Vehicle-Snow Interaction: Modeling, Testing and Validation

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October 12, 2009
Goodyear Tech Center, Luxembourg

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **12 OCT 2009**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Vehicle-Snow Interaction: Modeling, Testing and Validation**	5a. CONTRACT NUMBER **W56 HZV-08-C-0236**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Jonah Lee**	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Department of Mechanical Engineering University of Alaska Fairbanks, USA**	8. PERFORMING ORGANIZATION REPORT NUMBER **20246**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000, USA**	10. SPONSOR/MONITOR'S ACRONYM(S) **TACOM/TARDEC**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) **20246**

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**42**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

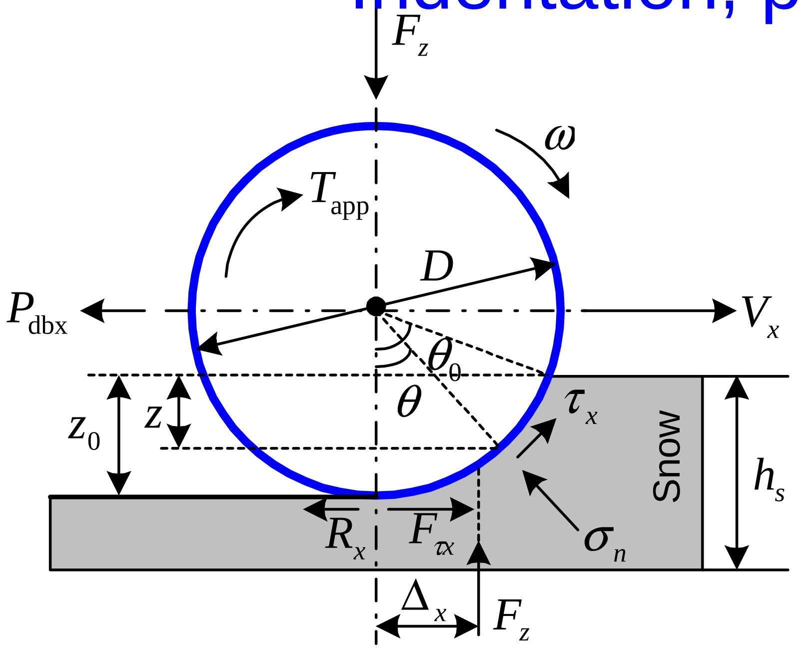
Outline

- Part I - Snow mechanics
  - Background
  - Experimental procedure
    - Tribometer for indentation, plowing, sliding tests
    - 3D X-Ray Microtomography for microstructure
  - Numerical modeling procedure
  - Typical results (indentation, plowing, compression, tension, penetration)
- Part II - Vehicle-snow interaction
  - Alaska Instrumented Vehicle and profilometer
  - Validation of models

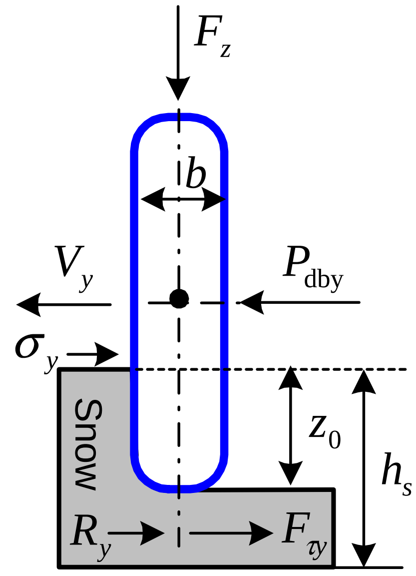
Background:
Characteristics of (Geometric) Snow Models

- Multi-scale in nature:
  - um scale at the sub-grain level (microscale)
  - mm scale at the grain level (mesoscale)
  - cm scale at the terrain level (macroscale)
- Stochastic in nature:
  - Stochastic models at each scale (e.g., Gaussian Random Field at the mesoscale, semi-variogram at the macroscale)
  - Key challenge:
    - Integrate ('patch') models at different scales

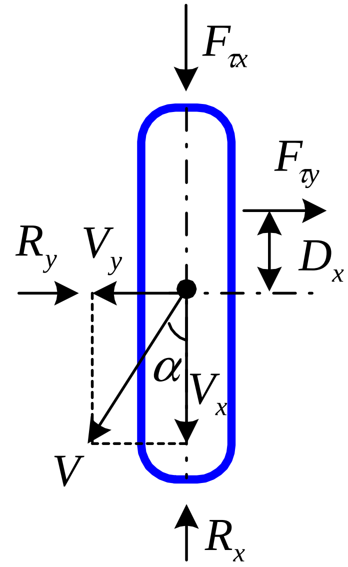
Background:
Indentation, plowing and sliding



(a) side view



(b) front view



(c) top view

- Resultant Forces due to Sinkage/Ploughing and Longitudinal/Lateral Slips
- Motion Resistance, Shear Force and Drawbar

Background:
Needs

- Microstructure (uncertainty) effect not assessed
- Need better understanding of deformation and failure mechanisms
- Little work done in plowing and sliding
- Size effect not understood

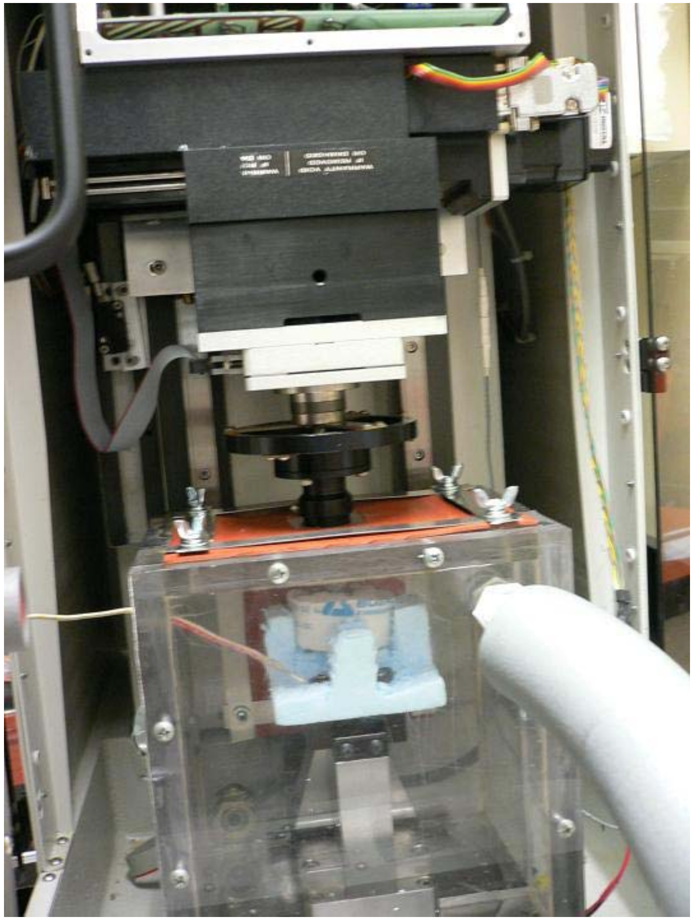
Background:
Goals and Approaches

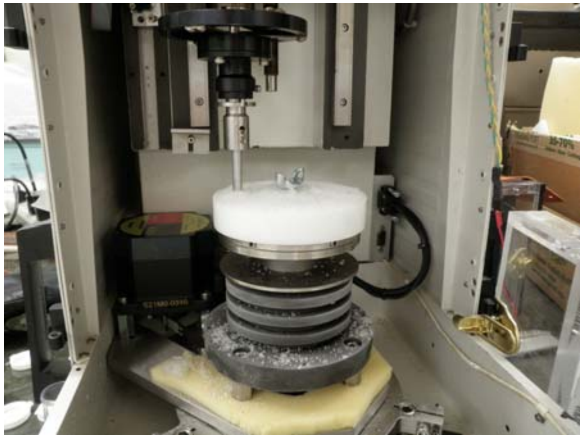
- Goals:
  - Develop models for the mechanical properties of different types of snow
  - Quantify the associated uncertainties and understand the sources of uncertainties
- Approaches:
  - Experimental:
    - Microscale tests using microtribometer
    - Microstructural statistics using microCT scanner
  - Numerical:
    - Microscale simulations using a meshless method with appropriate constitutive laws
  - Semi-analytical:
    - Continuum mechanics based stochastic models incorporating microstructural information

Experimental Procedure

- Collection and storage of snow
  - February to March, 2009, Tanana River, Fairbanks, Alaska
  - Fine-grained just underneath the surface
  - Coarse-grained about 20 cm from surface
  - Snow temperature ~-6 C
  - Stored in a freezer ~-25 C
- Microtribometer –
  - Temperature ~-10C
  - Pin sizes (1/8”, 1/4”, 3/8”, 1/2”)
  - Force or velocity control
  - Multiple steps and modes (indentation, pin-on-disk etc.)

Experimental Procedure: tribometer setup





Environment

Pin-on-disc setup

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Experimental Procedure:
Skyscan 1172 Microtomography

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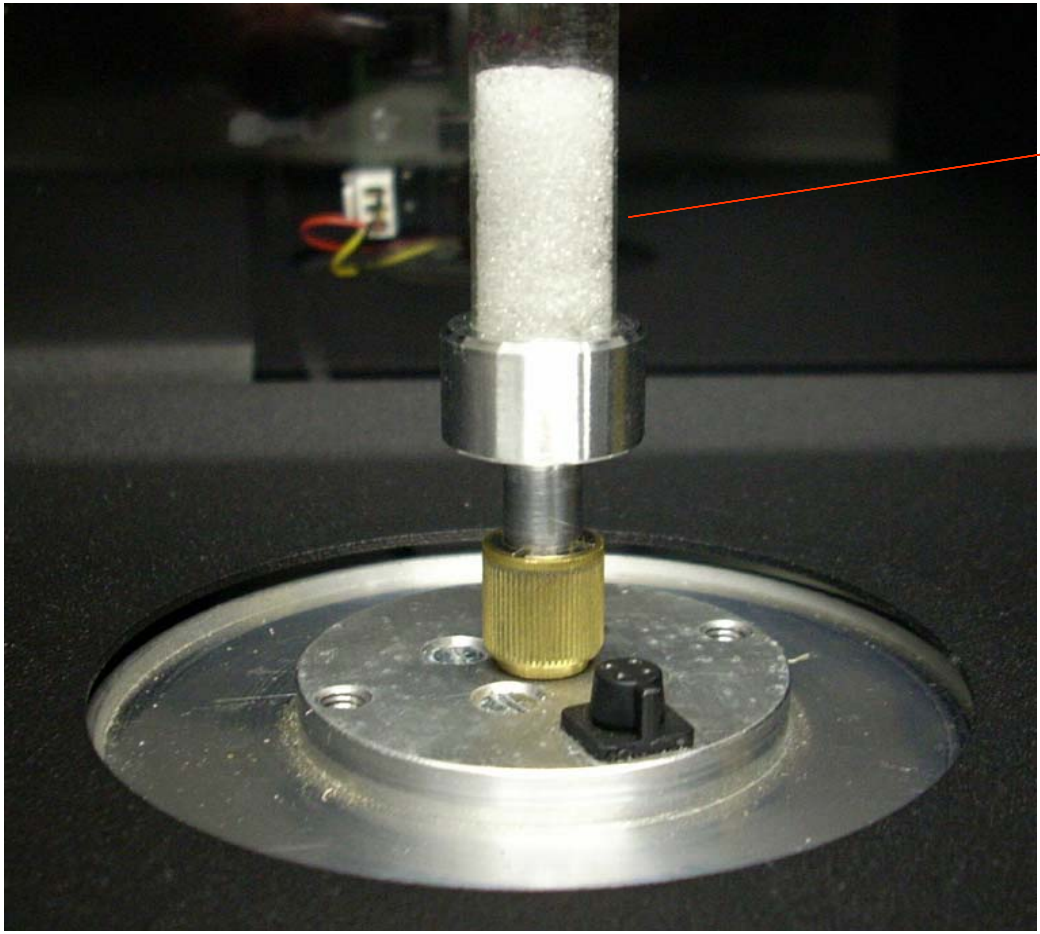
Experimental Procedure: Snow Sample Holder



Diameter 1 cm

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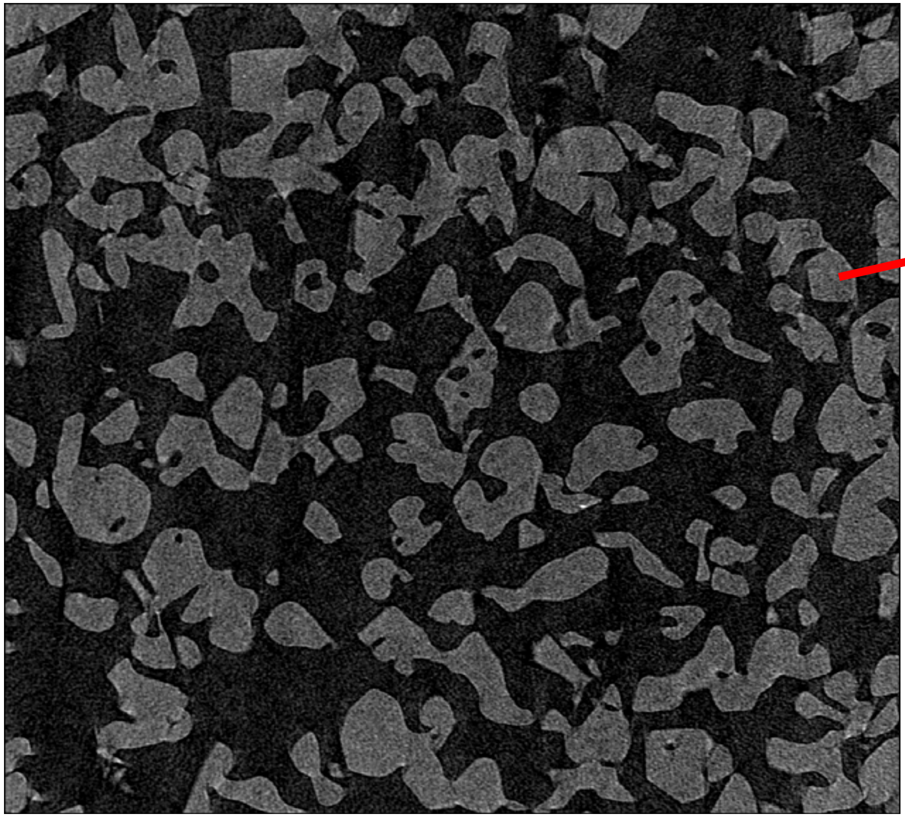
Experimental Procedure:
Grey-level Cross-Sectional Image
Sieved Snow < 1 mm Grain Size

