

Challenges in Predicting Planetary Granular Mechanics

Philip T. Metzger

NASA, John F. Kennedy Space Center, KSC Applied Physics Lab

YA-C3-E, Kennedy Space Center, FL 32899

Philip.T.Metzger@nasa.gov

Through the course of human history, our needs in agriculture, habitat construction, and resource extraction have driven us to gain more experience working with the granular materials of planet Earth than with any other type of substance in nature, with the possible exception being water. Furthermore, throughout the past two centuries we have seen a dramatic and ever growing interest among scientists and engineers to understand and predict both its static and rheological properties. Ironically, however, despite this wealth of experience we still do not have a fundamental understanding of the complex physical phenomena that emerge even as just ordinary sand is shaken, squeezed or poured. As humanity is now reaching outward through the solar system, not only robotically but also with our immediate human presence, the need to understand and predict granular mechanics has taken on a new dimension. We must learn to farm, build and mine the regoliths of other planets where the environmental conditions are different than on Earth, and we are rapidly discovering that the effects of these environmental conditions are not trivial. Some of the relevant environmental features include the regolith formation processes throughout a planet's geologic and hydrologic history, the unknown mixtures of volatiles residing within the soil, the relative strength of gravitation, and the atmospheric pressure and its seasonal variations.

The need to work with soils outside our terrestrial experience base provides us with both a challenge and an opportunity. The challenge is to learn how to extrapolate our experience into these new planetary conditions, enabling the engineering decisions that are needed right now as we take the next few steps in solar system exploration. The opportunity is to use these new planetary environments as laboratories that will help us to see granular mechanics in new ways, to challenge our assumptions, and to help us finally unravel the elusive physics that lie behind complex granular phenomena. Toward these goals, a workshop was held recently at NASA's John F. Kennedy Space Center, attracting over a hundred scientists and engineers from around the world and from a broad cross-section of scientific and engineering disciplines. This talk will provide an out-briefing from that workshop, communicating some of its early findings in regard to lunar and Martian exploration: (1) the requirements for working with granular materials, (2) the challenges that granular materials will pose, (3) the environmental conditions that affect granular mechanics, (4) instruments and measurements that are needed on the Moon and Mars to support granular material research, and (5) some of the possible research avenues that should be pursued.

Challenges in Predicting Planetary Granular Mechanics

Philip Metzger

NASA, KSC Applied Physics Laboratory

Common challenges

- Jamming in Hoppers
- Unintended Segregation versus Mixing
- Unpredictable stress loads
- Widely variable stress loads
- Compaction or dilation under vibration or shear
- Dealing with cohesive, dry powders

Scaling of Industrial Processes

- Reduced g, pressure, humidity, etc.
 - Scaling laws not fully worked out from first principles
- Scale-up of industrial processes requires significant experimental and prototyping effort
 - even under familiar terrestrial conditions
- Trial-and-error to properly scale the environmental conditions to the new size-scale of the process
 - laboratory experiments
 - demonstration units
 - prototypes
 - Full-sized prototype cannot be verified except *in situ* on the Moon or Mars
 - unless further scientific understanding is first obtained

Challenges with Lunar Soil

- Sharp, interlocking particles
 - Formation history and lack of weathering
 - Statics and dynamics contrary to terrestrial experience
 - Soil mechanics and powder processing protocols often rely upon that base of experience
 - Because first-principles physics not been solved yet
- Lunar excavation difficult
 - High friction
 - High cohesion in low g
 - Highly compacted

Lunar Environmental Differences

- Gravity
- Increased cohesiveness
- Electrostatics
 - Ultraviolet photoemission
 - Lack of atmosphere
 - Extreme dust dynamics
 - Surface charging (pos. and neg.) and grounding issues
- Volatiles adsorbed in/on the grains
 - Due to solar wind
 - Different than in a planetary atmosphere
- Vacuum conditions
 - Non-Stokesian, ballistic flow regime produces qualitatively different flow or shaking behaviors than in Earth's atmosphere
 - Lack of winnowing for ejected fine particles
 - May affect friction and cohesion
- Temperature extremes
 - Strain of granular material could jam material or damage equipment

