Vehicle-Snow Interaction:  
Modeling, Testing and Validation

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October 12, 2009  
Goodyear Tech Center, Luxembourg

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**Report Documentation Page**

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*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

- 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

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Experimental Procedure: Skyscan 1172 Microtomography
Experimental Procedure:
Snow Sample Holder

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

7.344 mm by 7.344 mm
Resolution: 1225 by 1225, Pixel size: 6 micron

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Experimental Procedure: Grey-Level Histogram

- **pore** is on the left side of the histogram
- **ice** is on the right side of the histogram
- **threshold** is indicated by a vertical line in the middle of the histogram
Experimental Procedure:
Segmentation

grey-level

binarized image

Black is ice

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Experimental Procedure:
Removal of Unconnected Parts

Binarized image

Remove speckles

Black is ice

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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)

Two-point probability function
Probability that two points a distance $r$ apart will lie in pore space
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
    - 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

Fine-grained snow depth=18mm, speed=5mm/sec

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Pressure (kPa) vs. Displacement (mm)
Microstructure after Indentation Tests via MicroCT

Fine-grained snow:
- Top View
  - Initial density: ~290 kg/m$^3$
  - Final density: ~590 kg/m$^3$

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Typical Indentation Simulation Results

Fine-grained snow, 71 mm/sec 1/4-inch indenter

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Typical Indentation Simulation Results: Cumulative damage

Fine-grained snow, 71 mm/sec

Normalized cumulative damage

Displacement (mm)
Failed Particles from Indentation Simulation

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Characteristics of Indentation Test Curves

Fine-grained snow, 5mm/sec

I  II  III  IV

Pressure (kPa)

Displacement (mm)

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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)

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

Fine-grained, 1/4-inch

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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).