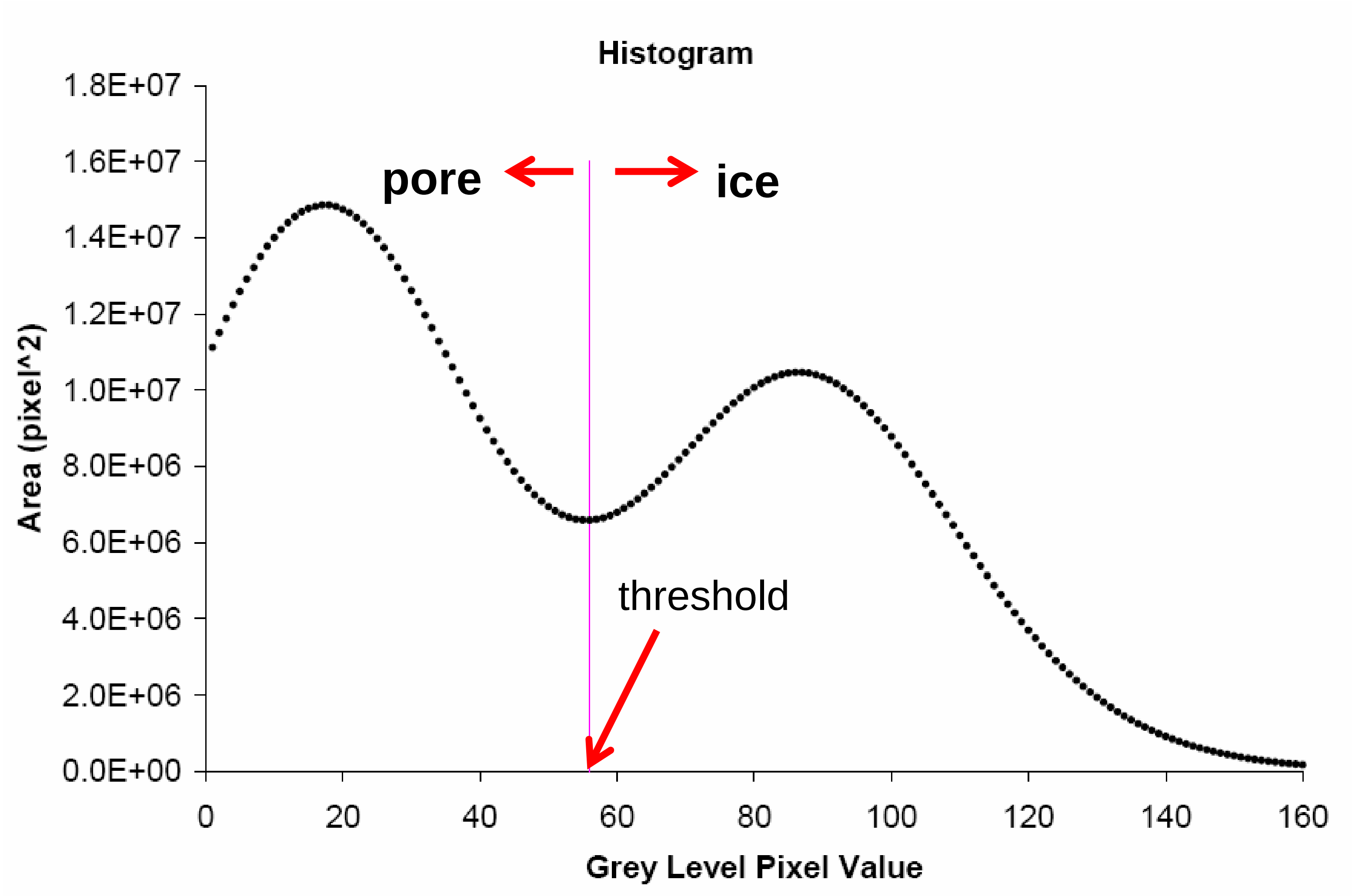


Brighter pixels represent ice

7.344 mm by 7.344 mm

Resolution:1225 by 1225, Pixel size: 6 micron

Experimental Procedure: Grey-Level Histogram



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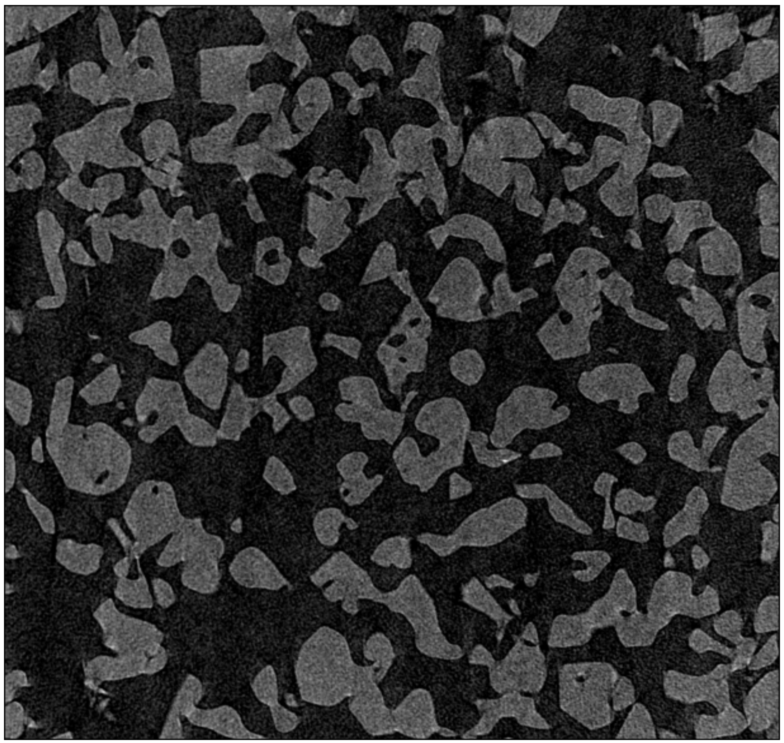
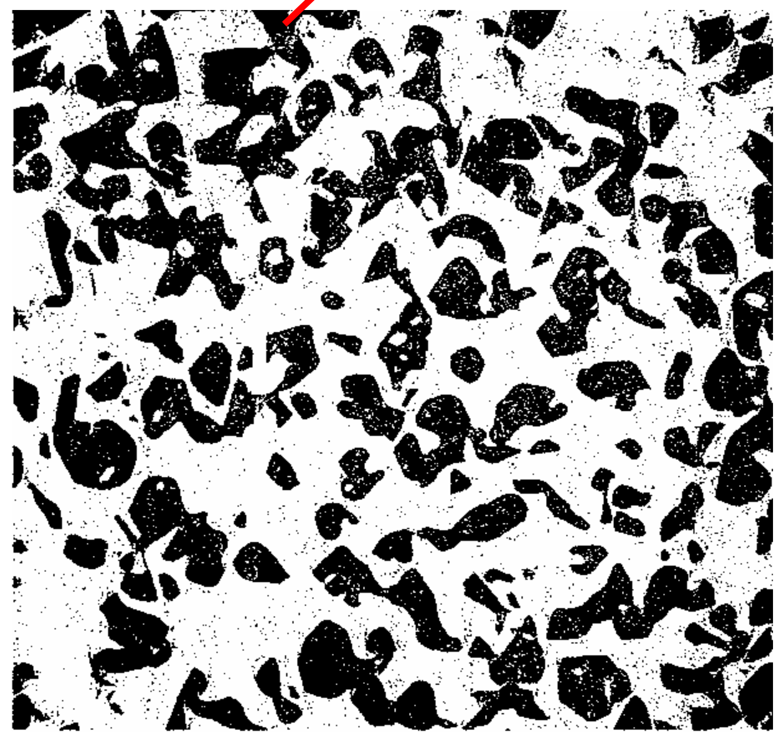
Experimental Procedure: Segmentation

Black is ice

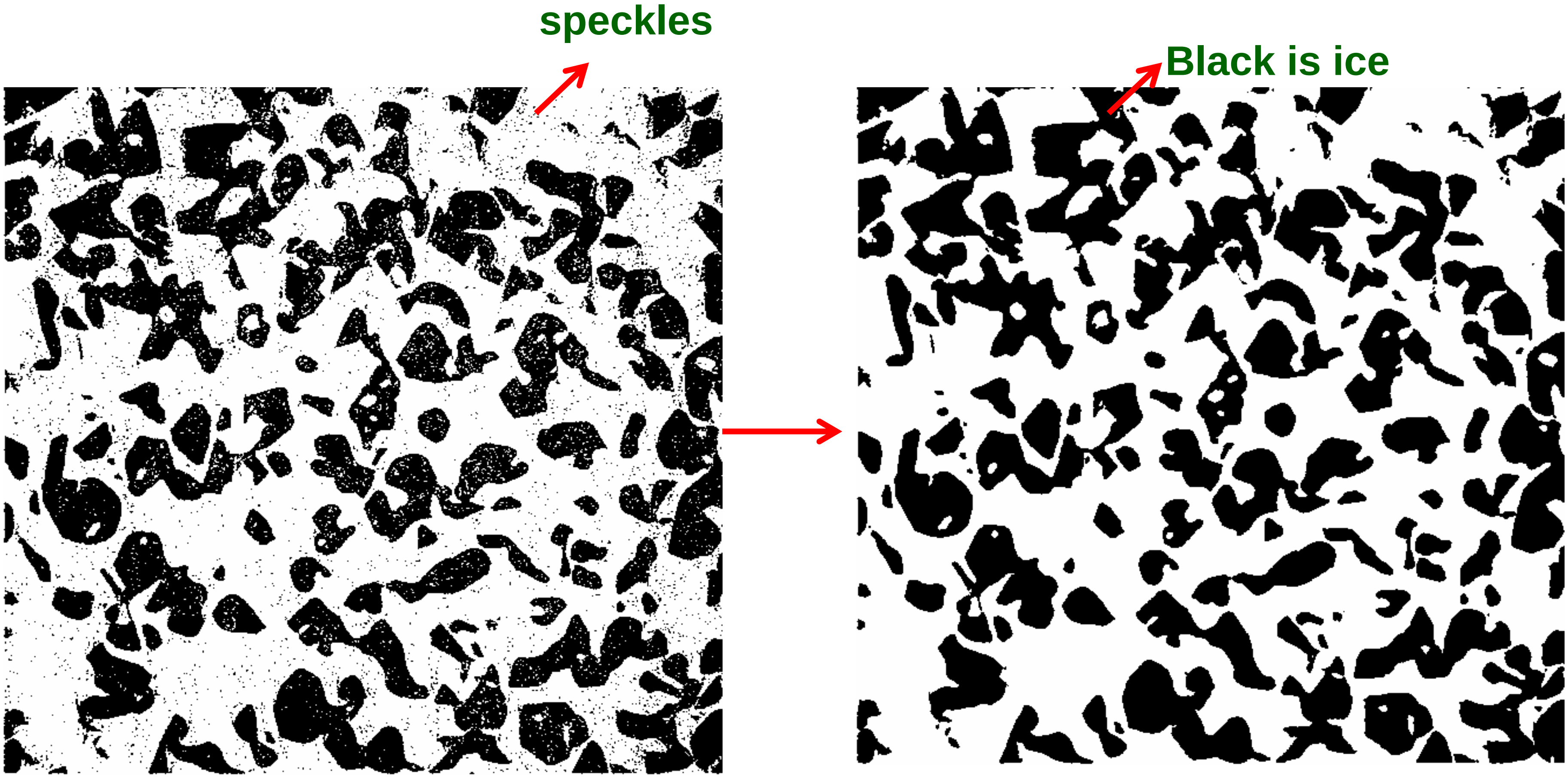


grey-level



binarized image

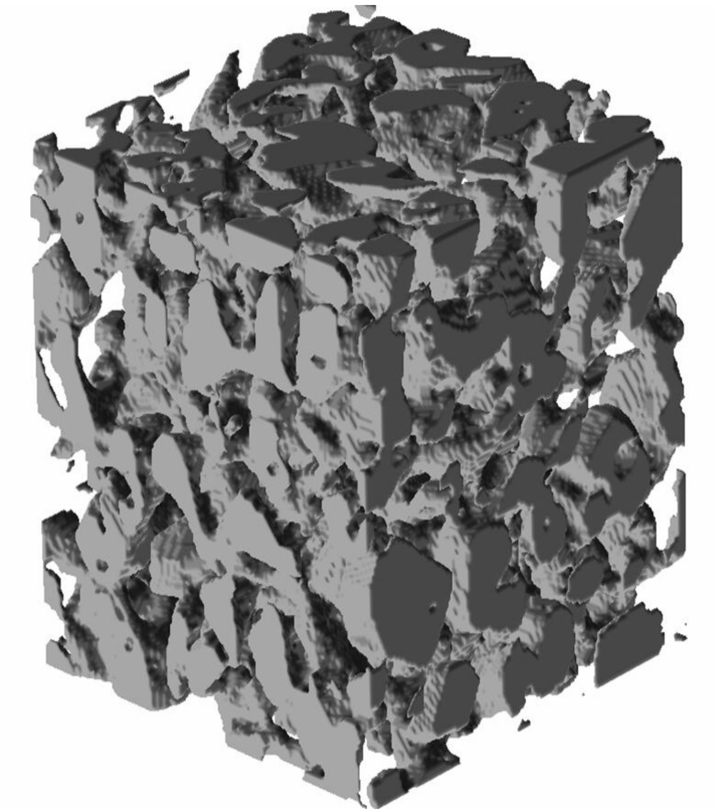
Experimental Procedure:
Removal of Unconnected Parts



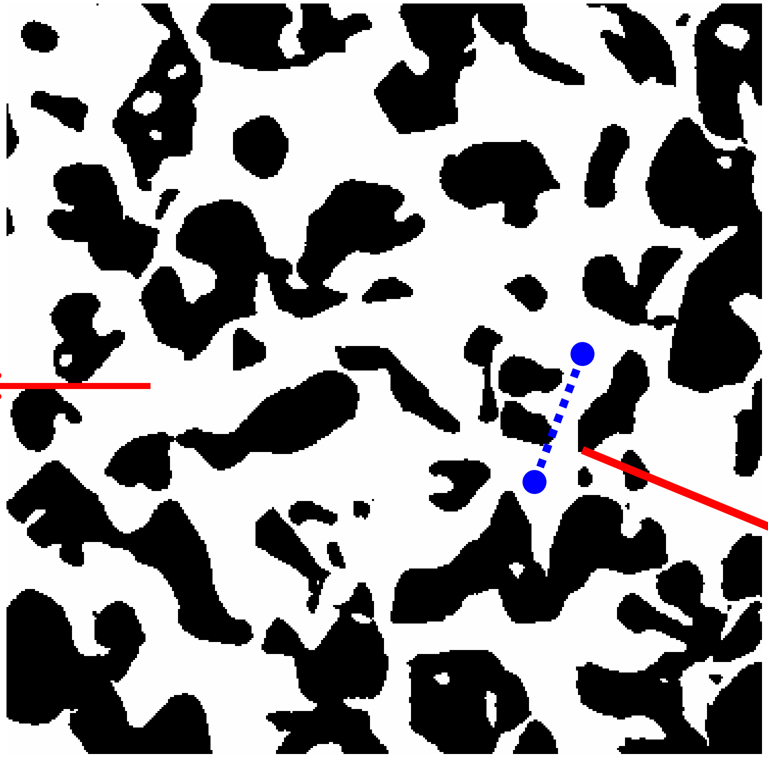
Binarized image

Remove speckles

Experimental Procedure:
3-D Visualization of a Cube of Snow Microstructure
Side Length = 3.618 mm



