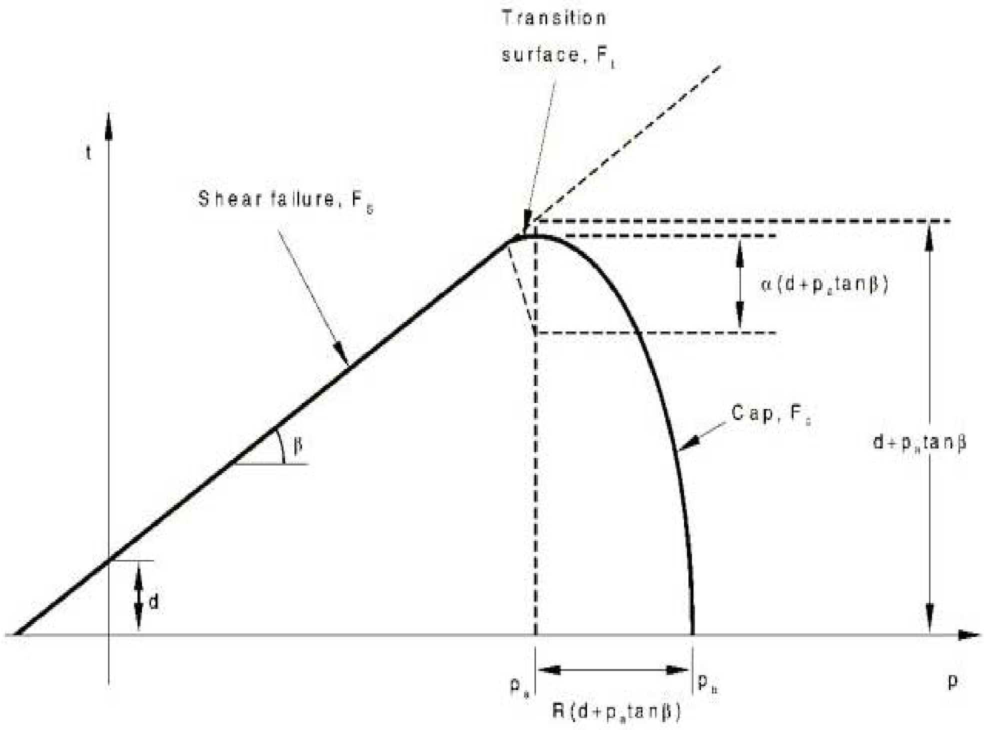
Saturated



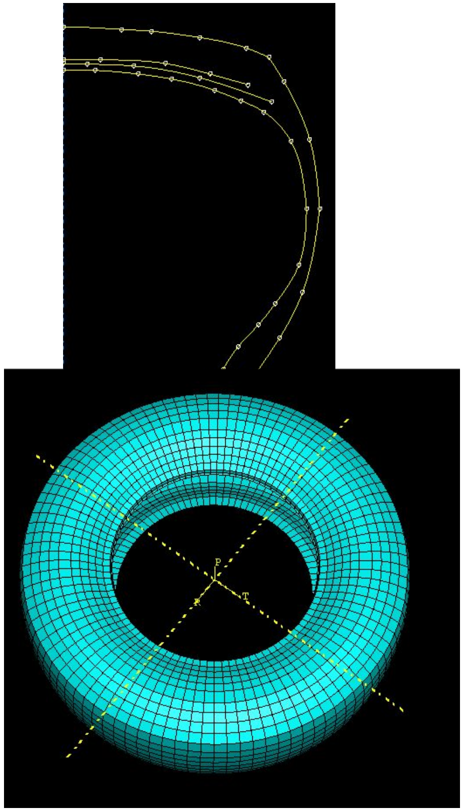
Dry

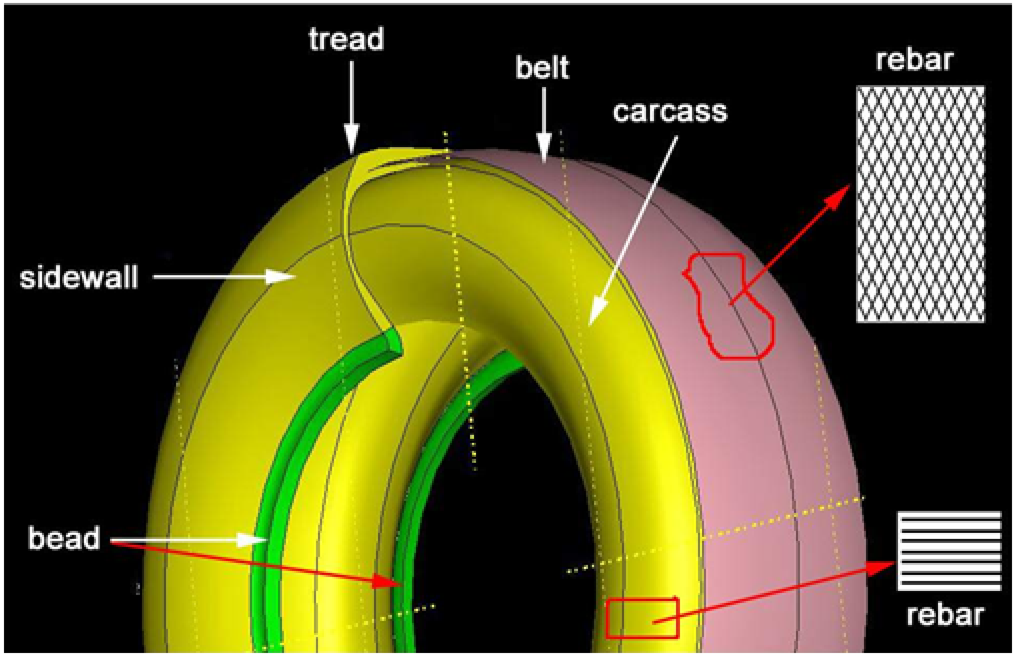
Deterministic Macro-Scale Snow Model

- Drucker-Prager Cap Model (After Shoop, 2001) for Fresh (Low-Density) Snow