Martian Environmental Differences

- Reduced Gravity (between the lunar and terrestrial cases)
- Increased cohesiveness due to several factors
- Electrostatic differences due to low humidity and pressure
 - Increased cohesion
- Uncertain particle size and shape distributions
 - Effects of weathering?
 - Affect on granular flow?
 - Need sample return or *in situ* microscopic analysis for ground truth
- Hydrological history is TBD so state of the regolith is also TBD
 - Subsurface characteristics
 - Volatile inventory and distribution
- Lower ambient pressure
 - Mars seasonal dependence in Non-Stokesian flow regime produces qualitative and quantitative differences in granular heaping behavior
- Low temperature
- Varieties of soil
 - Probably a much great variety than the lunar case
 - There is no single “Martian soil”

Inaccessibility of the Target Material

- Unlikely to have good soil characterization prior to the mission
 - Relative to terrestrial experience
 - Lunar soil is fairly homogenous and well characterized, compared to Martian soil
 - Challenge to predict behavior of Martian soil
- Difficult to predict excavation energy and torque requirements
 - Keep excavator mass and energy consumption at a minimum
 - Without knowing the characteristics of the regolith, including possible ice components
- Must base design & engineering on a few kilograms of real sample
 - Lunar soil exists on Earth in a few small samples – not enough for large experiments and not enough to go around to all researchers
 - If we do Mars sample return, it will provide only a small quantity of soil
 - Simulants must be developed to fill in the gap
 - Correct mechanical and physical properties
 - For Moon, should include the effects of agglutinates and other fines
 - For Mars, no ground-truth on which to base its properties
 - Martian soil is probably very heterogeneous comparing different geological units
- Fundamental granular properties needed
 - Lunar soil is fairly well characterized for mechanical properties
 - Martian soil is not
 - Design instrument packages or techniques to autonomously obtain the information needed from Mars
 - Possible sample return
 - In the mean time, guess the properties using best reasoning to develop simulants and models

Challenges with Volatiles

- Permafrost stability beneath structures
 - Ice composition and distribution?
- Unknown volatile outgasing due to heat loads
 - Thermophysics of these ices?
 - Thermal conductivity and porosity of the soils?
 - Effect of seasonal and diurnal barometric pumping for the Martian case?
- Predicting moisture dynamics in reduced g, extraterrestrial soil
 - Very complex and not completely understood, yet
 - Need to work out the physics for these phenomena, including gravity dependencies and barometric pumping effects
 - Lack of knowledge of the Martian soil porosity, pore size distribution, etc.

Mission-Related Challenges

- Mobility-transport of large size articles
 - Apollo missions were limited in the distance astronauts could travel due to uncertainties in the regolith/rover interaction
 - Getting stuck away from the habitation module could result in loss of life
 - ISRU will require larger articles such as autonomous dump trucks
 - Loss of capability could abort mission
 - Predict soil/tire interactions, bearing strength, etc., with sufficient confidence to enable larger mission scope
- Launch/landing
 - High-energy gas/soil interaction
 - Grain-scale gas flow easily predictable (Navier-Stokes, CFD)
 - But, averaging effects over many grains is beyond our ability
 - Emergence of macroscopic flow patterns not yet predictable
- Resource-infrastructure depends on mission plans and architecture
 - What is required for equatorial lunar base is different from a polar base

Dust

- Avoid creating dust in processing applications
- Challenge removing it
 - From people
 - From instruments / optics
 - From mechanical joints in hardware
- Avoid high use of consumables in the process
 - Filtration
 - Electrostatics
 - Magnetism
 - Other methods

Requirements for Working with Granular Materials

- Mission site selection
 - Pre-assess volatile content for ISRU and scientific value
 - Interpret visual images of geophysical flows (i.e., wet or dry)
 - In situ robotic drilling
 - Interpret other data sets
 - Predict local geotechnical characteristics
 - bearing capacity
 - traction on slopes
 - amenability to access, excavation, and processing
 - other characteristics of local regolith that affect mission operations

Requirements, Cont'd

- Launch & Landing
 - Surface & subsurface characterization to predict plume interaction effects
 - Landing surface preparation
 - Predict & prevent unwanted effects
 - loss of visibility
 - excessive asymmetric momentum transfer in flight
 - loss of stability or intended posture of landed spacecraft
 - damage to landing/launching spacecraft
 - contamination of landing spacecraft
 - damage / contamination to surrounding hardware
 - disturbance to area for scientific value (for cases in which mobility is limited, such as for robotic landers without rovers)

Requirements, Cont'd

- Mobility (driving on soil)
 - Robotic exploration
 - ISRU transport
 - extraction site to processing site
 - processing site to utilization site
 - *etcetera*
 - Habitation-related transport
 - From landing site to habitation site
 - From habitation site to Mars ascent vehicle
 - May include transport of large, habitation-related resources
 - Astronauts' scientific excursions
 - Adequate safety margins will expand range of excursions
 - Expand allowable terrain types for scientific access
 - Issues:
 - Traction versus "getting stuck"
 - Bearing capacity versus "getting stuck"
 - Energy efficient design
 - Speed
 - Performance on slopes

Requirements, Cont'd

- Construction and Surface Site Management
 - Surface Assets
 - Habitation modules
 - Ascent/descent vehicles
 - Transport vehicles
 - ISRU assets (storage, processing, etc.)
 - Power plant
 - Antennas
 - Berms
 - radiation protection
 - wind block
 - rocket plume effects
 - launch and landing “pad”
 - sensor arrays
 - Cranes, lifting for construction
 - Maintenance equipment and supplies
 - Test and repair assets

Requirements, Cont'd

- Construction Issues
 - Surface assets stability and alignment
 - Bearing capacity prediction and control
 - Anchoring
 - Differential creep
 - Effects of volatiles, seasons, thermal cycles
 - Effects of human-caused heat loads on volatiles
 - Slope stability
 - Surface and subsurface characterization before digging or construction
 - Identify subsurface boulders
 - Characterize rock distribution
 - Depth to bedrock
 - Volatile content versus depth
 - Trenching to lay cables, hoses, fibers, sensors
 - Stress propagation in piled sand for radiation protection

Requirements, Cont'd

- Excavation
 - for ISRU
 - for scientific access
 - Potential methods / processes
 - Blast casting
 - Fluid jet
 - Transport carriage
 - Auger
 - Scrapers/blades
 - Shovels
 - Buckets
 - Hoes

Requirements, Cont'd

- Transport for ISRU
 - Mechanical loading in hardware
 - Hardware dynamic response
 - Load supported by regolith
 - Jamming, flow
 - Dust generation and control
 - Unintended segregation effects
 - Energy efficiency
 - Crushing/compaction
 - Loss of volatiles

Requirements, Cont'd

- Storage for ISRU
 - preserve volatile content via thermal and/or atmospheric conditions
 - mechanical effects of thermal cycling
 - crushing
 - compaction
 - jamming
 - container rupture
 - predict stress propagation for container design
 - slope stability versus time and environmental effects

Requirements, Cont'd

- Processing for ISRU
 - Removal and transport from storage
 - Pouring from hoppers, etc.
 - Comminution (crushing, grinding)
 - Agglomeration (cementation, Sintering, Compaction)
 - Sieving / Segregation / Separation
 - Mixing
 - Phase change to liquid, gas or plasma
 - Process granulars formed by phase change *from* liquid, gas or plasma
 - Volatile extraction
 - Prevent / resolve jamming

Requirements, Cont'd

- ISRU Waste disposal
 - Transport to disposal site
 - Bucket, shovel or dump truck
 - Scrapers/blades
 - Ensure stability
 - Prevent creation of dust near habitation site

Requirements, Cont'd

- Dust Mitigation
 - biological group must define limits for dust generation, soil kicking up (filtration), etc.
 - Airborne particulate monitoring

Requirements, