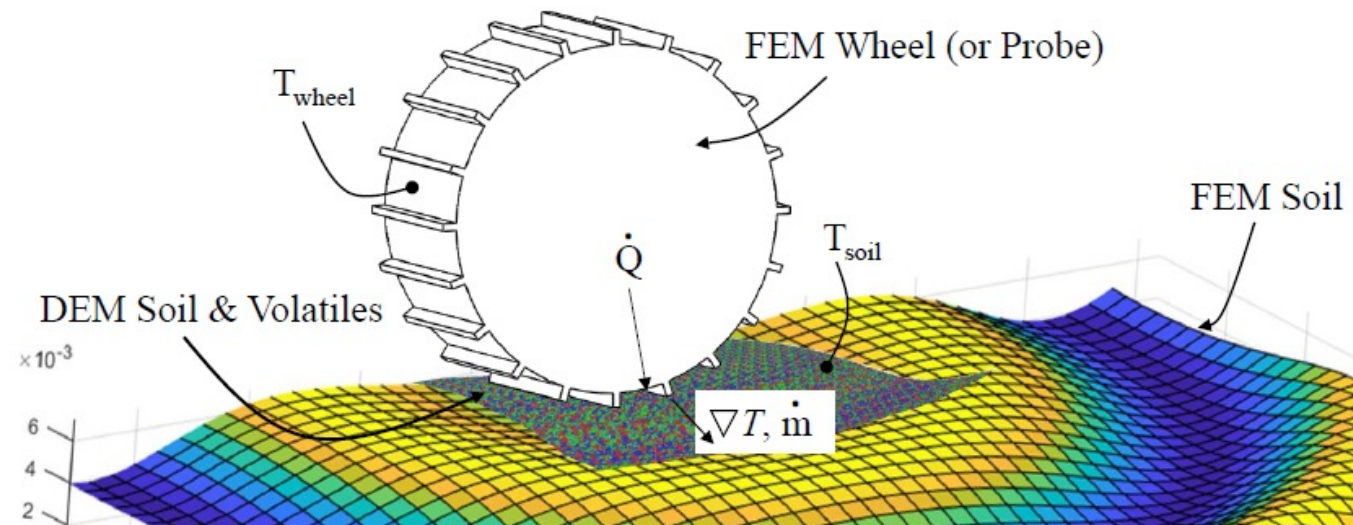




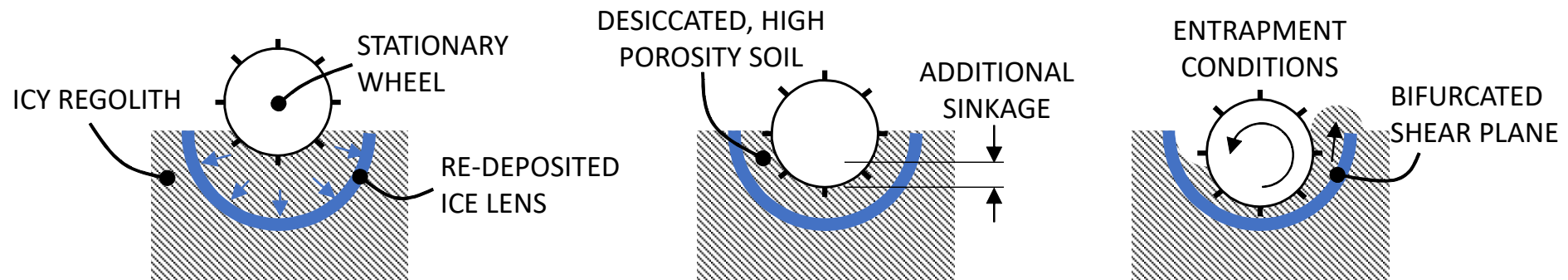
Development of Multi-Physics Modeling Tools for Testing Behavior of Lunar Regolith



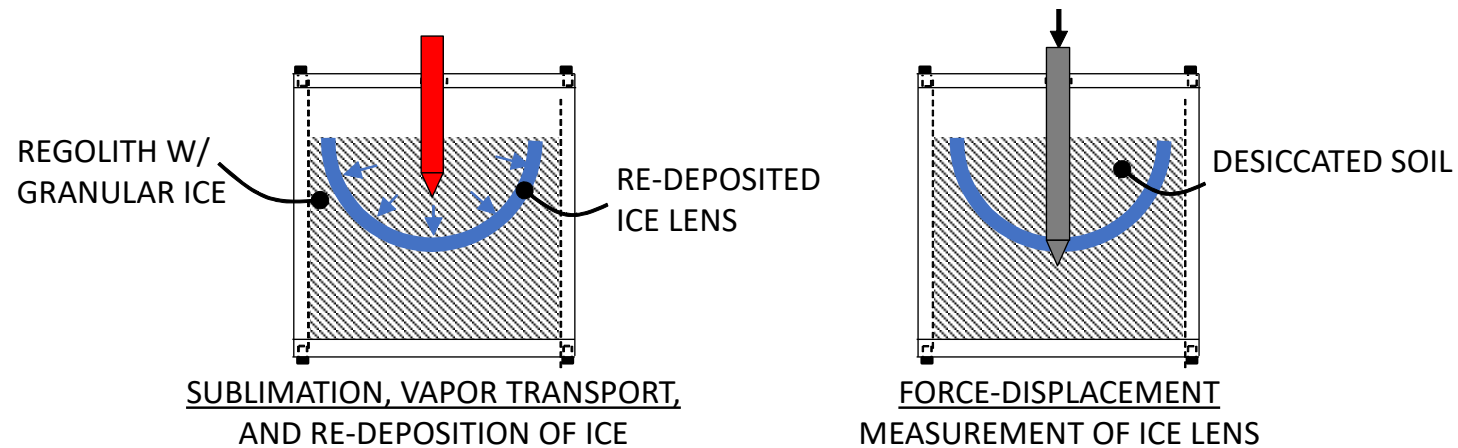
Space Resources Roundtable 2023 (Golden, CO)
Presented by Zoheir Khademian, PhD

Problem statement

- Hazards to rovers in Permanently Shadowed Regions (PSRs)
 - Greater heat loss from wheels if volatiles present
 - Entrapment hazard from desiccated soil/ice lens



- Challenges when drilling/sampling for volatiles

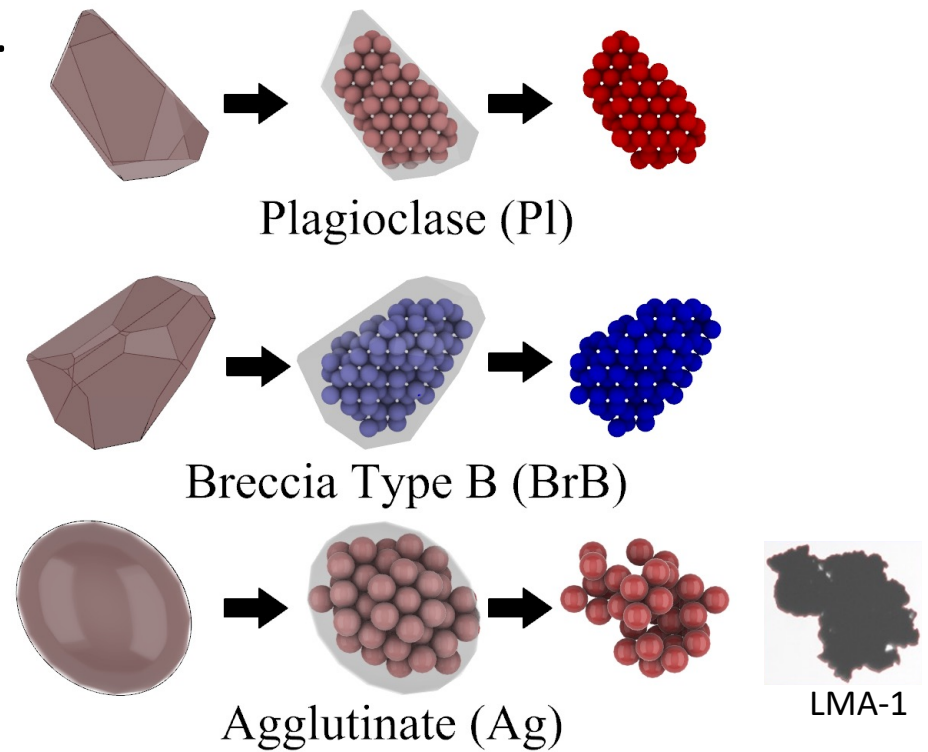
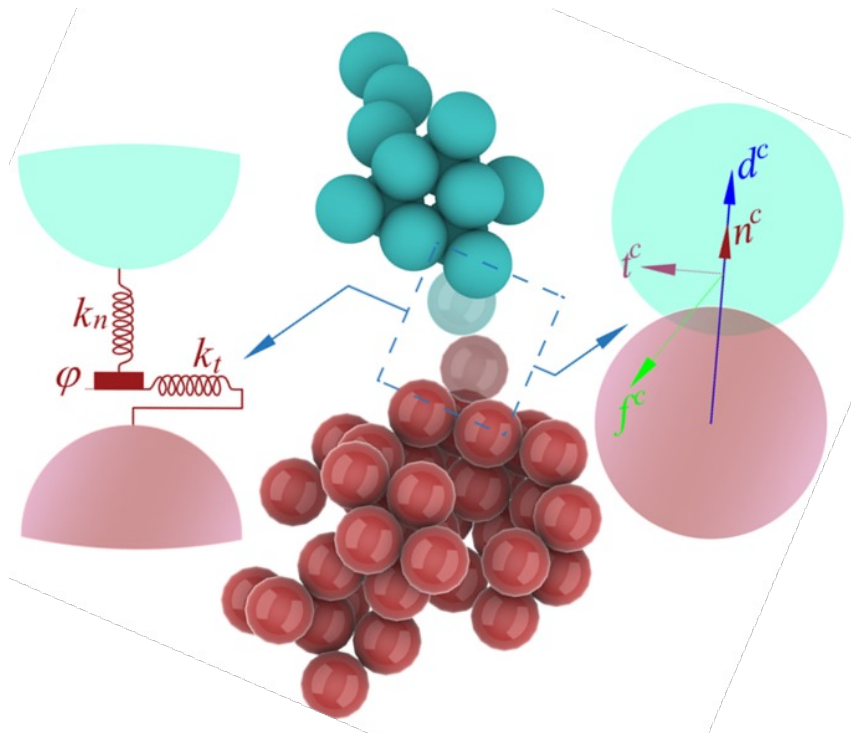