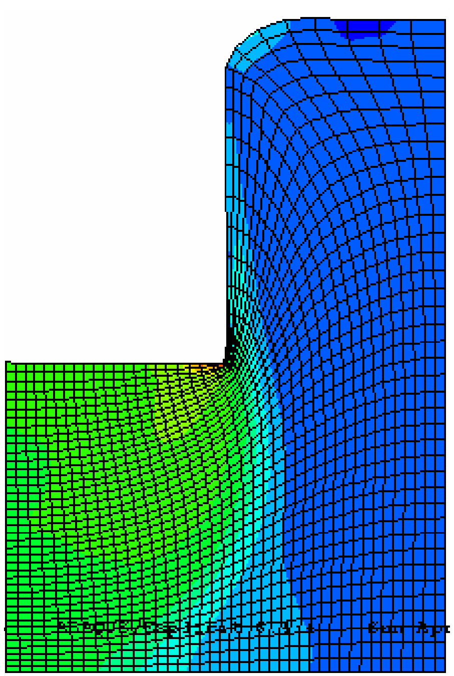


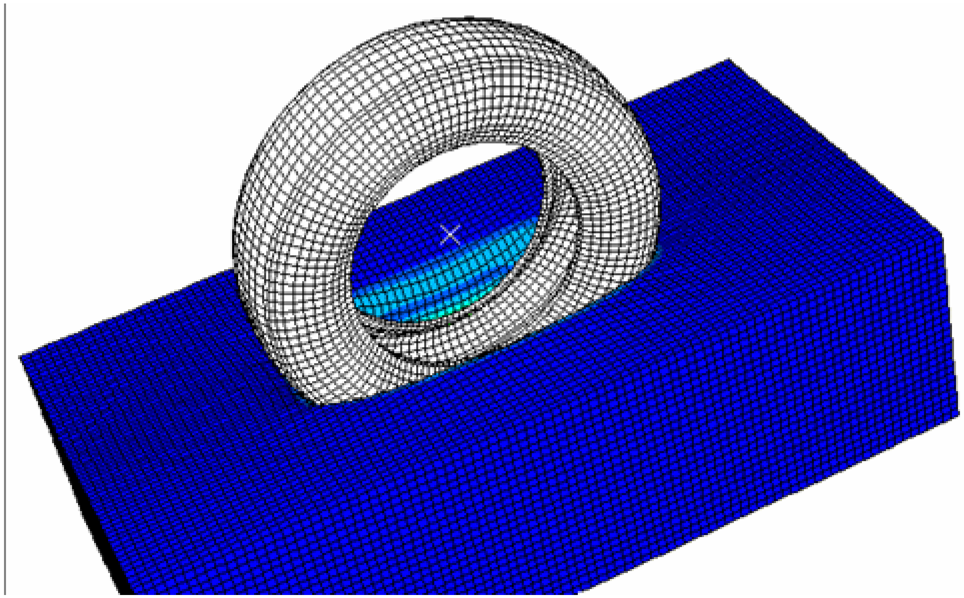
Abaqus/CAE Tire Model





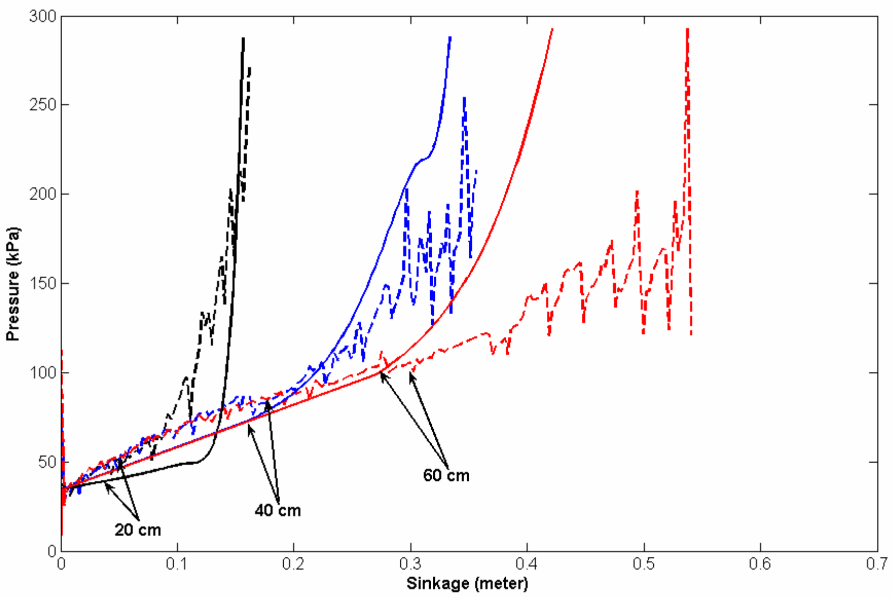
Macro-Scale Plate and Static Tire Indentations with Frictional Contact (Density = 200 kg/m^3)





