Development of modeling tools for testing thermo-hydro-mechanical behavior of lunar regolith

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Introduction: Understanding the thermomechanical response of lunar regolith is a prerequisite for planning a wide range of lunar surface operations including ice sampling, drilling, rover mobility, and habitat construction. This paper presents a novel approach using the Discrete Element Method (DEM) for explicitly modeling regolith grains with accurate size and shape distributions. An automated calibration procedure is adopted within this method to fine-tune the microscale mechanical and thermal properties of the regolith at any level of resolution applied to grain shape and particle size. This allows for scalability of the modeled domain to keep computational time at manageable levels for different size experiments. The results show that DEM may be used to simulate the complex thermomechanical response of lunar regolith and the transport of sublimated vapors through a regolith matrix using free open-source software tools. Microscale parameters may be calibrated by robust automated methods to match complex thermomechanical responses of regolith and ice-regolith mixtures. These combined tools may then be used to inexpensively evaluate lunar hardware and lunar surface operations across a wide range of possible ground conditions to be encountered on the Moon.

Lunar Regolith Models:

The combination of grain shape and particle size distribution have been identified as major drivers in the complex particle flow response of extraterrestrial granular materials [1]. A technique was developed using Distinct Element Method (DEM) in an open-source software YADE to explicitly model granular regolith as a cluster of different-sized DEM spheres with these clusters being generated from scanned grain shape and particle size distributions. Shape indices were obtained from a particle analyzer and were included in the models through stochastic inputs such as minimum and maximum aspect ratios, cross-sectional areas, and volumes of the grains. A user-defined set of input parameters was used to determine the volume of the modeled sample, limits on the modeled grain size, grain shape complexity, and mass ratio of regolith grain types in the model. This technique was also used to reproduce agglutinates with irregular shapes and internal voids and vesicles. The input grain shape complexity index directly relates to the computation time and defines the resolution of modeled grain surfaces that can range from single-sphere grains to grains with high-resolution shapes. To capture the effects of real grain size and shape distributions on the thermomechanical response of regolith at any given resolution, an automated calibration procedure was adopted [2] to fine-tune micro-scale mechanical and thermal properties of regolith.

Thermo-hydro-mechanical Simulations:

Due to a lack of ground truth measurements, modeling ice-regolith thermomechanical response, sublimation of the ice, and its possible re-deposition can provide understanding of the heat transfer in cryogenic conditions. Virtual heated cone penetrometer tests were conducted in YADE DEM. Fig. 1 shows the DEM model of heat transfer through an ice-regolith mixture with different ice types and vapor transport after the sublimation of ice particles.

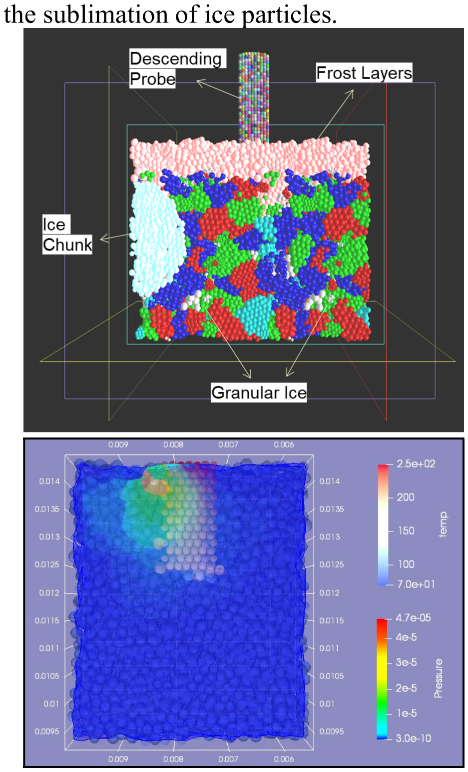

Fig. 1. Model of heated icy regolith for volatile sampling tests (top). Flow of vapor after ice particles are sublimated (bottom)

Force-displacement measurements were taken as the probe penetrated through a regolith sample containing granular ice at 10% by weight (Fig. 2). After an initial penetration of 4.6 mm, the probe was heated to

250 K temperature under vacuum conditions. The force-displacement data of the probe is shown in Fig. 2. The model simulated sublimation of ice particles and the subsequent flow of vapor through regolith. This test was then repeated without heating of the probe with these results also shown in Fig. 2.

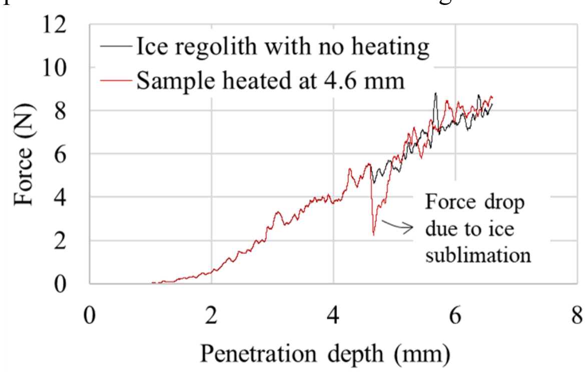

Fig. 2 Force – displacement for heated and unheated cone penetrometer tests

Comparing the force-displacement curves between the heated and unheated cone penetrometer cases showed a drop of 3 N in the case of the heated cone penetrometer. In the second penetration period, the force on the heated probe again reaches the force level of the unheated test. This force drop for the heated cone penetrometer test implies a potential increase in porosity and reduction in cohesive characteristics of icy regolith if sublimation occurs locally which could lead to potential challenges for rover mobility or sampling accuracy of water ice content in regolith.

Automated Calibration Procedure:

An automated calibration scheme [2] was integrated with YADE DEM. The calibration procedure begins by generating initial sets of microscale inputs randomly selected from a user-defined range of allowable input values. The mechanical response of the regolith is then tested using virtual tests such as triaxial compressive strength tests, cone penetrometer tests, vane shear tests, and angle of repose tests. Following testing of the initial sets of samples, the most fit microscale parameters are selected to continue iterating until an optimal set of microscale parameters is found which matches a desired macroscale response. The calibration process continues until a predefined calibration target is reached, typically set to be within 1% residual error of desired stress-strain, force-displacement, time-temperature, and/or slope contour curves. The automated calibration routine represents a robust tool to address the most significant challenge of DEM which is the calibration of microscale inputs to fit the modeled response to a desired macroscopic response.

Consolidated-drained triaxial compressive strength tests were conducted on mixtures of GRC-3 geotechnical lunar highlands regolith simulant and LMA-1 lunar agglutinate simulant. Using the grain generation technique explained above, the simulants were reproduced in YADE DEM and triaxial tests were conducted to mimic the experimental conditions in the lab tests. The micromechanical properties of the simulants were then calibrated using the automated calibration technique with calibrated results shown in Fig. 3 and compared to the stress-strain curves obtained from physical experiments under three confinement levels. Other mechanical tests were conducted in the lab for cross-validating the calibrated micromechanical properties of the modeled GRC-3 and LMA-1 grains including cutter blade, vane shear, and wheel-regolith interaction experiments.

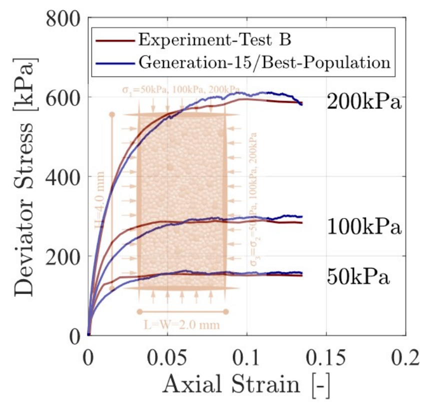

Fig. 3 Results of automatic calibration of deviatoric stress-axial strain response during triaxial tests.

The developed DEM-based technique for modeling thermomechanical response of icy regolith can benefit the broader DEM modeling community while addressing several key applications within NASA's Moon-to-Mars campaign. Examples include evaluating performance of rover wheels in PSRs with unknown ground conditions such as concentrations and forms of volatiles, low soil compaction, and variations of soil grain shapes and sizes. Heat transfer through icy regolith is also poorly understood and these modeling tools could be used to evaluate the transport of vapor and the change in ground conditions caused by sublimation of volatiles which could cause additional uncertainty for *in-situ* ice sampling results or even lead to rover entrapment.

References:

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