Experimental Procedure:
Extract Statistical Information from Images



Porosity
(pore volume
fraction)

Probability that two points a distance r apart will lie in pore space

Two-point probability function

Numerical Modeling: Generalized Interpolation Material Point (GIMP) method (1/2)

- Geometry from CT images
  - 148x148x148 voxels (48 um resolution); 7.1mmx7.1mmx7.1mm
  - Each voxel (ice) is mapped to a material point (particle)
  - ~1 million particles
- Boundary conditions
  - Periodic on the sides (for indentation)
  - Frictionless
  - Speed of indentation is 71 mm/sec
- Indenters
  - 1/16”, 1/8”, 1/4”

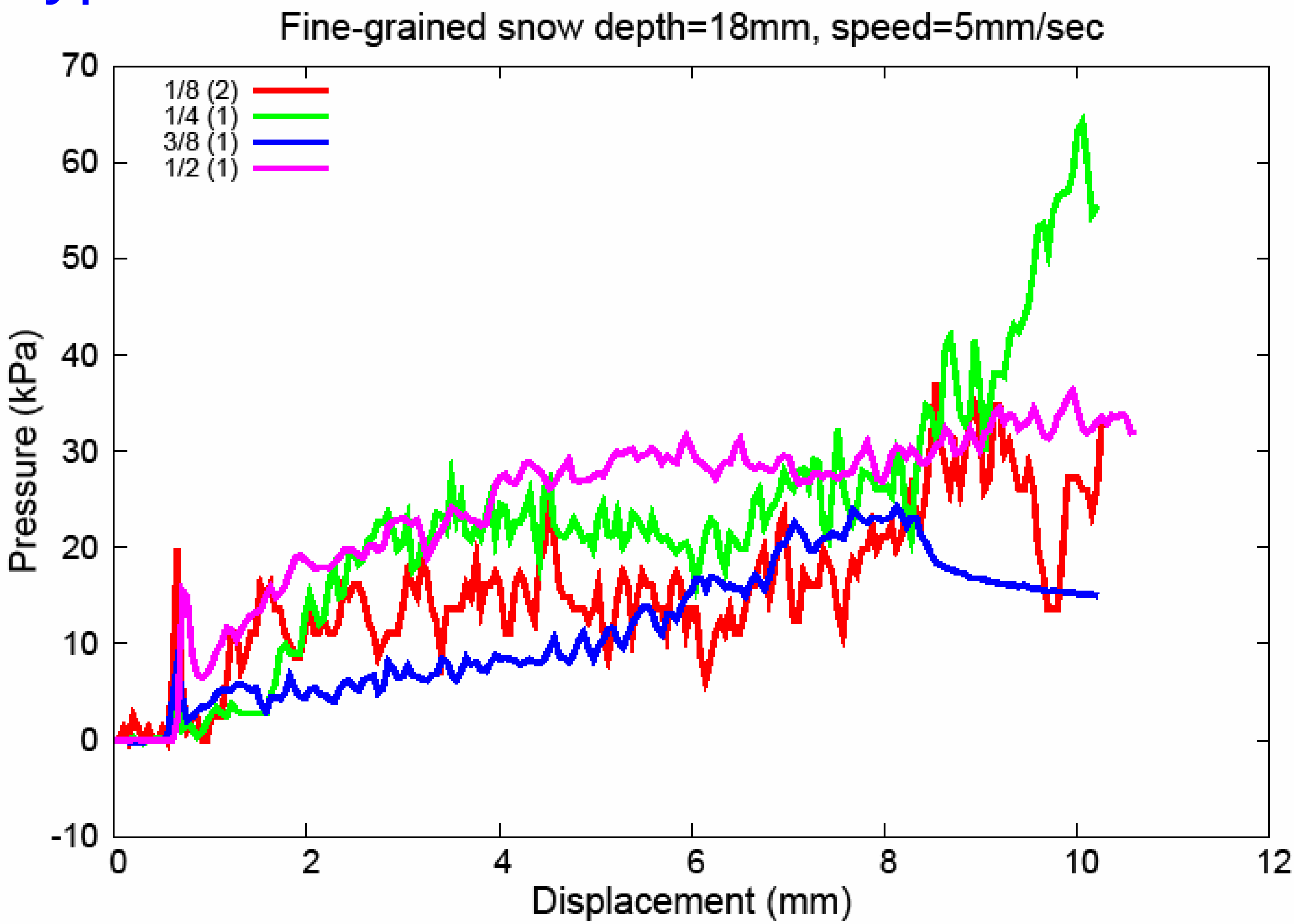
Generalized Interpolation Material Point (GIMP) Method (2/2)

- Software: parallel code Uintah installed on a Sun cluster at Arctic Region Supercomputing Center
- Constitutive law used for ice particles
  - Elastic-brittle [cf. Johnson & Schneebeli (1999), Marshall and Johnson (2009)]
    - Failure according to maximum tensile stress
    - Post failure
      - Stress set to zero if mean stress is tensile
      - Stress set to mean stress if compressive
- Algorithm
  - Dynamic, explicit

Tests and Simulations

- Tests
  - Compression
  - Indentation
  - Plowing
  - Sliding on compacted snow (future work)
  - Penetration (future work)
- Simulations
  - Compression and Tension
  - Indentation
  - Plowing
  - Sliding (future work)
  - Penetration
  - Triaxial tests

Typical Results: Indentation tests for fine snow



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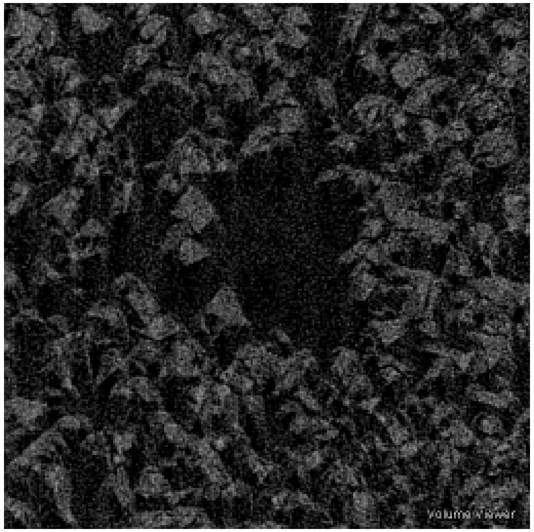
Microstructure after Indentation Tests via MicroCT

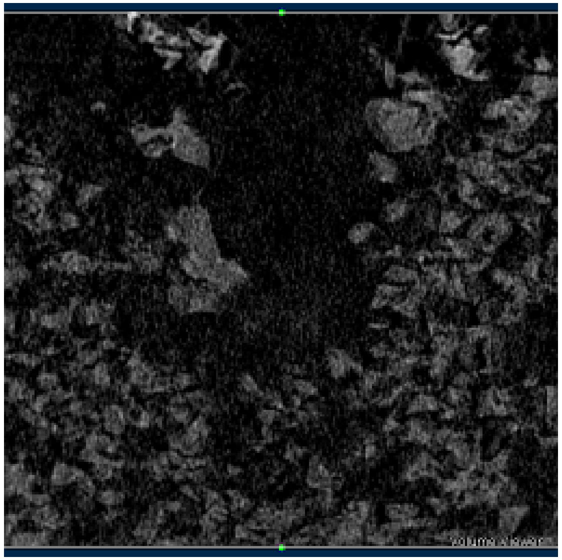


Top View

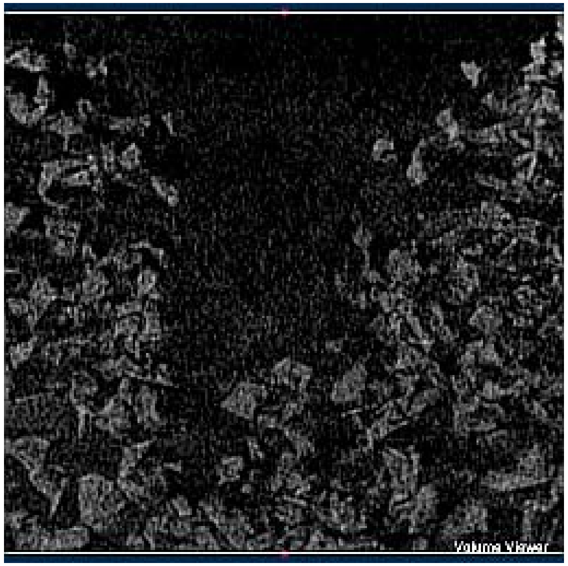
Fine-grained snow:

Initial density: ~290 kg/m^3

Final density:~590 kg/m^3

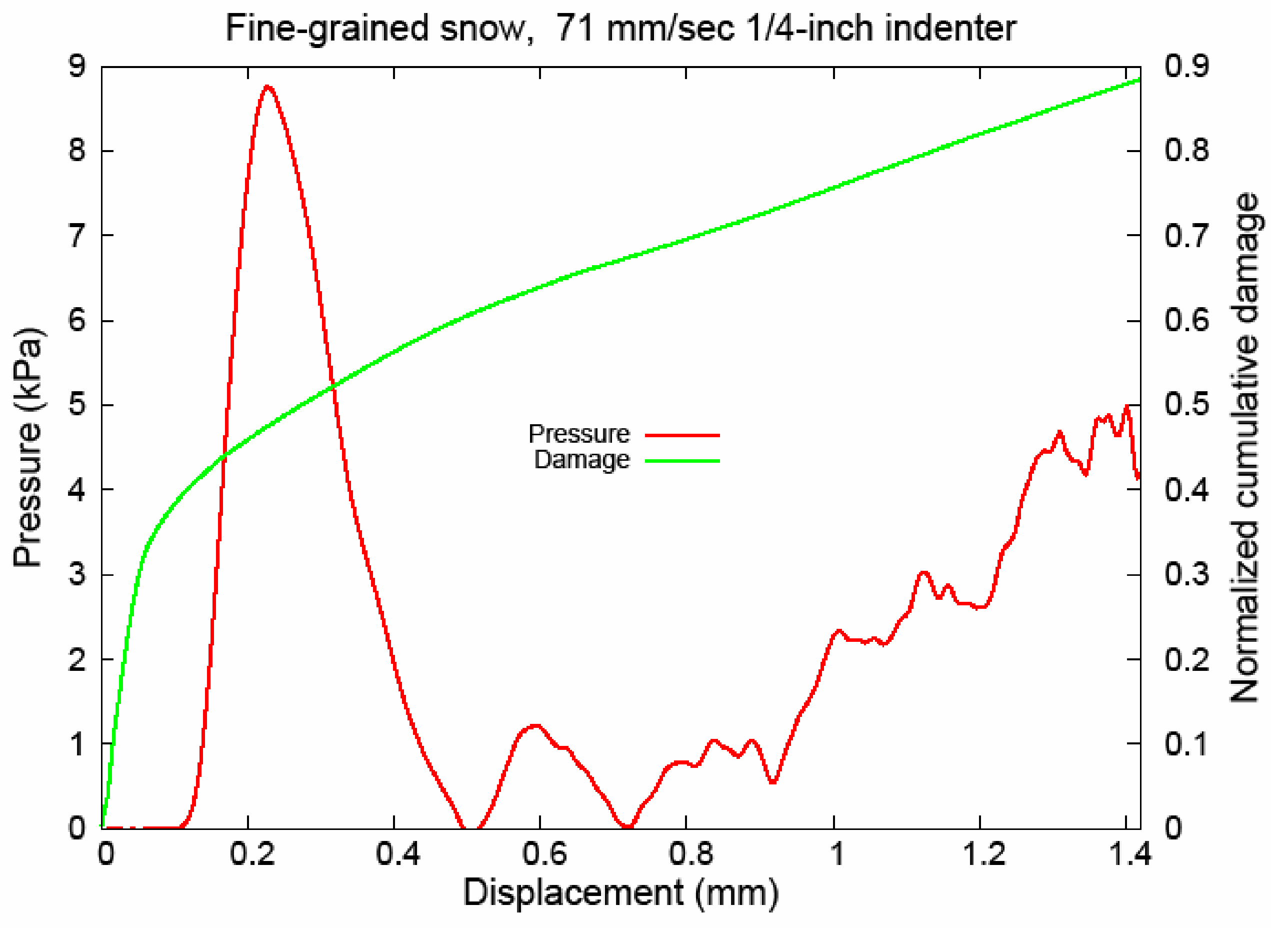


Side View

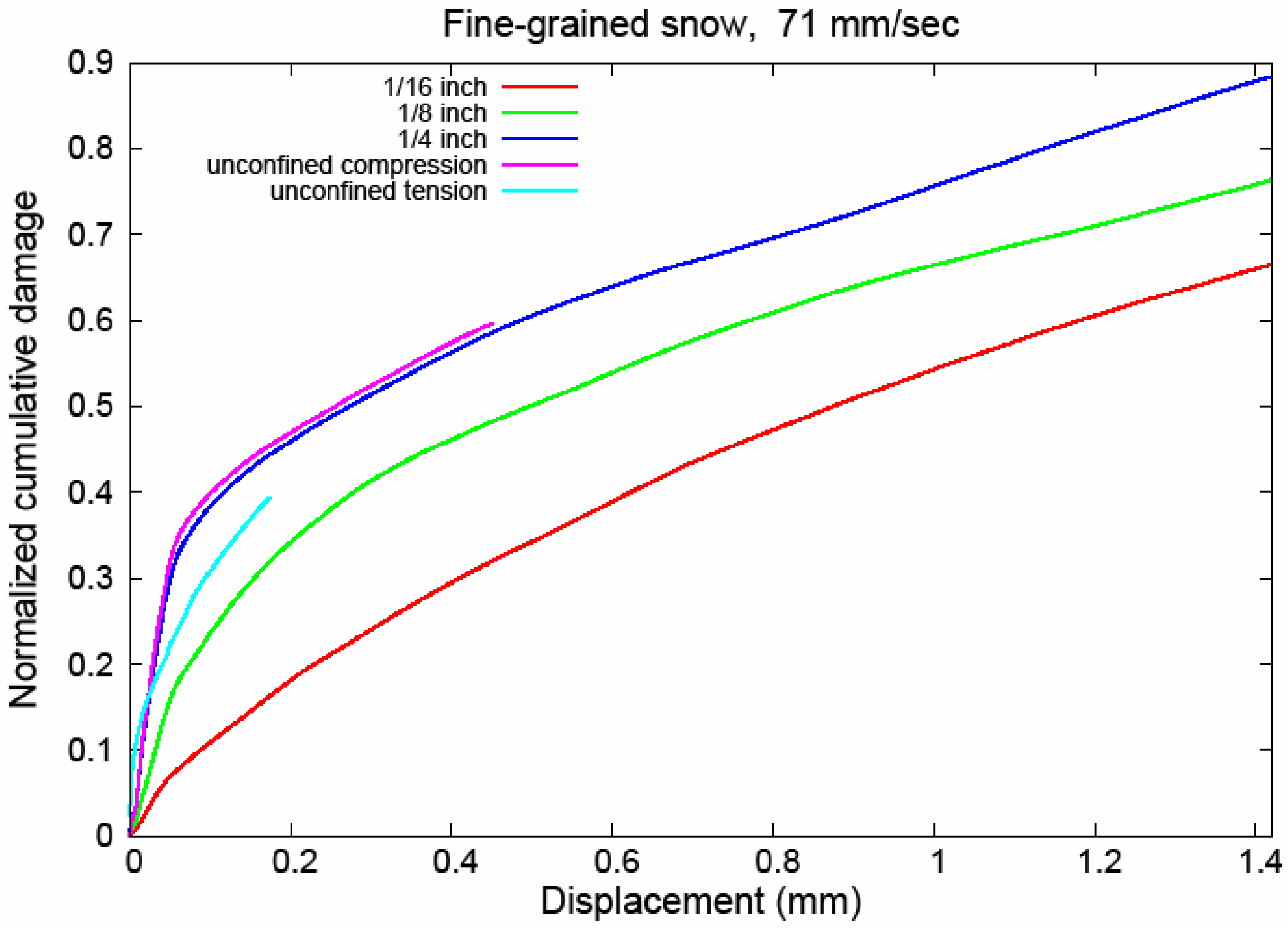


Side View

Typical Indentation Simulation Results



Typical Indentation Simulation Results: Cumulative damage



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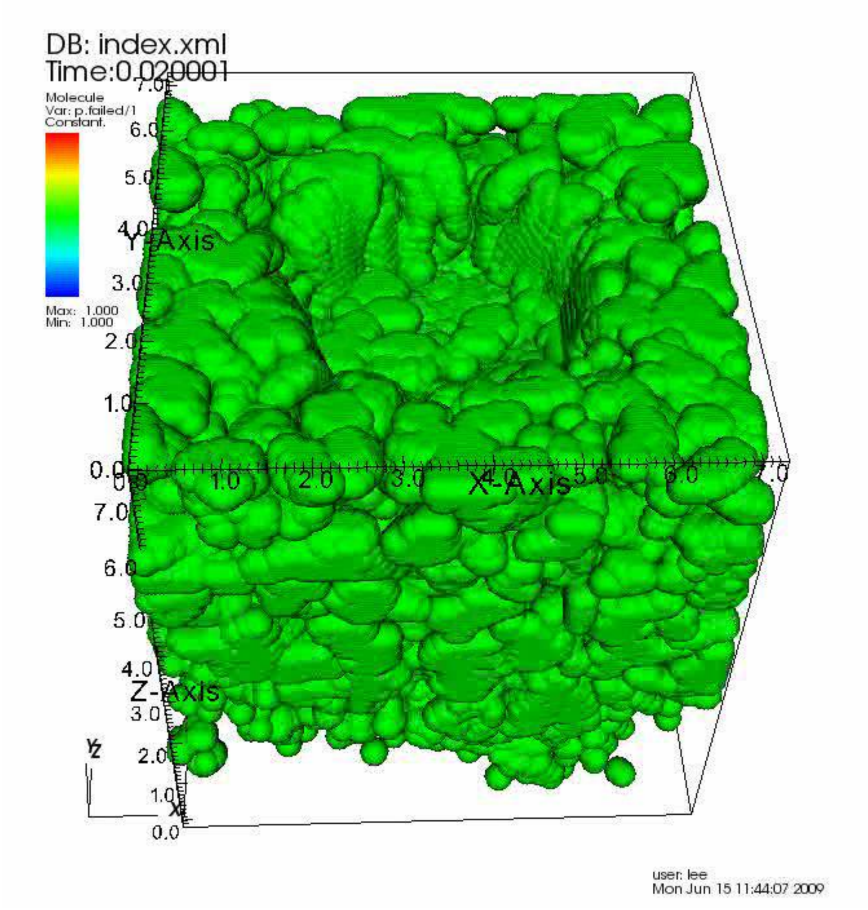
Failed Particles from Indentation Simulation



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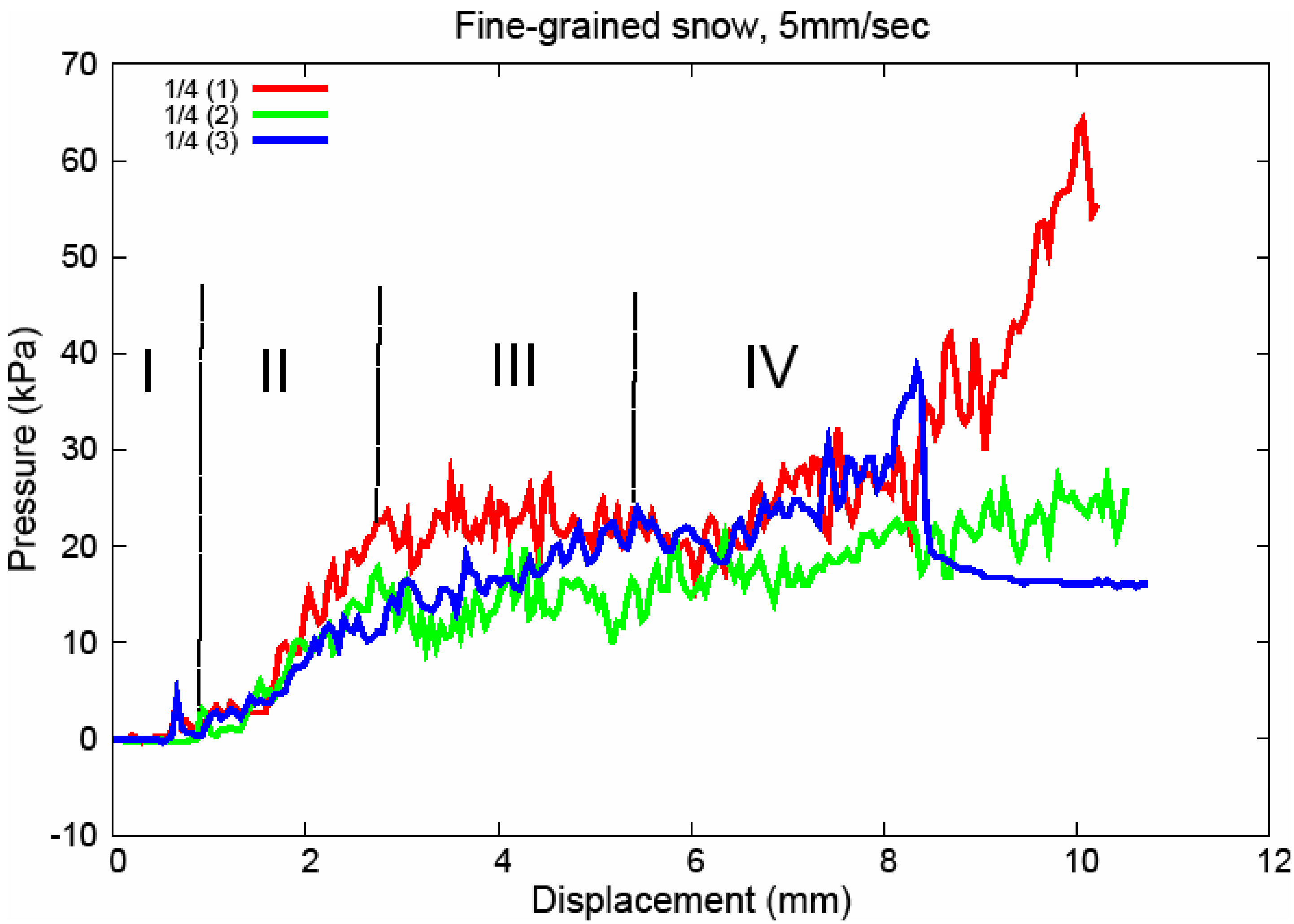
Characteristics of Indentation Test Curves



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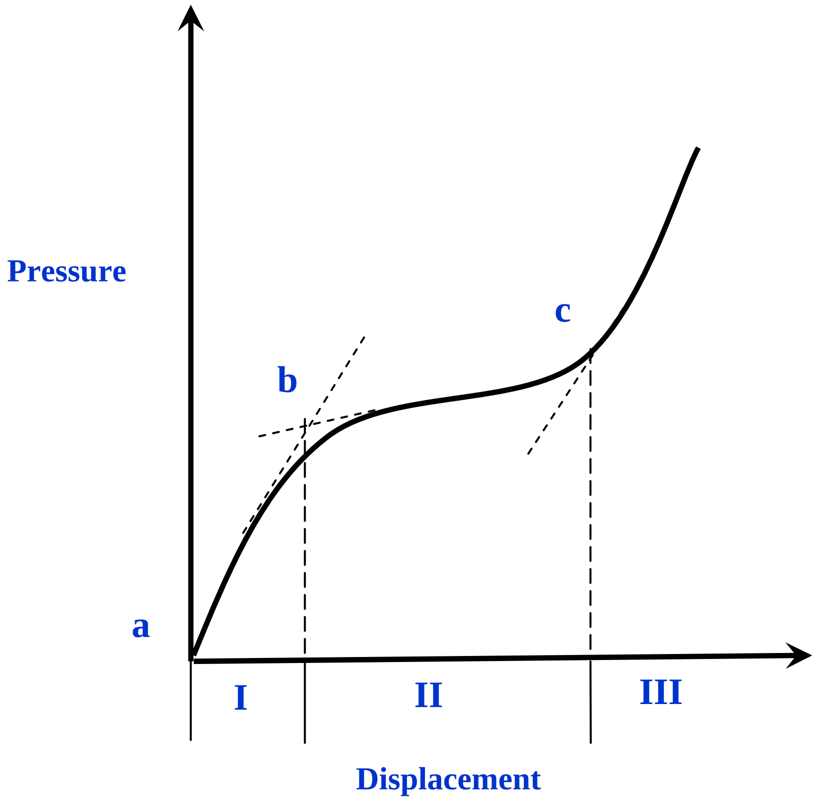
Background: Indentation modeling using continuum mechanics



Three zones:

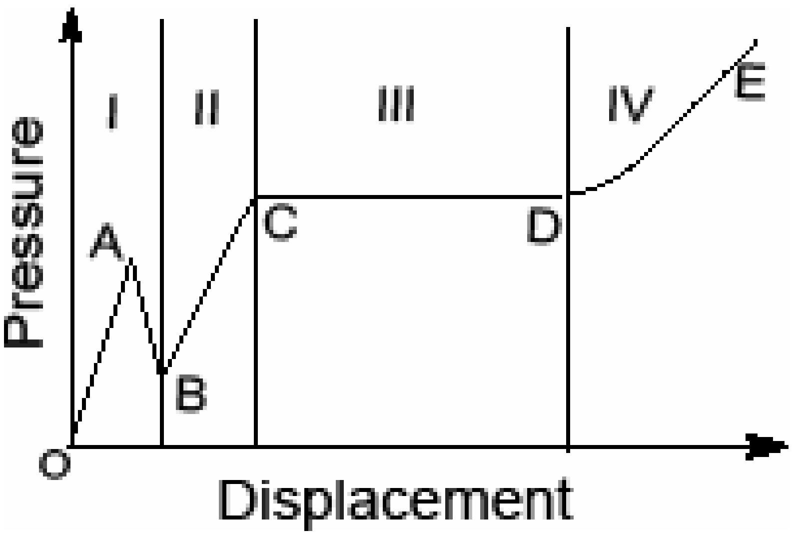
I: Elastic

II: Hardening (via cavity expansion theory and Drucker-Prager criterion)

III: Densification (via upper bound theory and Drucker-Prager criterion)

*J.H. Lee, J. of Terramechanics (2009)

Potential Deformation Mechanisms



A: Upper 'yield' point (inelastic due to damage)

B: Lower 'yield' point

- OAB: Initial yield zone

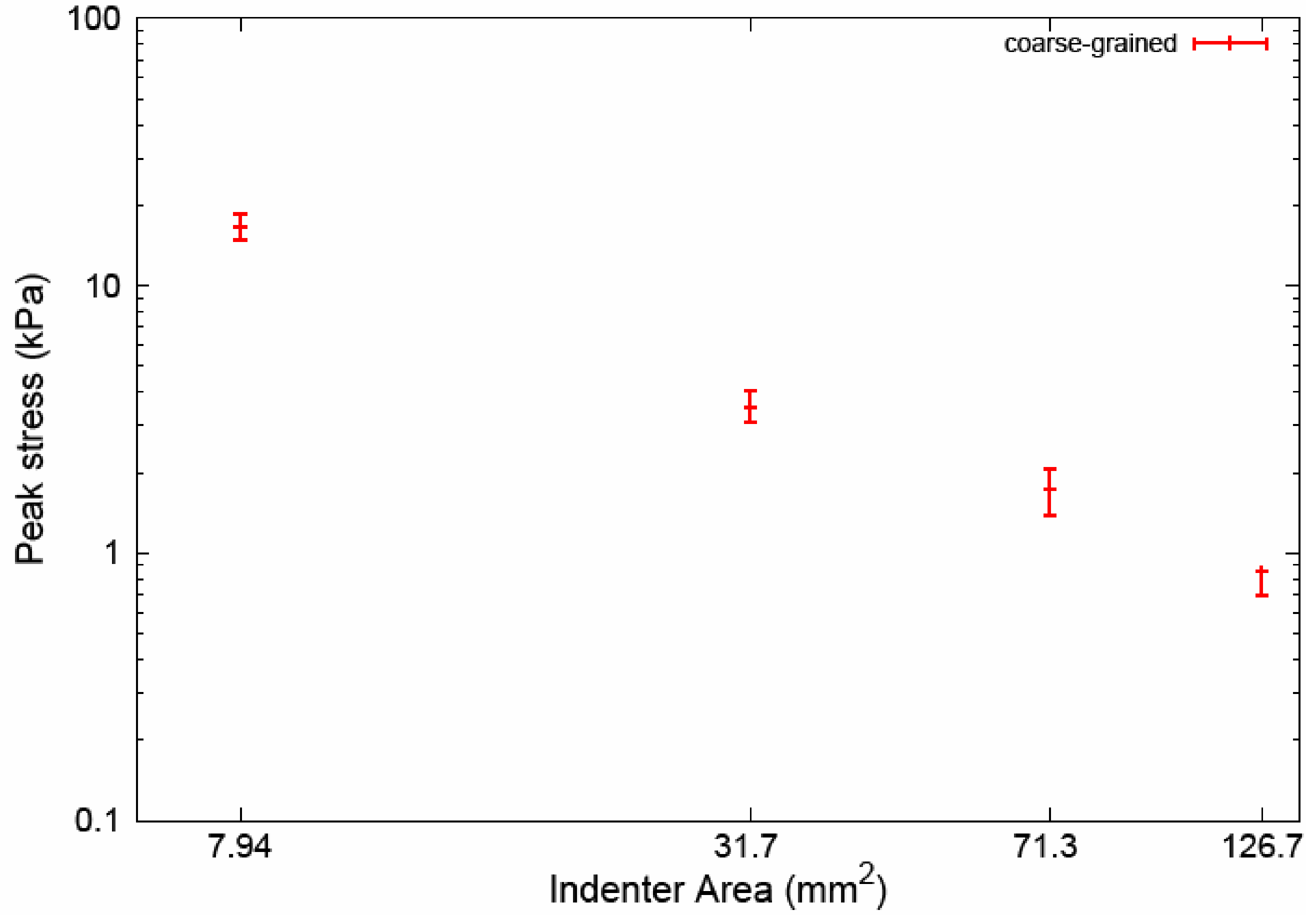
B-C: Hardening (additional damage)

C: Plateau stress

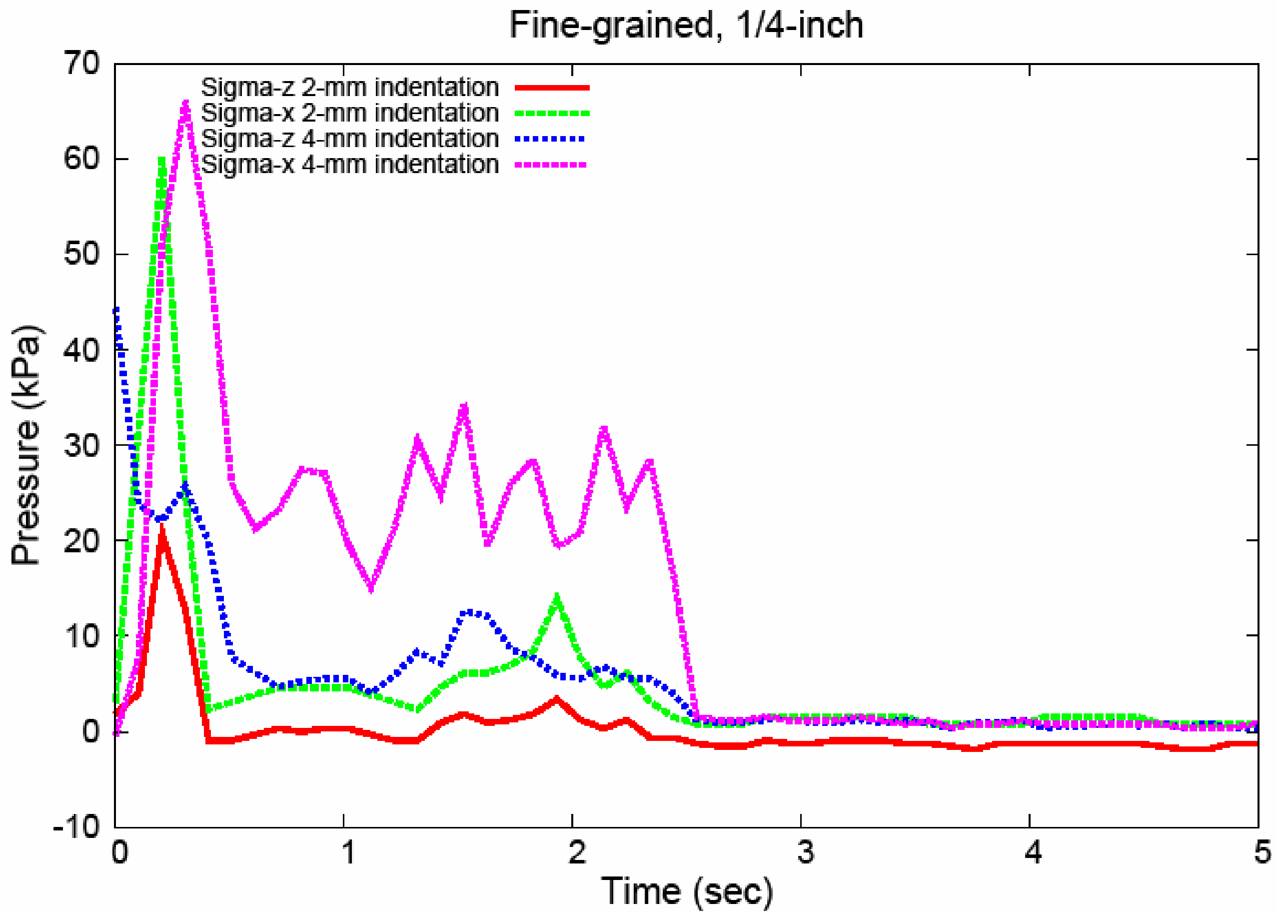
C-D: Compaction (little additional damage)

D-E: Densification (pressure bulb hits bottom)

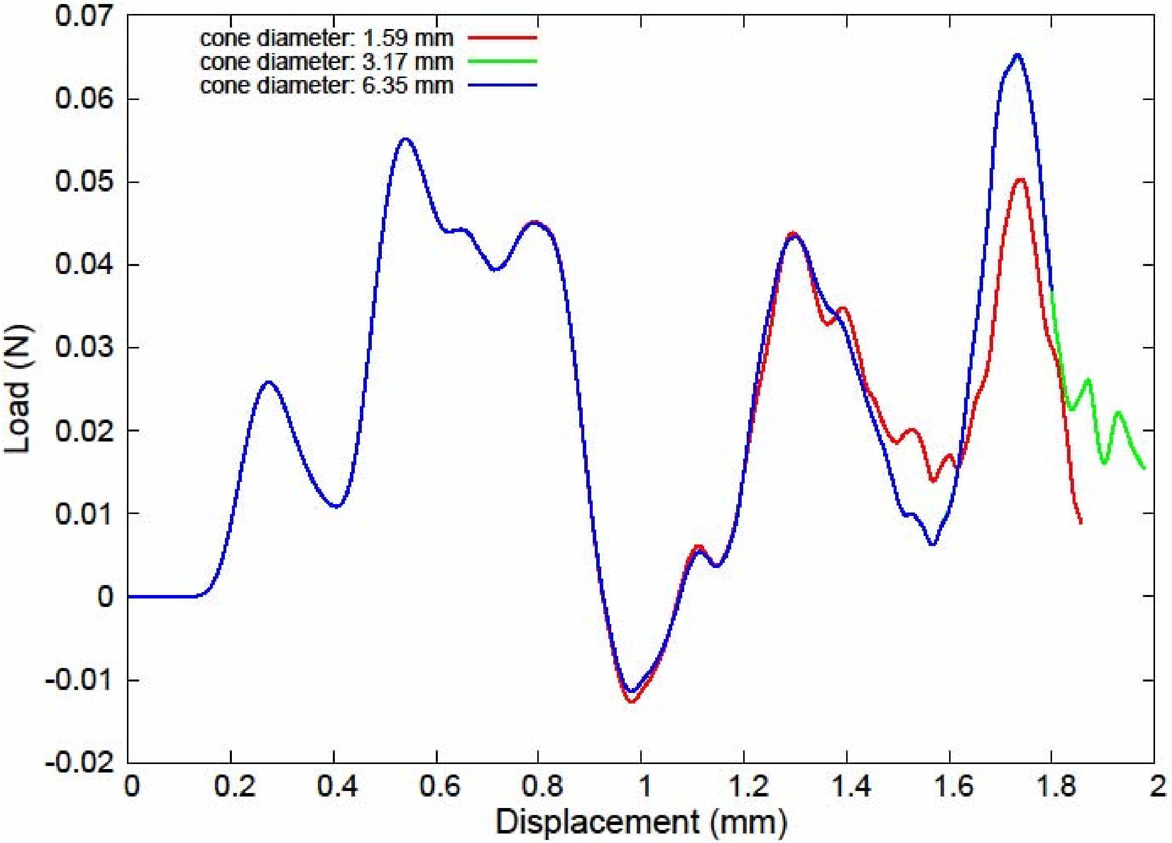
Initial Peak Stress ('Upper Yield'): Coarse-grained



Results: Plowing tests

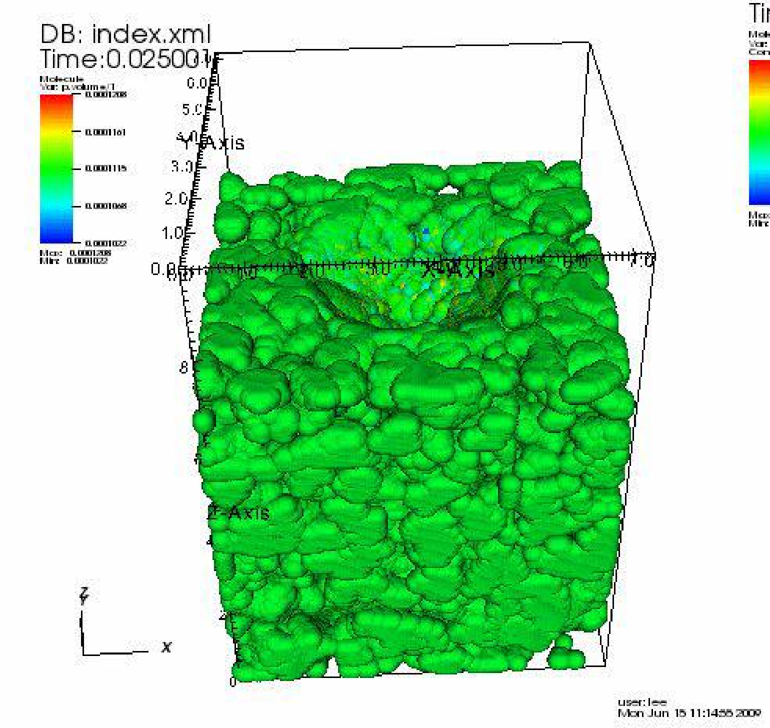


Results: Snow Penetration Simulations (45 deg inclusion angle)*

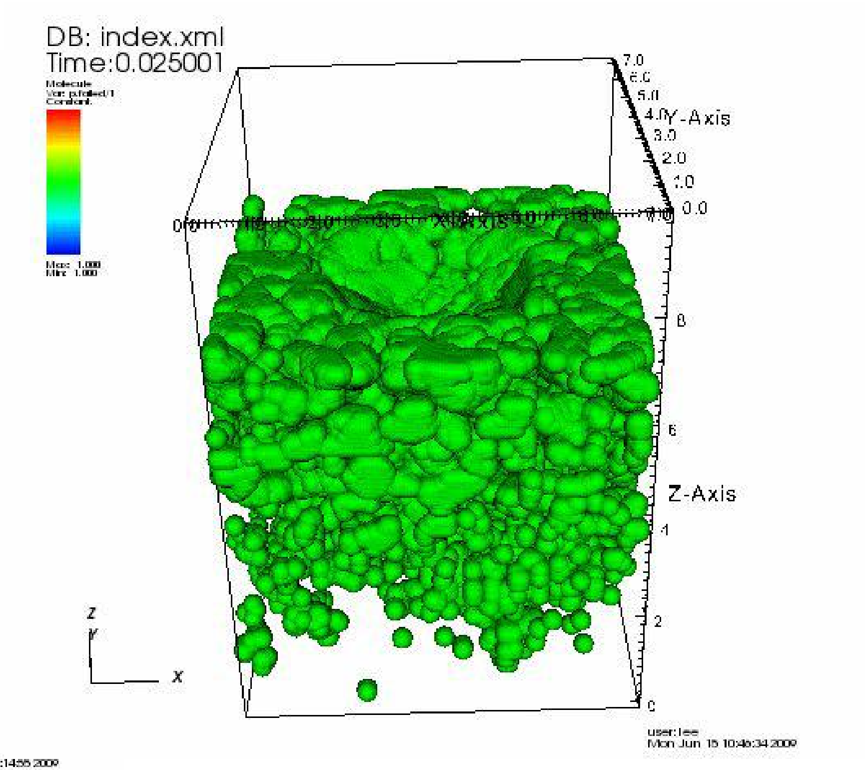


***Lee et al., Proceedings of ISTVS 2009**

Results: Typical Penetration Geometry



Deformed snow



Failed particles

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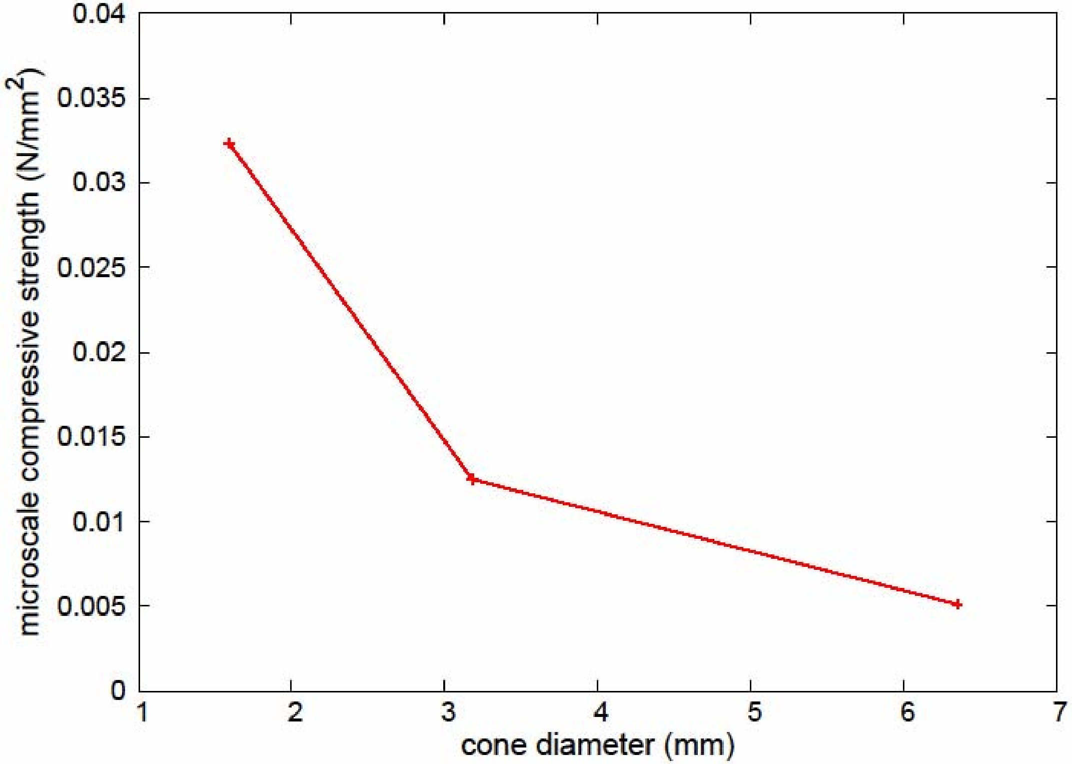
Results: Strengths from Inversion of Penetration Signals



Microscale compressive strength from simulation is 0.0063 N/mm^2

Part II:
Vehicle-Snow Interaction

- An instrumented vehicle (Alaska Instrumented Vehicle) to collect data about vehicle and wheel states
- A vehicle-mounted profilometer to measure terrain topology
- Equipment to obtain microstructure and mechanical properties of snow

Alaska Instrumented Vehicle

- 2008 Jeep Commander (with ESP)
- Vehicle states:
  - Longitudinal slip (via wheel longitudinal speed and wheel angular speed from ESP)
  - Vehicle speed, sideslip, wheel slip angle, yaw, pitch and roll (VBOX II SX ?+ ESP)
  - Wheel forces and moments
    - Kistler's wheel-force transducers (a set of 4)
- Validation on pavement first

Terrain Profiling

- Vehicle-mounted profilometer (Kern and Ferris, 2007)
  - Inertial navigation system (INS) to determine the position and orientation of the vehicle
    - Differential GPS system
    - Inertial measurement unit (IMU) – gyros and accelerometers for orientation and position
  - Scanning laser for profiling
  - 4-meter wide scan (claimed accuracy of vertical measurements 0.7-1.0 mm)
  - Claimed horizontal precision is 1mm for short-distance traveled

Measurements Needed

- Depth of snow cover ~5 cm – 30 cm
- Snow density and in-situ compressive strength
- Mechanical properties and microstructure by collecting and transporting select samples from field to lab
- Vehicle and wheel states

Tentative Test Protocols: Before Vehicle Travel

- Select areas for types of snow - (dry, wet, windblown etc.), depth of snow, strength of snow – with enough room to maneuver the two vehicles (AIV and profilometer)
- Measure snow depth by profiling ground twice – with and without snow (winter first, summer later)
- Measure snow properties along the intended path before vehicle travel

Tentative Test Protocols

- Passes:
  - Single pass: rut created by front wheels not traveled by rear wheels for virgin snow
  - Multiple passes for compacted snow
- After vehicle travel:
  - Measure sinkage (3D) using profilometer
  - Measure deformed mechanical properties of snow
- Maneuvers:
  - Combination of driven and driving wheels
  - Longitudinal and lateral motions
  - Effects of ESP

Development and Validation of Models for Virtual Proving Ground

- Development of stochastic terrain models
- Improvement of indentation model (J. Lee, 2009)
- Validation of stochastic tire-snow interaction model for combined slip (Li et al., 2009)
- Validation of finite element tire-snow interaction model for combined slip (J. Lee, under review)
- Validation of time-dependent tire-snow interaction model for combined slip (Lee and Liu, 2006)

People

- Daisy Huang, Ph.D. student, UAF: mechanical properties of snow.
- Steve Meurer, US Army Cold Region Test Center, Fort Greely, Alaska (the only winter test track in Alaska) : instrumentation and vehicle-snow interaction.
- Tom Johnson, Mechanical Engineer, UAF: instrumentation and vehicle-snow interaction.
- Dr. Al Reid, TARDEC: terrain profiling
- Open position of a postdoctoral fellow in vehicle-terrain interaction.

Collaborators

- Dr. Jim Guilkey, Schlumberger
- Hongyan Yuan, Penn State University, stochastic modeling of snow
- Dr. Jerry Johnson, UAF: snow mechanics and physics
- Professor Hans-Peter Marshall, Boise State University: snow mechanics and physics
- Professor Corina Sandu, Virginia Tech University: terrain topology, vehicle-terrain interaction
- Professor Zissimos Mourelatos, Oakland University: uncertainty modeling

Acknowledgements

- Arctic Region Supercomputing Center (ARSC).
- US Army TARDEC through the Simulation Based Reliability and Safety (SimBRS) research program.
- US Army TARDEC through the Automotive Research Center (ARC) led by the University of Michigan.
- US Army Cold Region Test Center (CRTC).