Abaqus Explicit and Updated Lagrangian Scheme

Macro-Scale Pressure-Sinkage Relationship



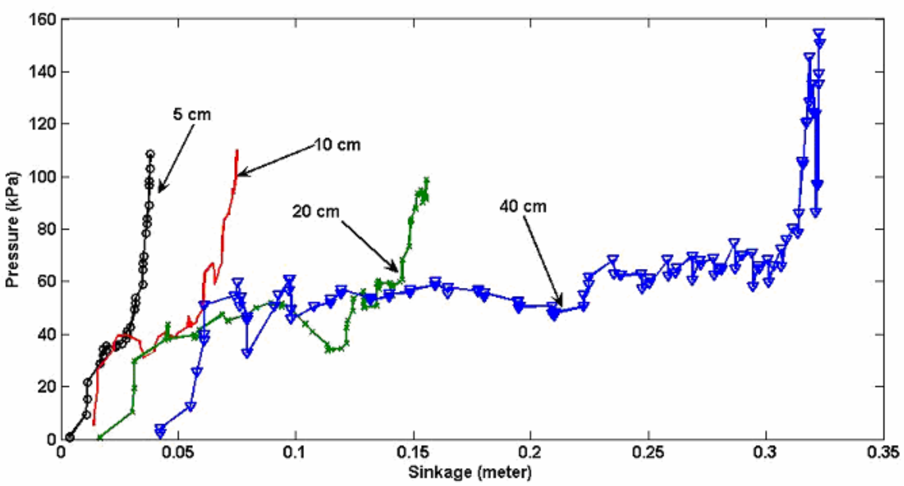


Plate Indentation

Static Tire Indentation

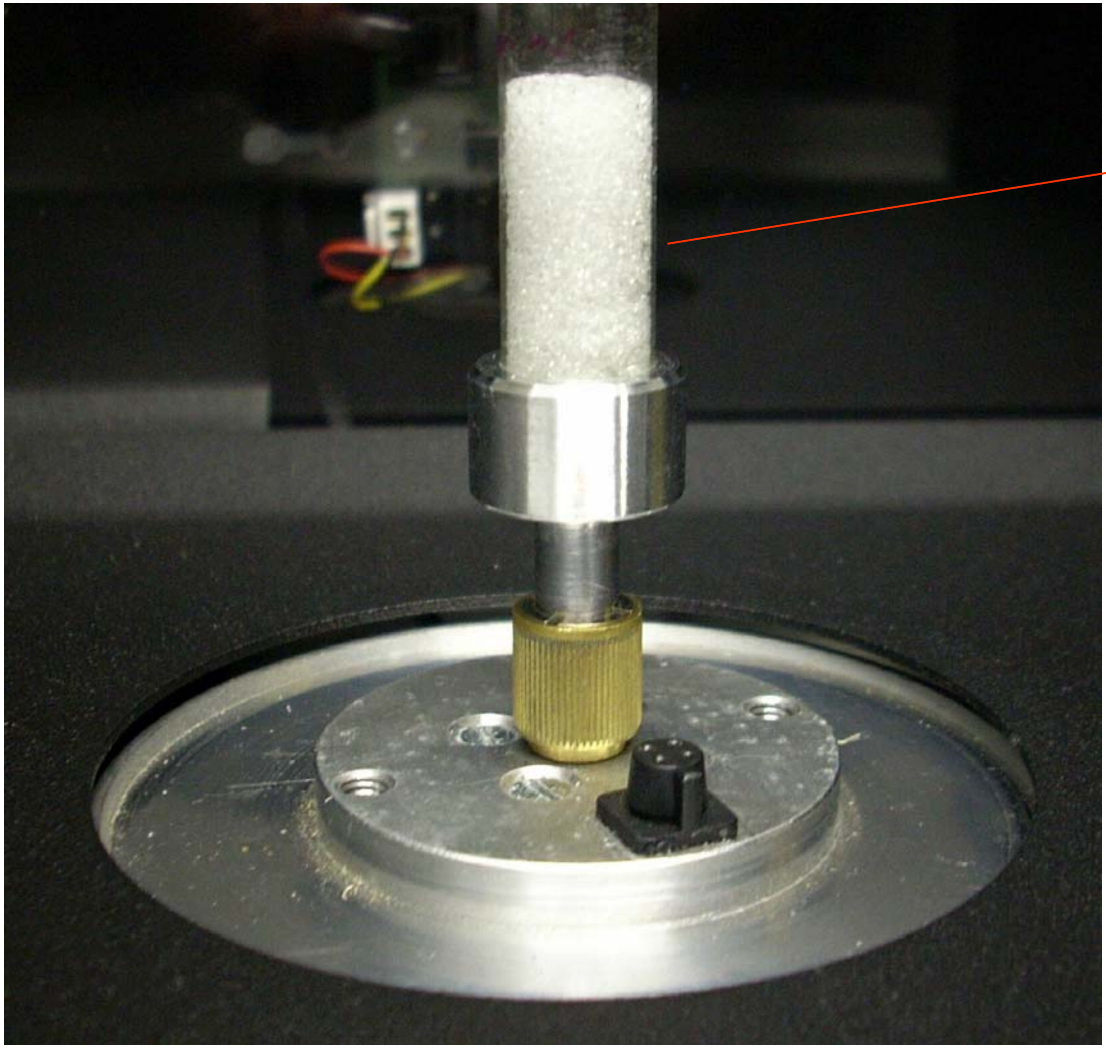
Source: J.H. Lee, J. Terramechanics (2009)

Addressing Uncertainty of Snow by Understanding Effects of Microstructure

- Collect snow samples from field
- Store snow in a freezer at -25 C
- Conduct 3D X-Ray MicroTomography
- Large-scale numerical simulations of indentation and other tests and compare with experimental results

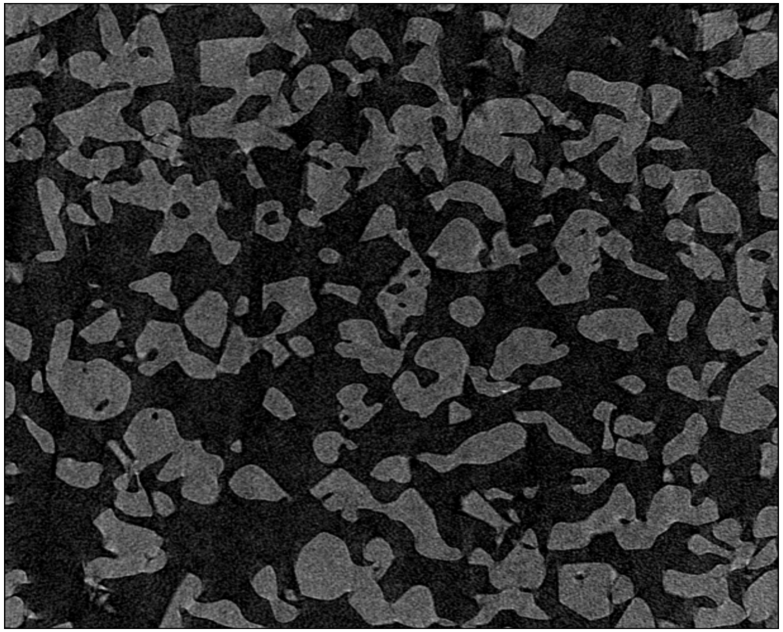
Skyscan 1172 Microtomography

Snow Sample Holder



Diameter 1 cm

Segmentation Using ImageJ

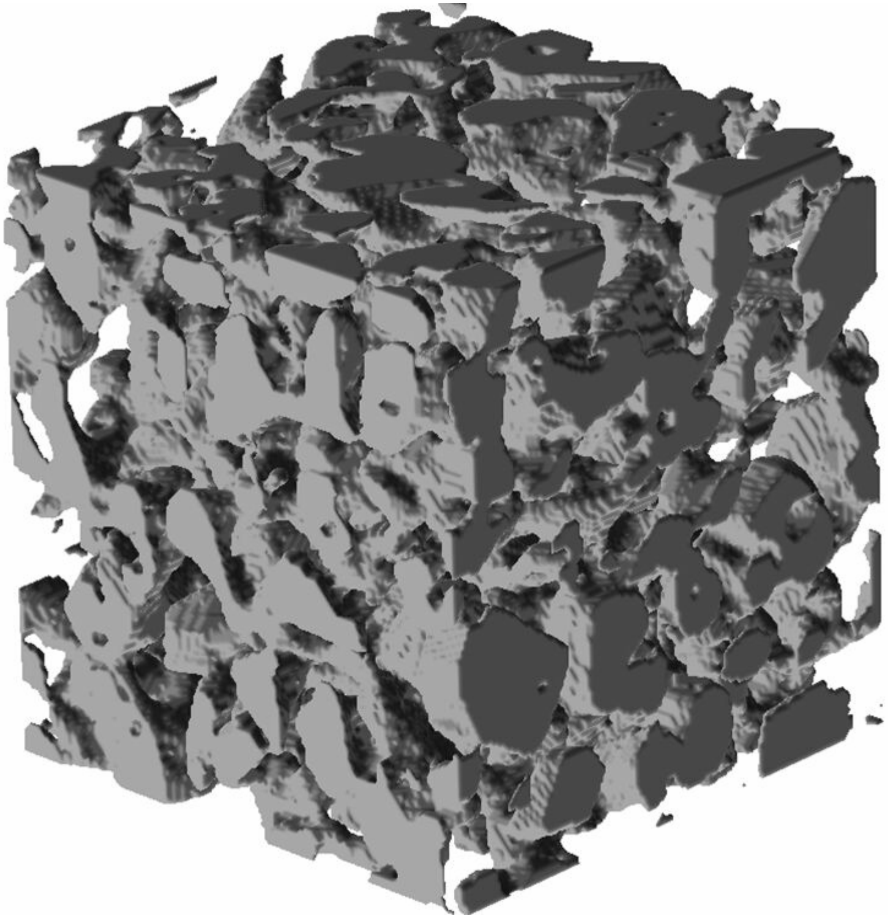


grey-level

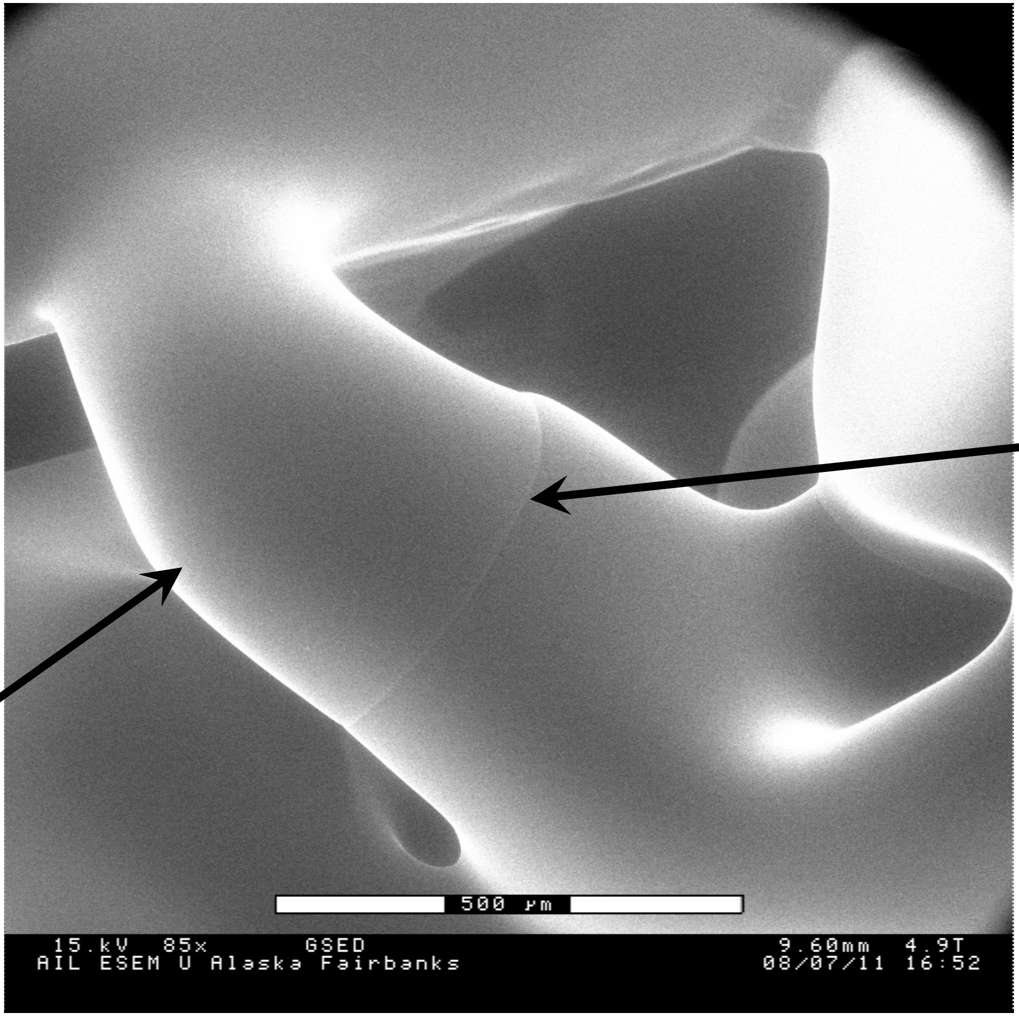
Black is ice

binarized image

Example of Snow Microstructure
Side Length = 3.618 mm



Viscoplastic Ice Model with Damage



Grain Boundary

Ice Bond: Maximum Tensile Strength=2 MPa

Source: Kircher, Huang, Lee, August 2008

Viscoplasticity
SUVIC-I (Aubertin and Lee)

- **S**train rate history-dependent **U**nified **V**iscoplastic model with **I**nternal variables for **C**rystalline materials – **I**ce
- Isotropic polycrystalline ice ***("snow ice")*** at

$$T \geq -55^{0} C; 10^{-8} \leq \varepsilon \leq 10^{-2}\, s^{-1}; 0.04\,\mathrm{MPa} \leq \sigma_{eqiv} \leq 20\,\mathrm{MPa}$$

- ***Unified model*** – plasticity, creep and their interactions are modeled in the same way
- Three ***internal variables***: back stress (kinematic hardening), yield and drag stress (isotropic hardening)
- Evolution of the state variables: combined action of hardening, dynamic recovery
- ***Viscoplastic*** – introduction of a yield surface makes a clear distinction between elastic and inelastic behavior.

Summary of SUVIC-I

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^{e} + \dot{\varepsilon}_{ij}^{i}; \qquad \dot{\varepsilon}_{ij}^{e} = \frac{\dot{S}_{ij}}{2G} + \frac{\dot{\sigma}_{kk}}{9K}\delta_{ij}.$$

$$\dot{\varepsilon}_{ij}^{i} = A\left\langle \frac{X_{ae} - R}{K} \right\rangle^{N} n_{ij} \exp\left(-\frac{Q}{R_g T} \right), \; n_{ij} = \frac{3}{2}\frac{S_{ij} - B_{ij}}{X_{ae}},$$

$$X_{ae} = \sqrt{\frac{3}{2}\left(S_{ij} - B_{ij}\right)\left(S_{ij} - B_{ij}\right)}$$

$$\dot{\varepsilon}_{e}^{i} = \sqrt{\frac{2}{3}\dot{\varepsilon}_{ij}^{i}\dot{\varepsilon}_{ij}^{i}} = A\left\langle \frac{X_{ae} - R}{K} \right\rangle^{N} \exp\left(-\frac{Q}{R_g T} \right)$$

- Decomposition of elastic and inelastic strain rate
- Inelastic strain rate a function of back stress (B), yield stress (R), drag stress (K) and temperature
- X (reduced stress)

Summary of SUVIC-I (cont.)

$$\dot{B}_{ij} = \frac{2}{3} A_1 \dot{\varepsilon}^i_{ij} - \frac{A_1}{B'_e} B_{ij}, B'_e = B_0 \left(\frac{\dot{\varepsilon}^i_e}{\dot{\varepsilon}_0} \right)^{\frac{1}{n}}$$

$$\dot{R} = A_3 \dot{\varepsilon}^i_e \left(1 - \frac{R}{R'} \right), \dot{K} = A_5 \dot{\varepsilon}^i_e \left(1 - \frac{K}{K'} \right).$$

$$R' = R_0 \left(\frac{\dot{\varepsilon}^i_e}{\dot{\varepsilon}_0} \right)^{\frac{1}{n}}, K' = \left(\frac{\dot{\varepsilon}^i_e}{A \exp\left(-\frac{Q}{R_g T} \right)} \right)^{-\frac{1}{N}} \left(X'_{ae} - R' \right)$$

$$X'_{ae} = \sigma' - B'_e ;\ \sigma' = \sigma_0 \left(\frac{\dot{\varepsilon}^i_e}{\dot{\varepsilon}_0} \right)^{\frac{1}{n}}$$

- Evolution of back stress (B), yield stress (R) and drag stress (K)
- Saturation values of state variables (i.e., steady-state creep state)

Numerical Integration: Theta family Taylor series expansion

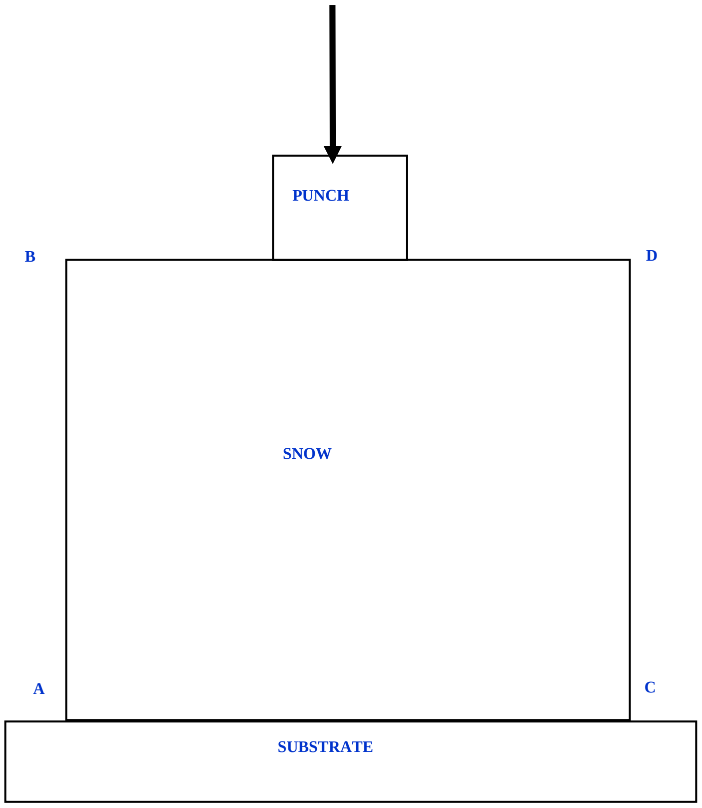
$$\Delta\varepsilon^i = \Delta t\left[(1-\theta)\dot{\varepsilon}_t^i + \theta\dot{\varepsilon}_{t+\Delta t}^i\right];\ 0 \le \theta \le 1$$

$$\dot{\varepsilon}_{t+\Delta t}^i = \dot{\varepsilon}_t^i + \sum_i \frac{\partial \dot{\varepsilon}^i}{\partial \beta_i}\dot{\beta}_i \Delta t.$$

$$\dot{\sigma}_{ij} = \left[L_{ijkl} - \frac{\xi}{1+\xi}\frac{1}{\bar{\bar{H}}}P_{ij}Q_{kl}\right]\dot{\varepsilon}_{kl} - \frac{\dot{\varepsilon}_t^i}{1+\xi}P_{ij}.$$

Indentation Configuration

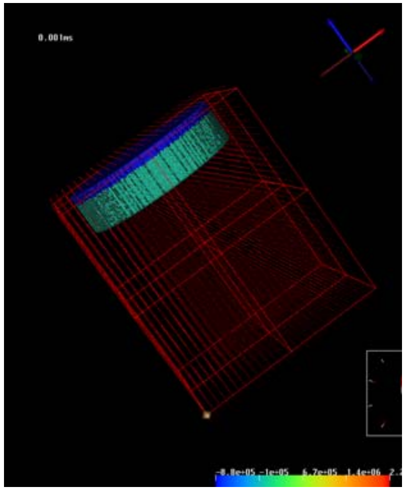
Periodic B.C.
AB and CD

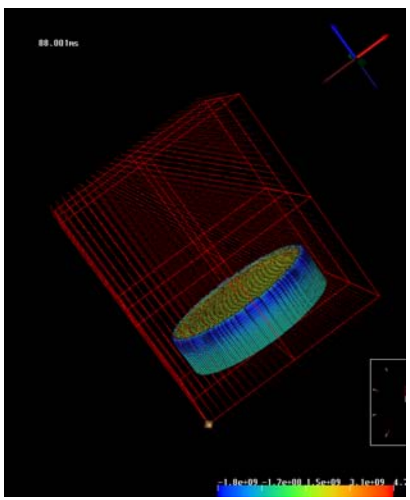


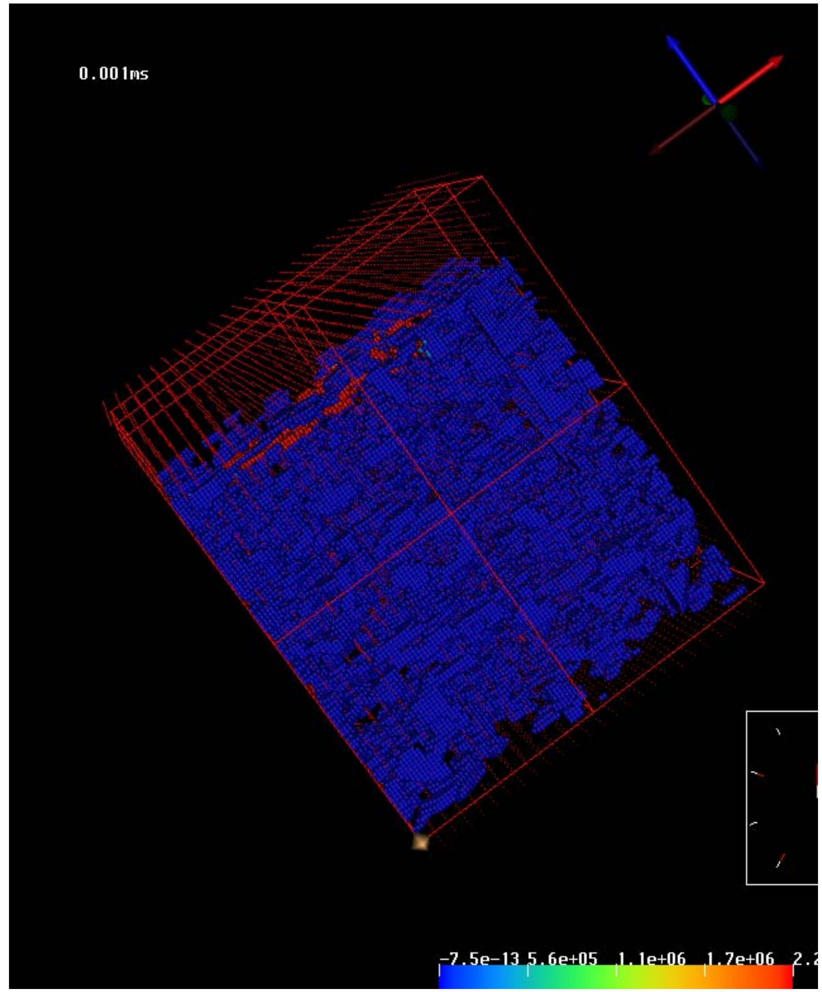
Snow Model (Low-Density)

- Original size 612x612x498 pixels
- Each pixel is 12 um
- VOI used is 400x400x400 pixels
- Down sampled to 100x100x100 pixels using ImageJ
  - Each pixel is 48 um
- Uintah utility pfs2 to convert voxels into material points for multiple processors
- Indentation speed is 48 mm/sec.
- Visualization using SCIRun

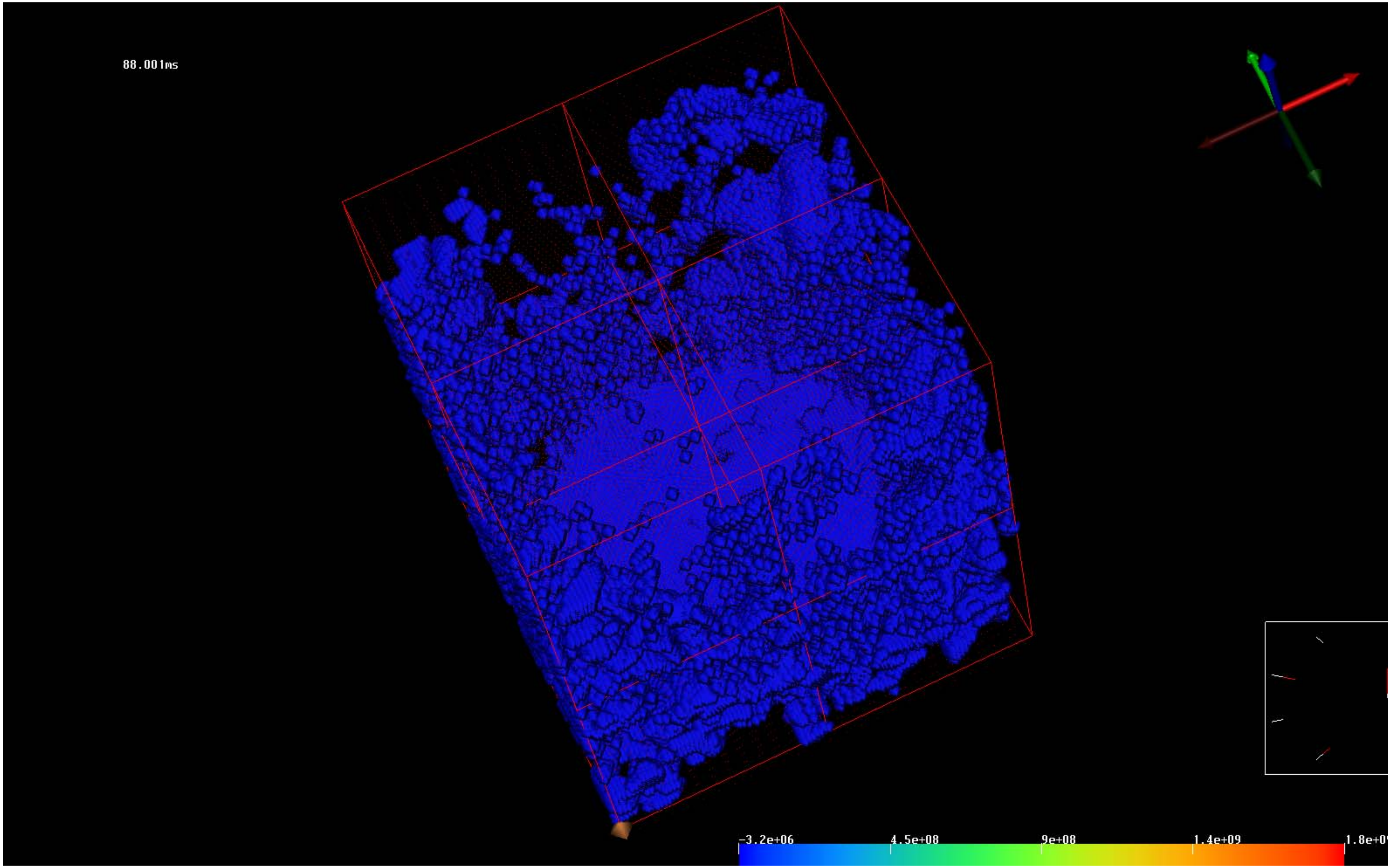
Indenter and Initial Snow Geometry
8 Processors – Uintah Explicit



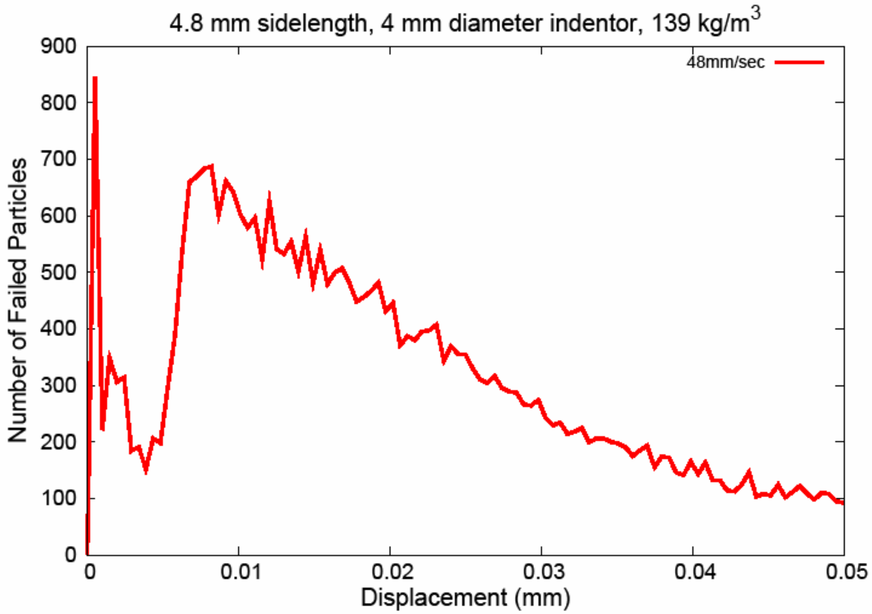


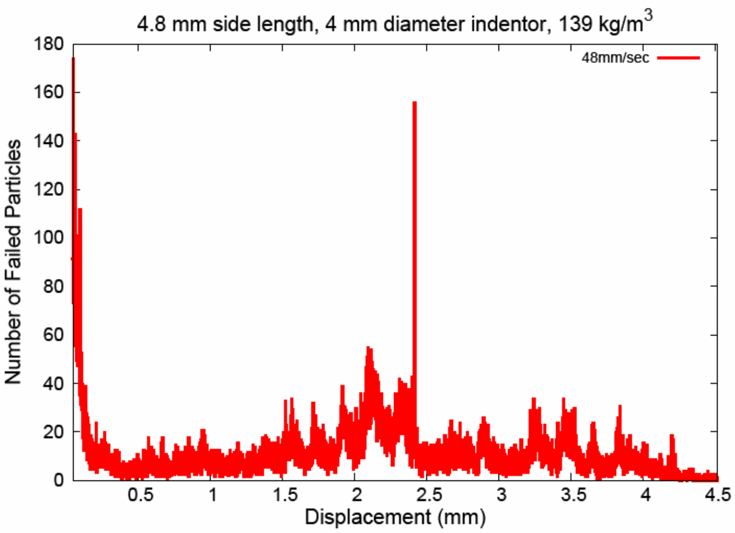


Final Snow Geometry

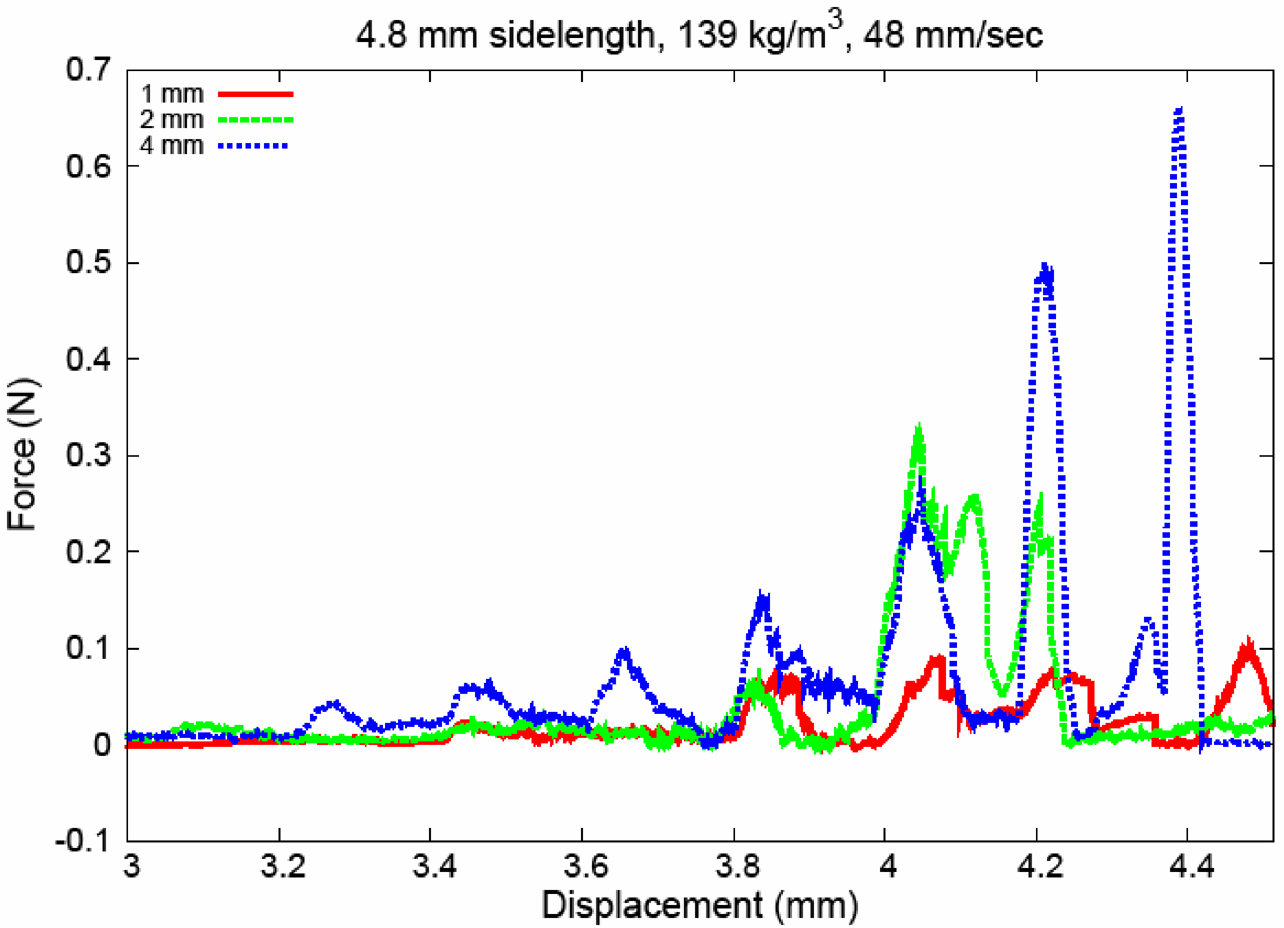


Failed Ice Particles vs. Time

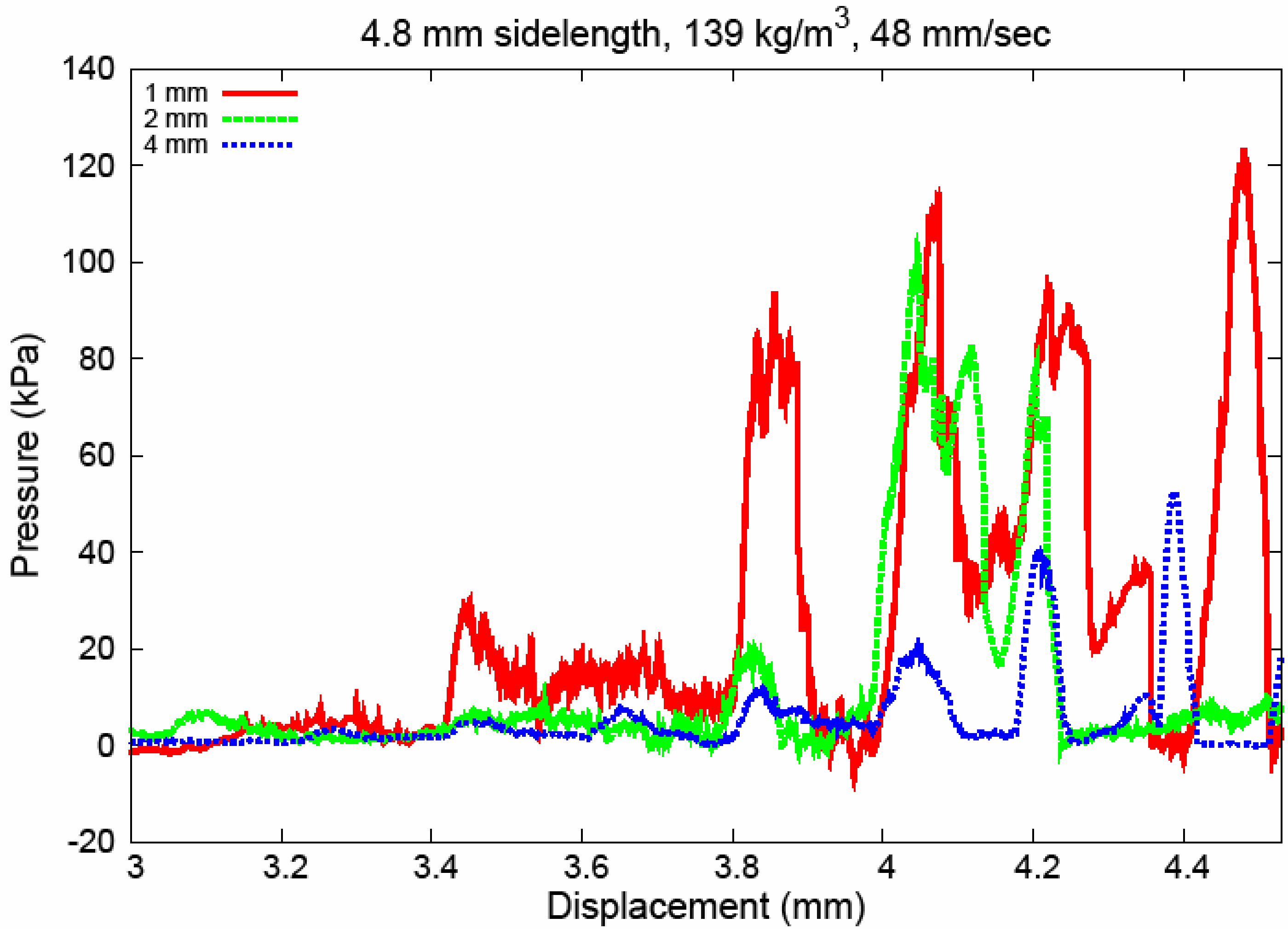




Load-Displacement Relationship

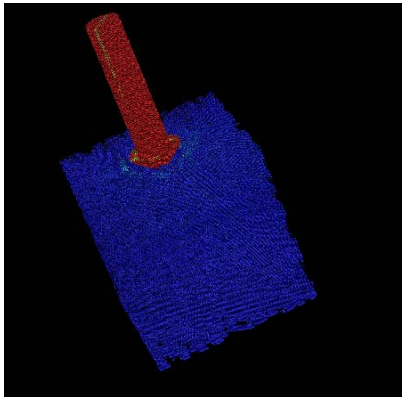


Pressure-Displacement Relationship

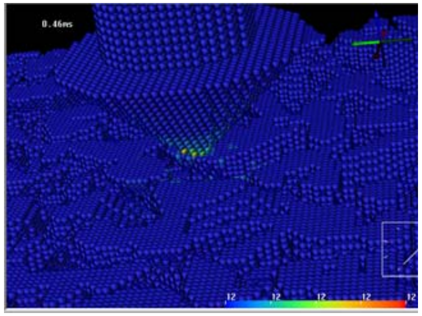


Animation of Progressive Failure of Particles

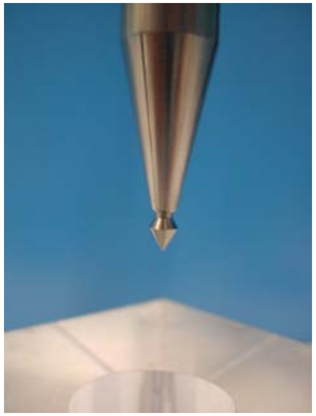
Examples of Future Work



- Snow/Soils penetration tests
- Traction tests of rubber on snow/soils
- Triaxial tests of snow/soils
- Frozen sands



Micro-CT imaging & mechanical testing



Micro-CT imaging & SnowMicroPenetrometer testing

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Thank You!

Questions?