Objective

- **Multi-physics simulation software to evaluate:**
 - Rover mobility hazards near PSRs
 - Thermal design of hardware and rover power estimates
 - Control strategies for operating in PSRs and surviving the lunar night
 - Methods of sampling for volatiles and achieving more accurate estimates for in-situ volatile concentrations
 - Plume-regolith interaction
 - Thermal management of buried habitats
 - Thermal modeling of lunar cold traps
 - Compaction of lunar regolith by diurnal temperature cycles

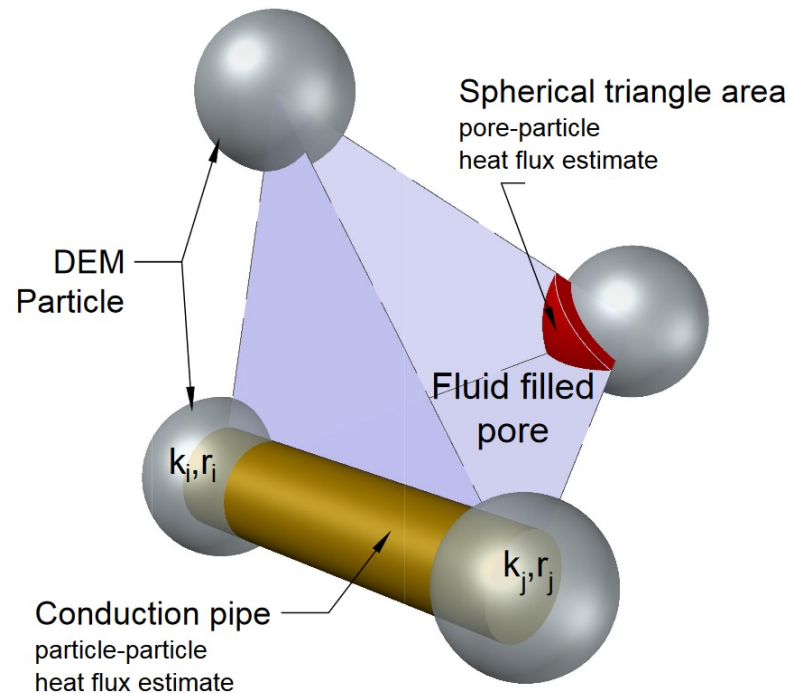
Methodology

- Discrete Element Method modeling:
 - Developed in an open-source software (YADE)
 - Explicit grain generation with realistic shape and size distributions with simple particle-particle interaction constitutive laws
 - Single sphere grains with complex constitutive laws.

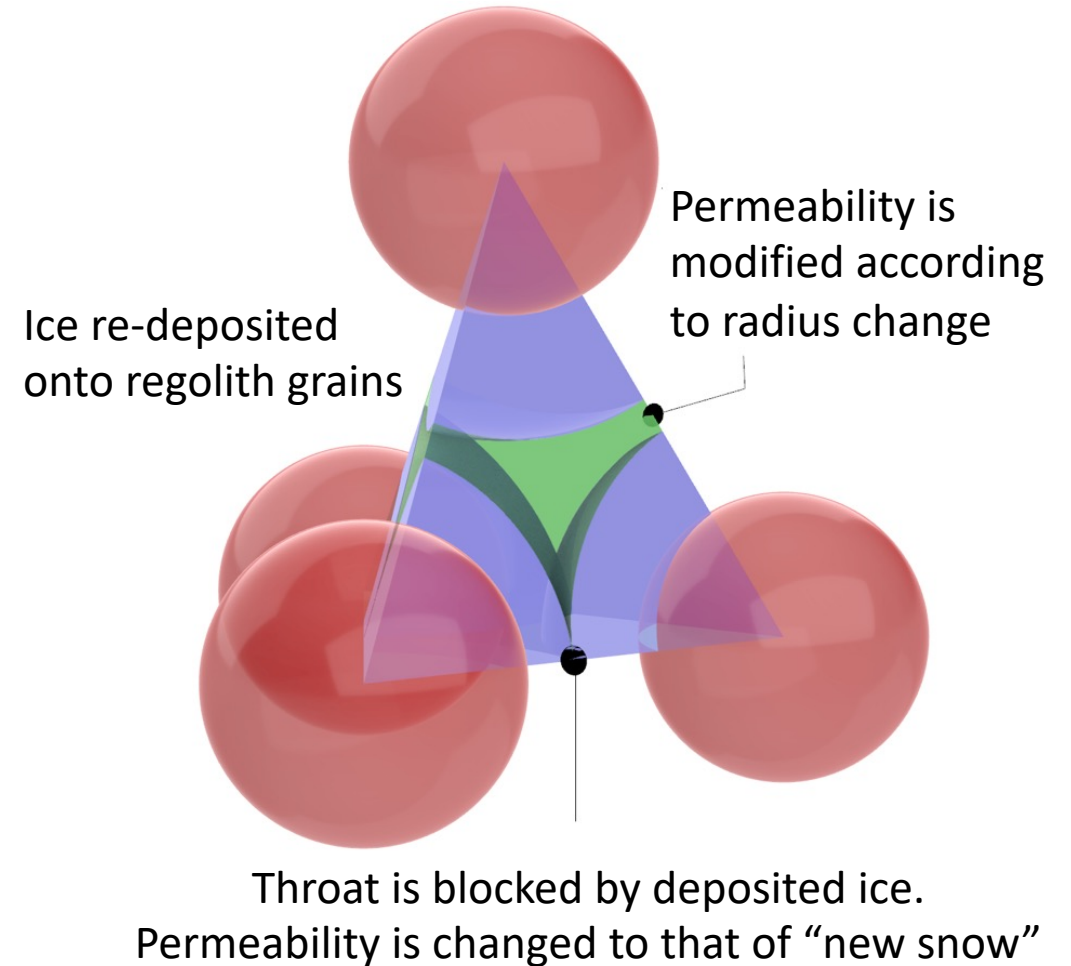


Methodology

- Discrete Element Method modeling:
 - Conductive heat transfer in icy regolith
 - Ice sublimation and vapor transport
 - Advective heat transfer
 - Ice/volatile re-deposition

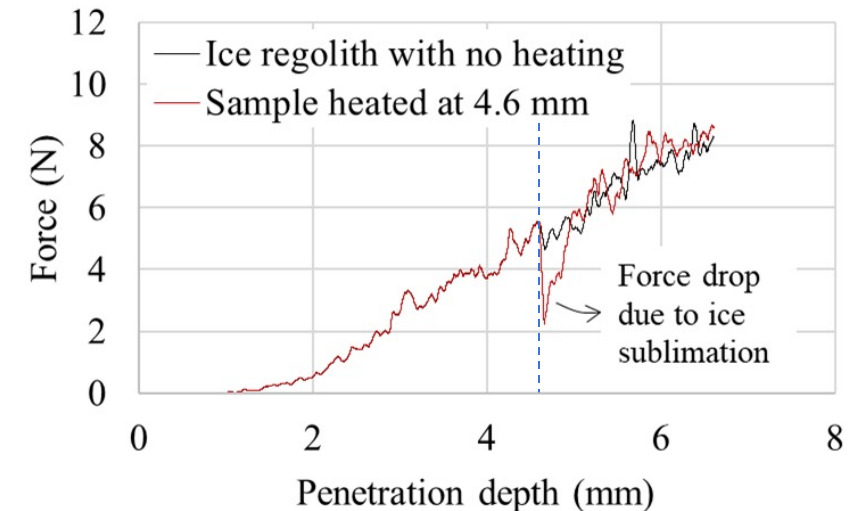
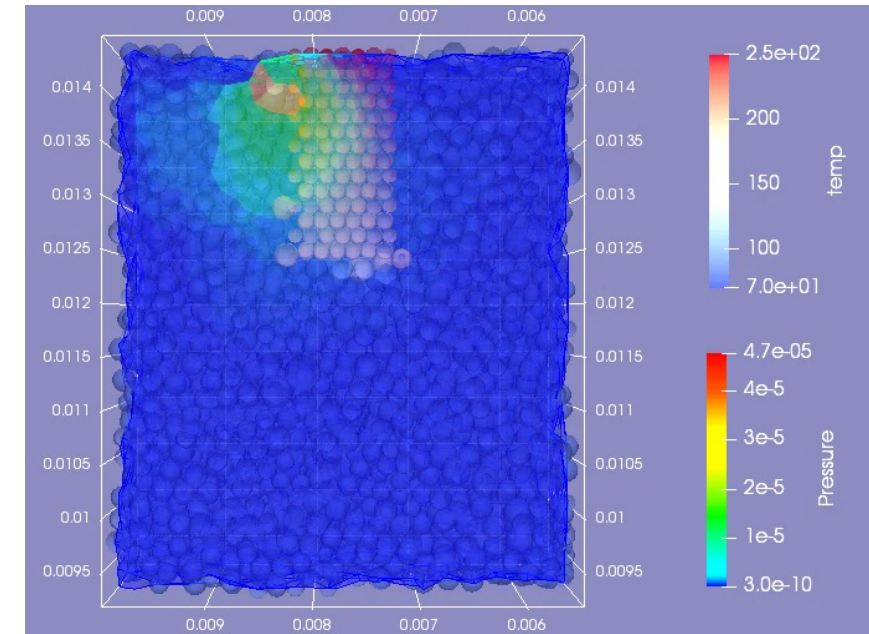
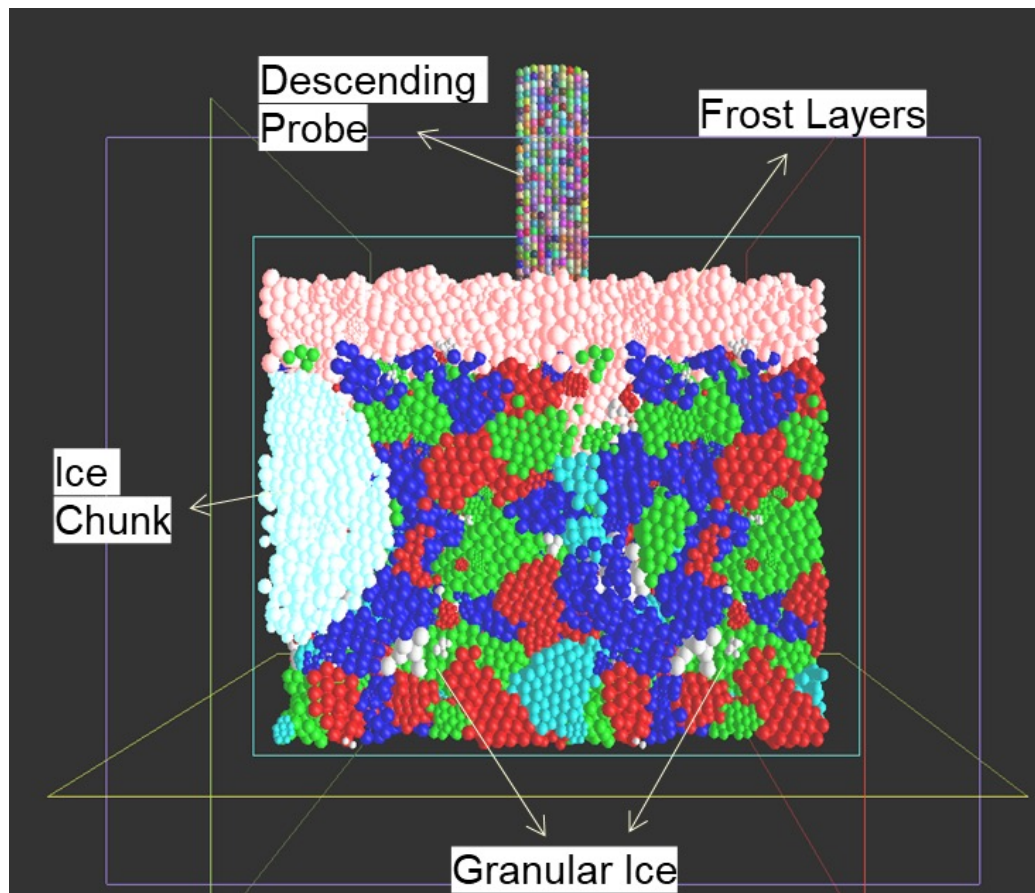


Caulk, et al (2019)



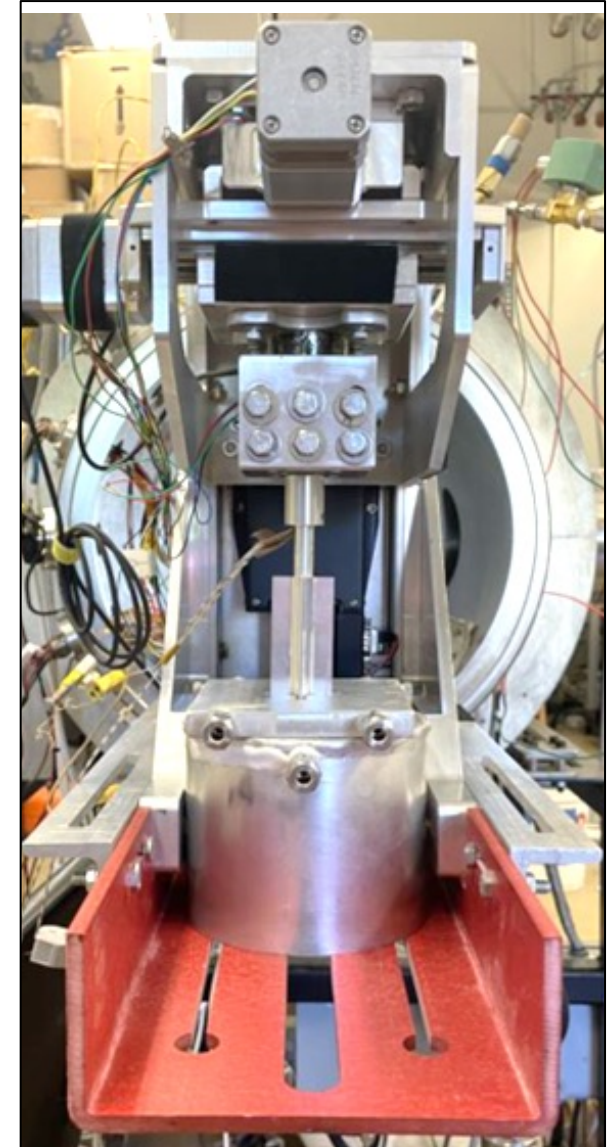
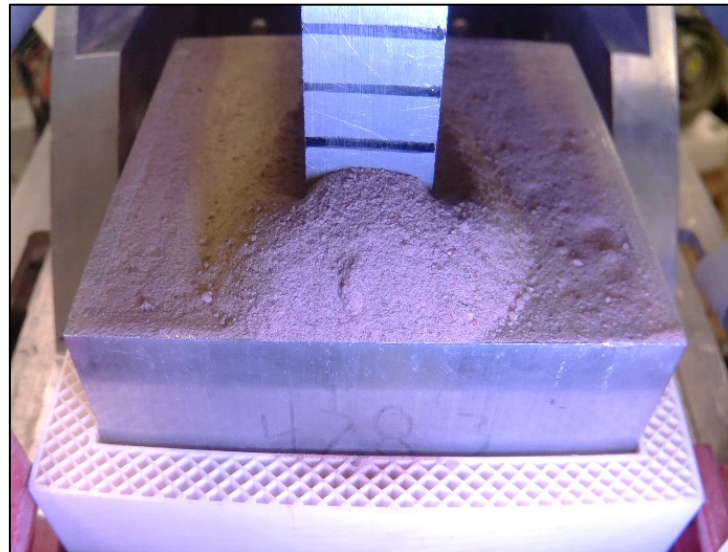
Heated Cone Penetrometer Tests

- Mechanical and thermal interactions
- Sublimation of ice and transport of vapor
- Change in mechanical response after sublimation

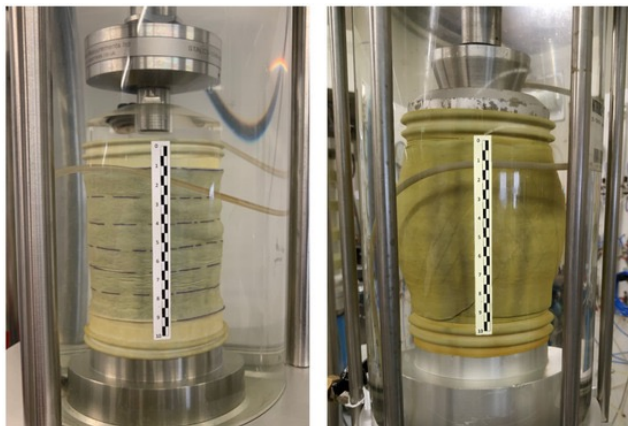


Methodology

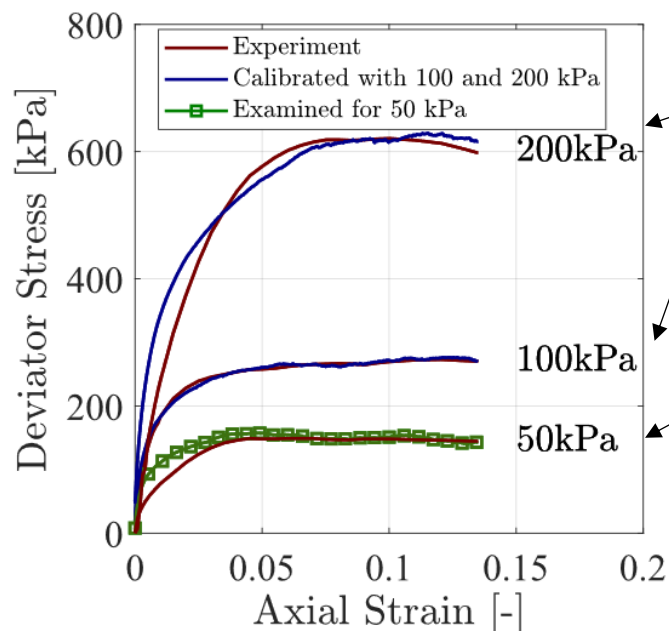
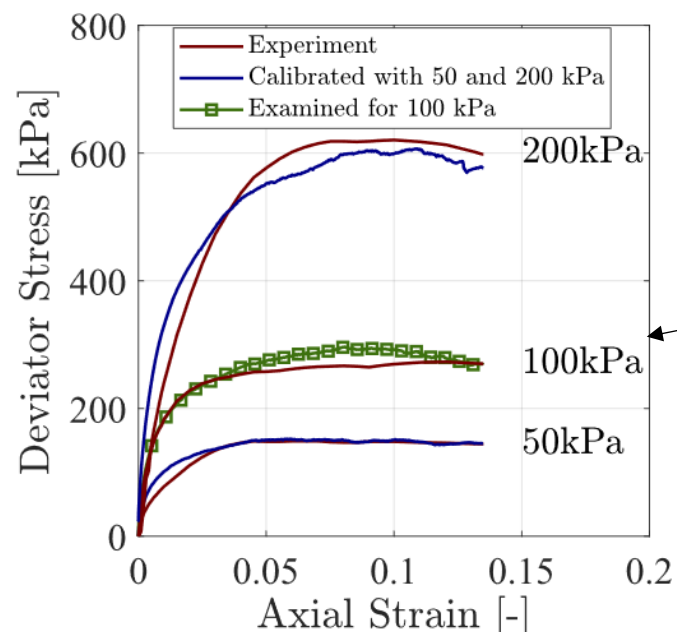
- Automated software tools to calibrate models to fit observable data
 - **Lab-scale experiments**
 - Triaxial compressive test
 - Angle of repose test
 - 3D heat transfer through regolith
 - Vane shear test
 - **In-situ data**
 - Plume-induced crater geometry
 - Rover tracks/ruts
 - Footprints



Methodology: Automated Calibration Tool



Da Fonseca et al. (2021)

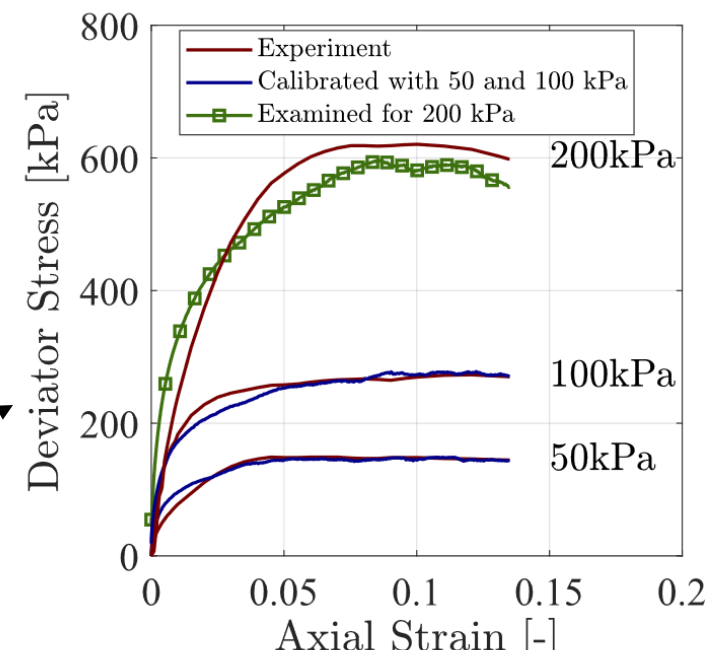


Micromechanical inputs
calibrated to fit training sets

Model's predictive performance
evaluated against test sets

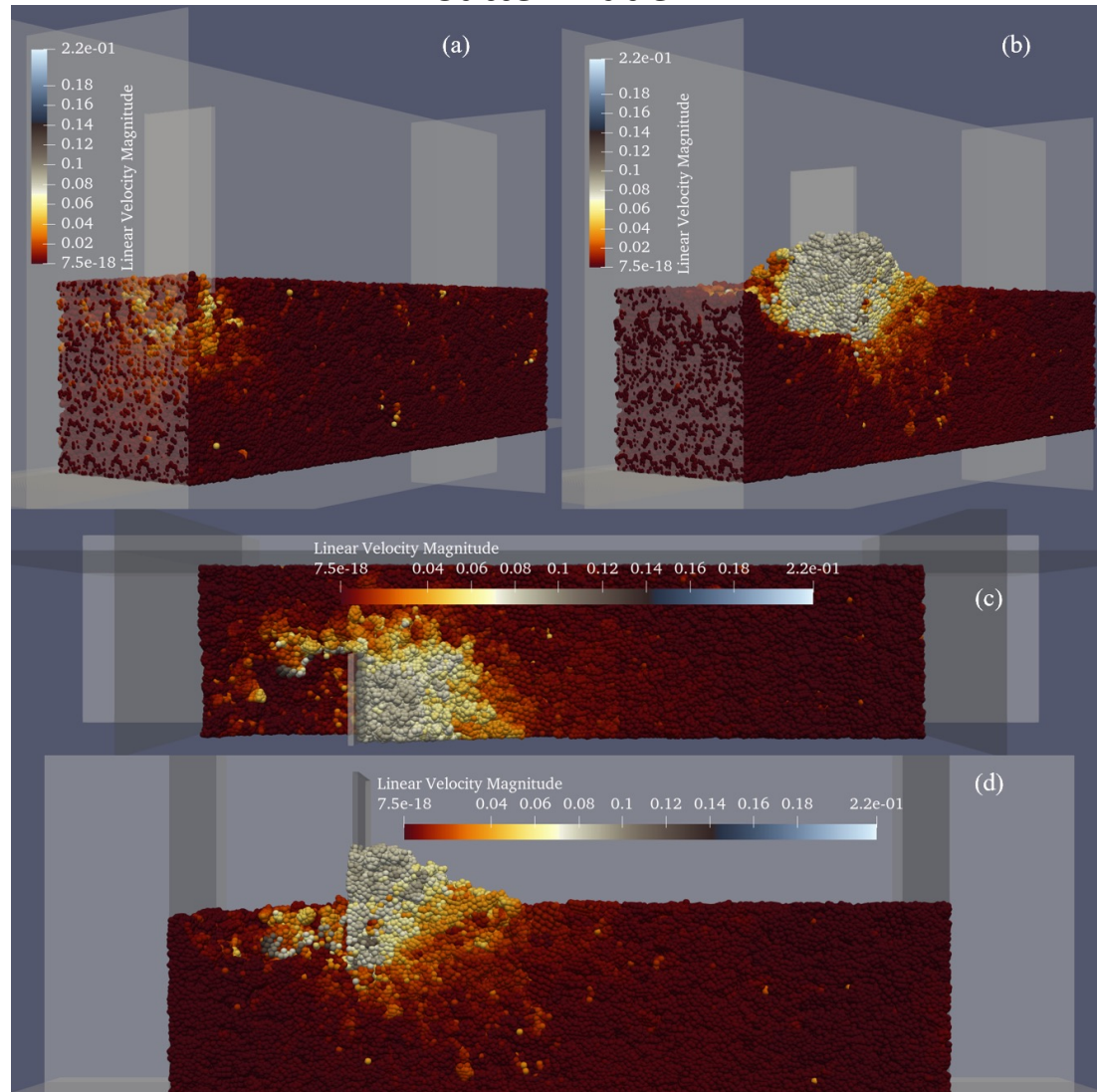
Results indicate that calibration
process can be used to
interpolate regolith response

... and extrapolate to new
environments and conditions

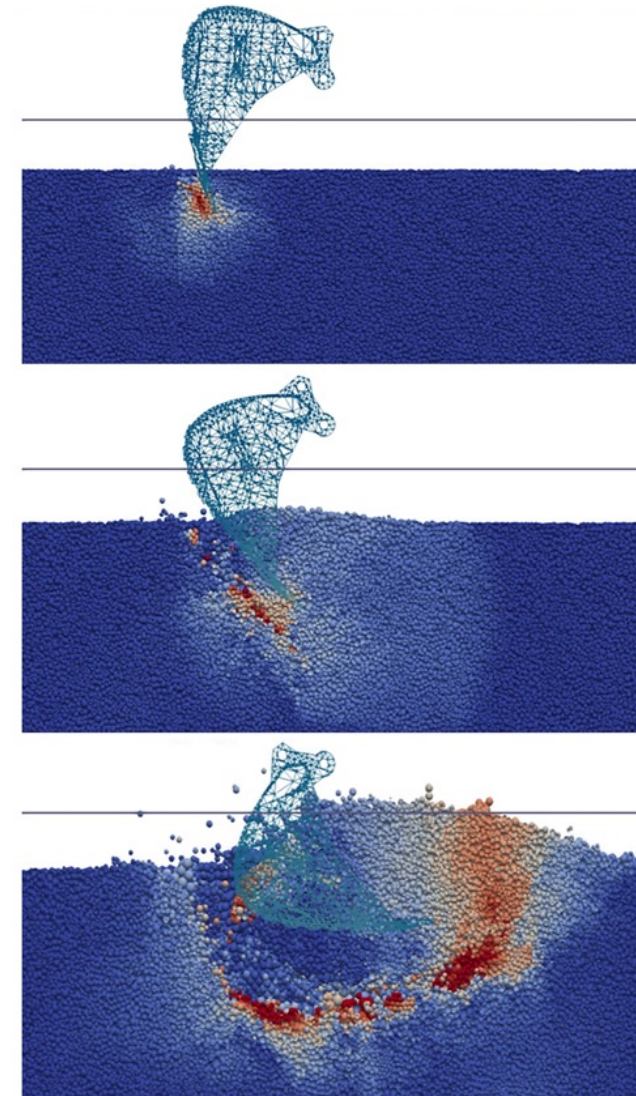


Applications: Large-Scale DEM Models

Cutter Blade

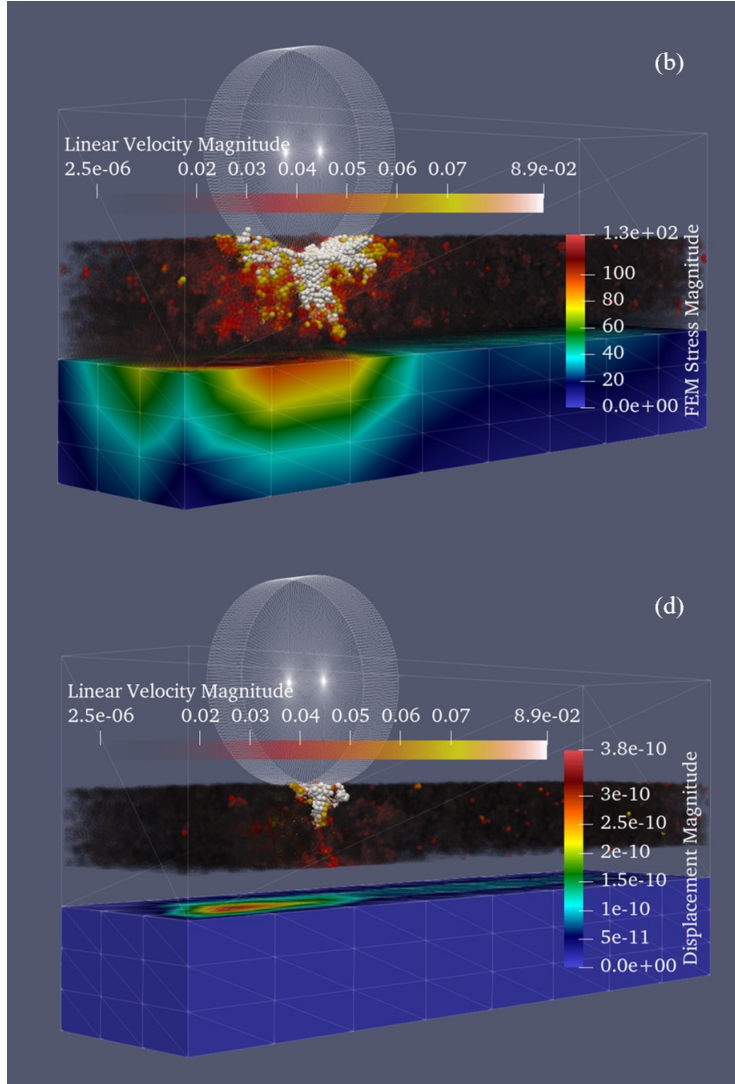


Bucket Excavator

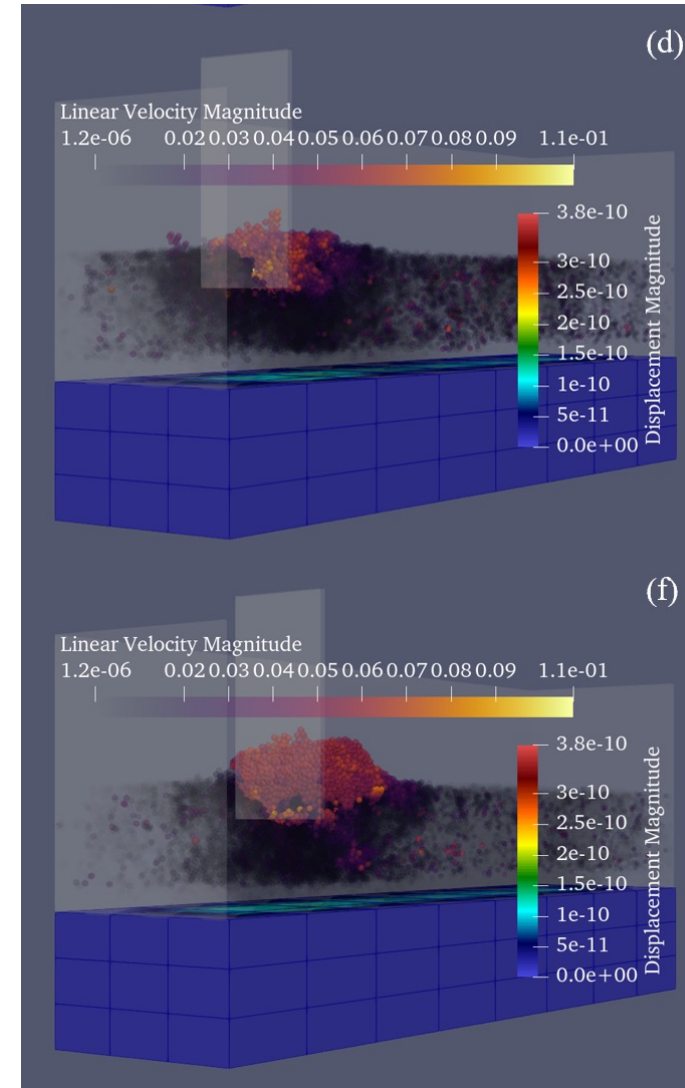


Applications: Large-Scale DEM-FEM Models

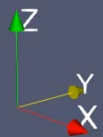
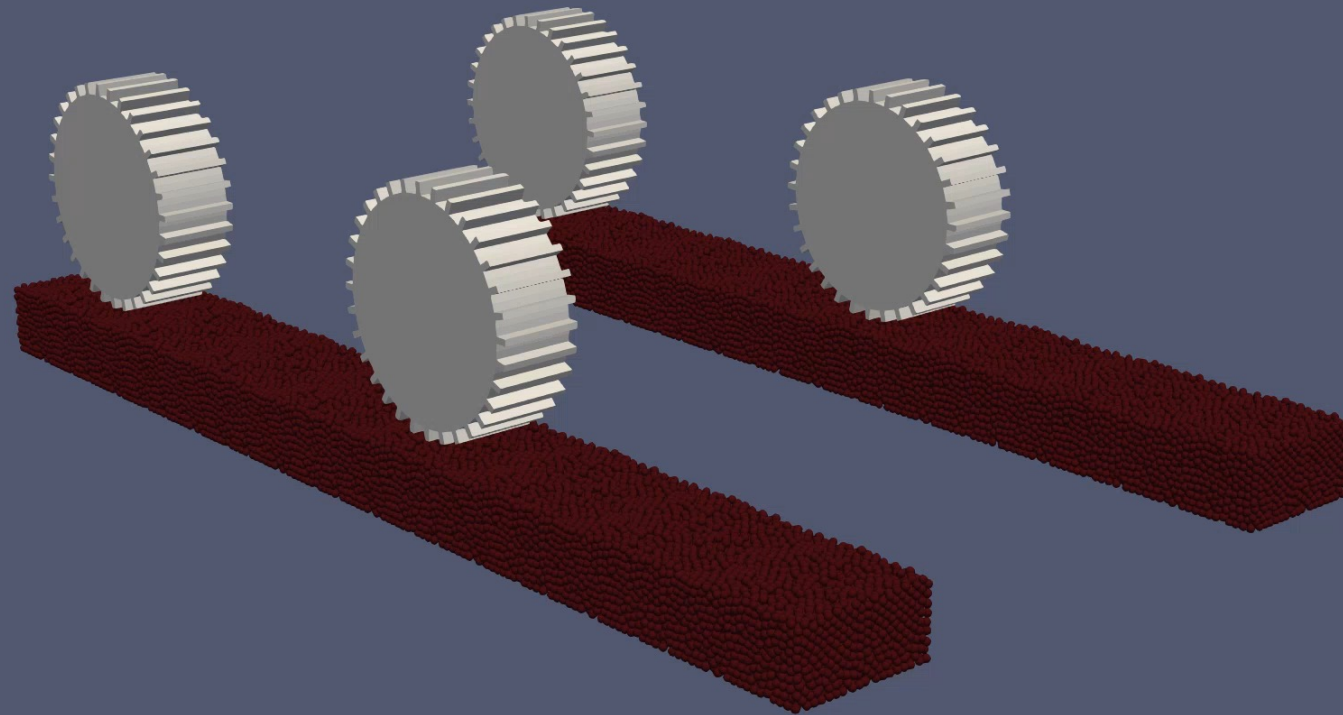
Wheel Traversing over Regolith



Cutter Blade Test



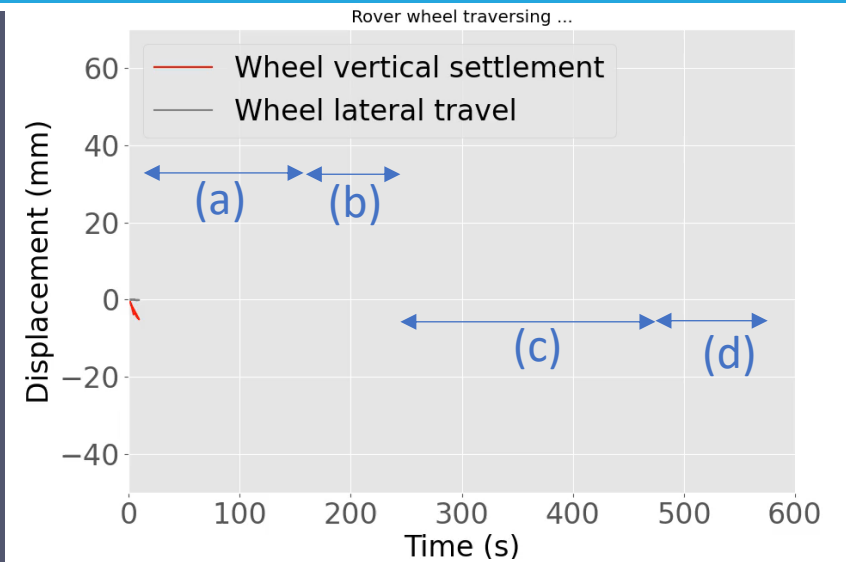
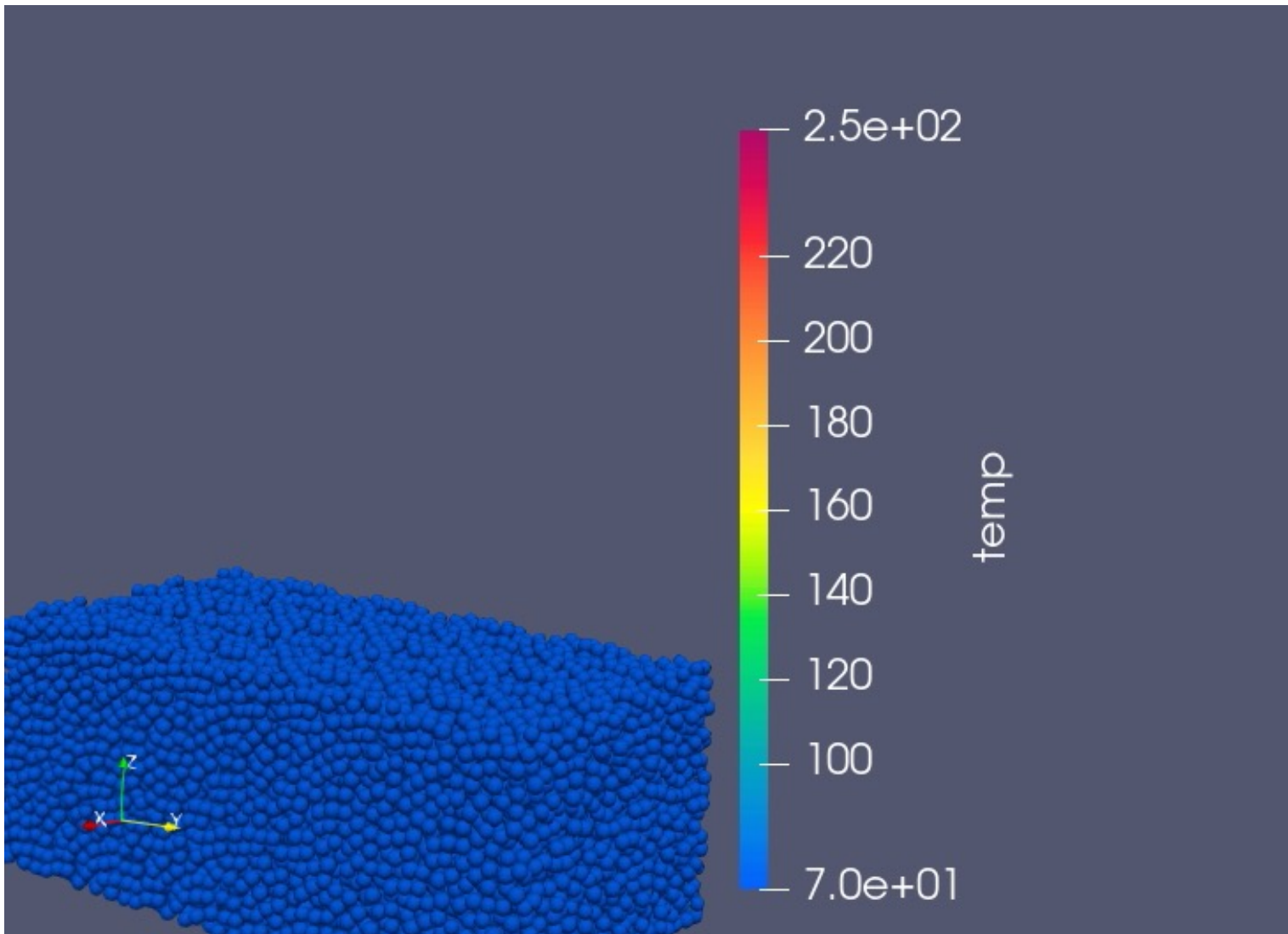
- Input and output parameters:
 - Torque -> slip ratio and velocities
 - Slip ratio and velocities -> Torque and drawbar pull



Wheels communicate with each other through stiff springs simulating rover chassis

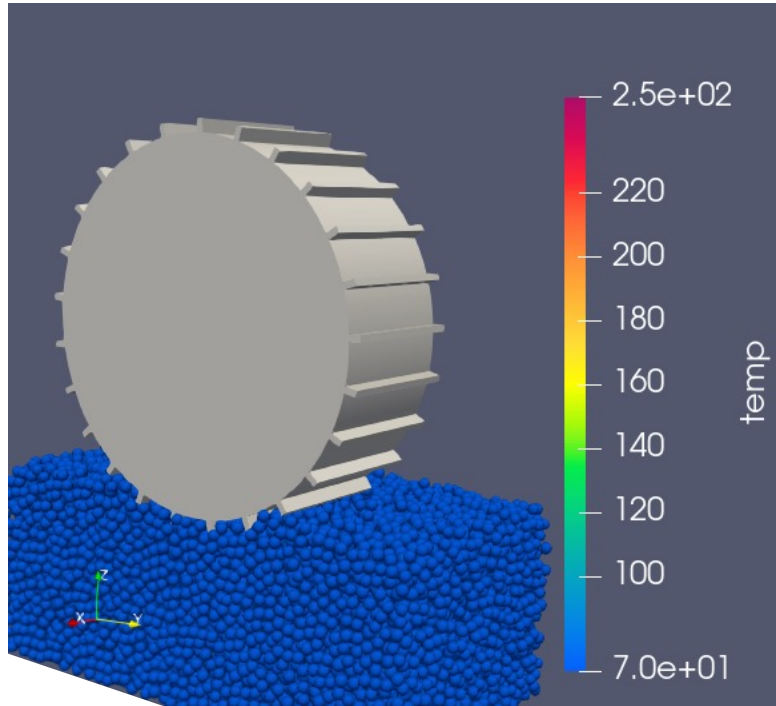


Rover wheel entrapment



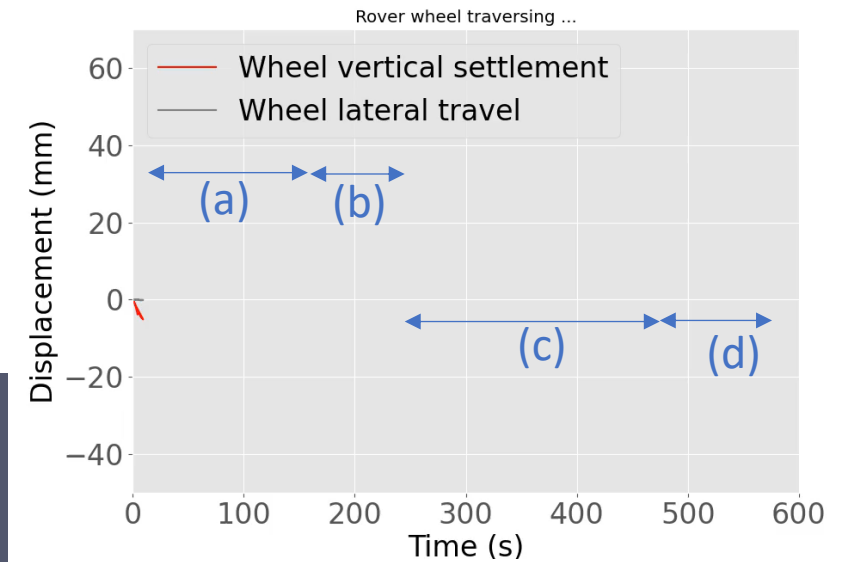
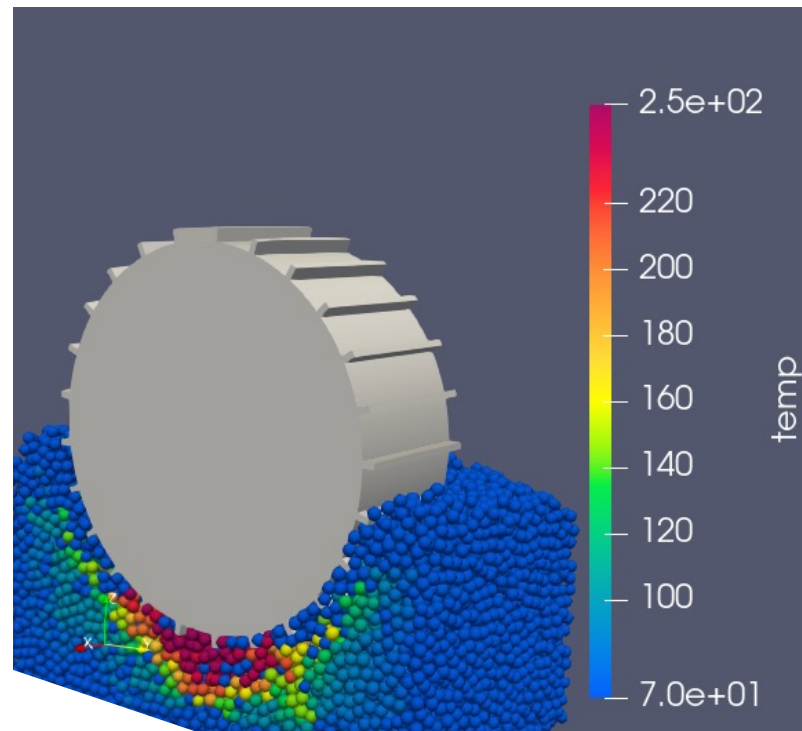
- (a) Initial sinkage
- (b) Secondary sinkage due to sublimated ice
- (c) Rover traversing
- (d) Wheel entrapment

Rover wheel entrapment



After initial settlement
under lunar gravity

After secondary settlement
due to sublimated grains



- (a) Initial sinkage
- (b) Secondary sinkage due to sublimated ice
- (c) Rover traversing
- (d) Wheel entrapment

Summary

- Multi-physics modeling tools for simulating soil mechanics, heat transfer, phase change, and vapor transport problems relevant to lunar environment
- High-fidelity model of regolith
- Automated calibration tools
- Applicable to rover trafficability, ice mining and sampling, plume-surface interaction, regolith-tool interactions, thermal control systems, geotechnical characterization, ...

Free open-source software tools for simulating lunar regolith:
<https://github.com/outTechFOSS2023/Outward-Terramechanics>

Questions?



Zoheir Khademian, PhD
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Free open-source software tools for
simulating lunar regolith, soil-wheel,
and soil-tool interactions:
<https://github.com/outTechFOSS2023/Outward-Terramechanics>



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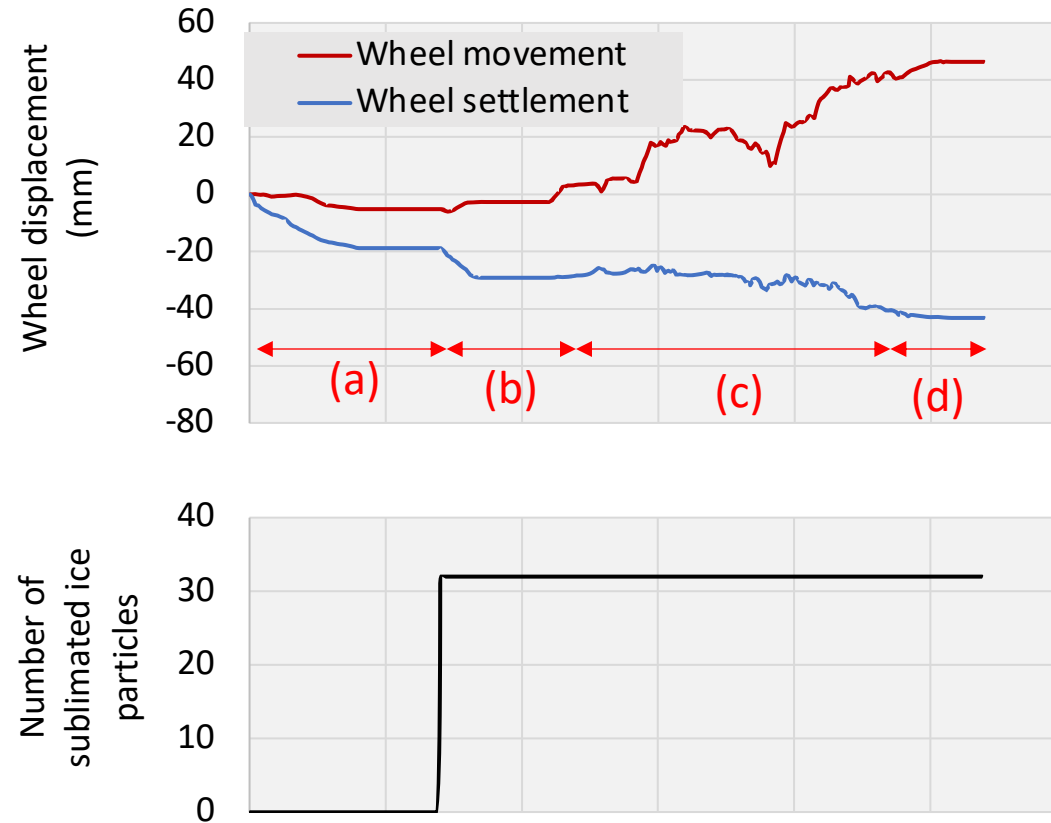


Nima Goudarzi, PhD
ngoudarzi@outward.tech

Rover wheel entrapment

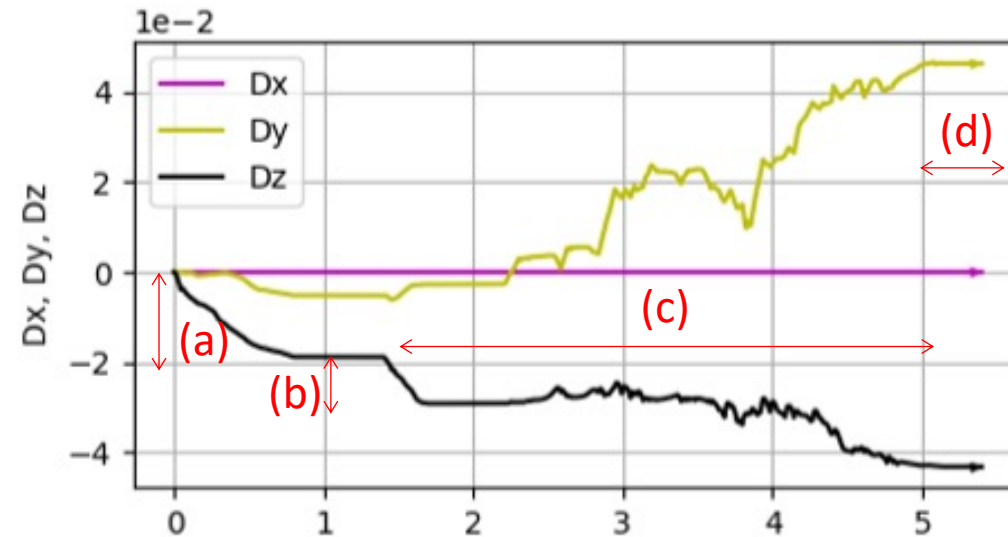
- (a) Initial sinkage
- (b) Secondary sinkage due to sublimated ice
- (c) Rover traversing
- (d) Wheel entrapment

- 32 ice particles are sublimated
- Regolith porosity is locally increased, leading to wheel entrapment.

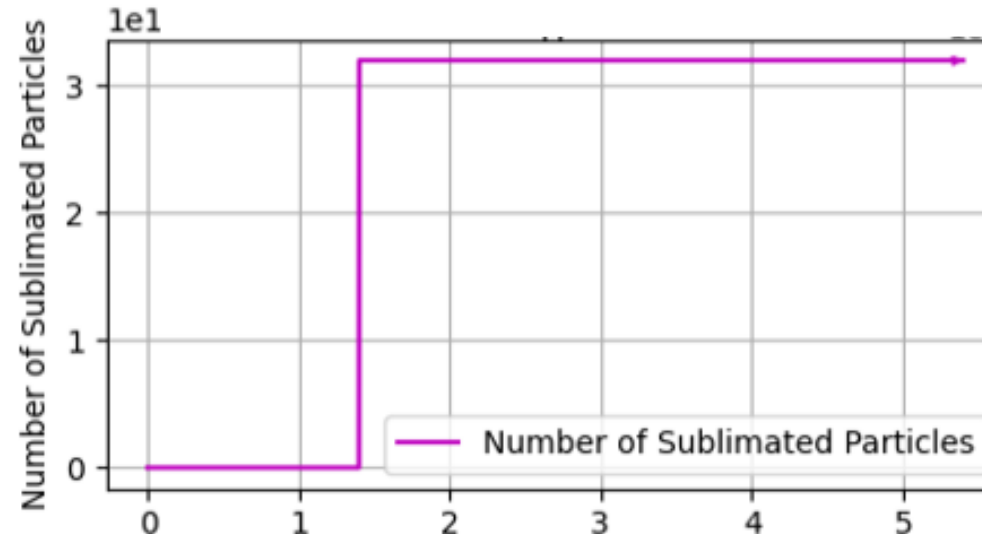


Rover wheel entrapment

- (a) Initial sinkage
- (b) Secondary sinkage due to sublimated ice
- (c) Rover traversing
- (d) Wheel entrapment

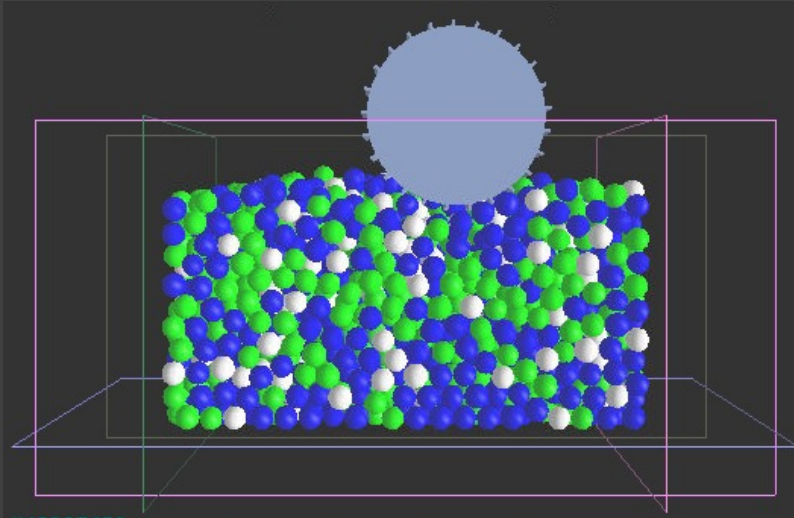


- 32 ice particles are sublimated
- Regolith porosity is increased locally
- Leading to wheel entrapment

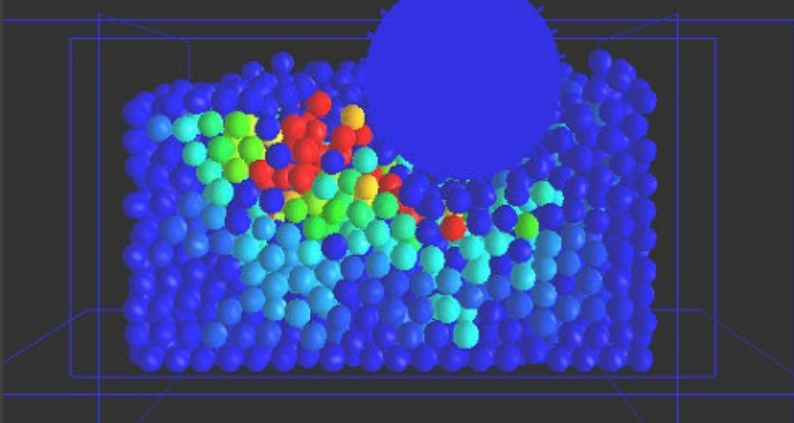


Rover wheel entrapment

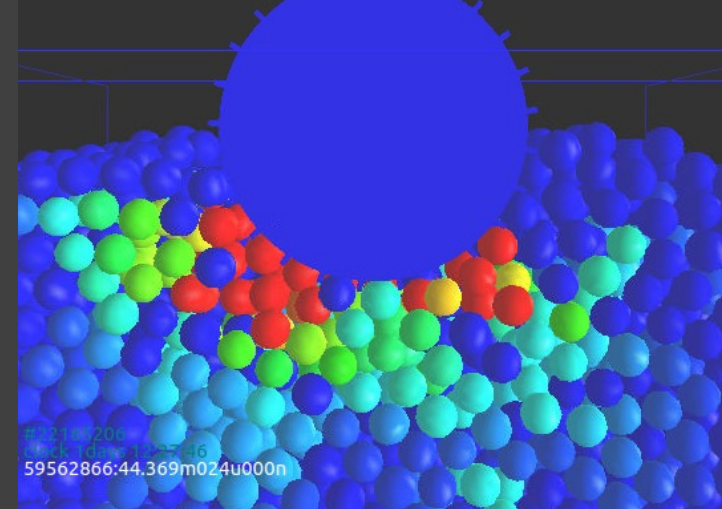
- Initial wheel settlement on icy regolith



- Wheel entrapment



- Secondary wheel settlement due to ice sublimation



- Input and output parameters:
 - Torque -> slip ratio and velocities
 - Slip ratio and velocities -> Torque and drawbar pull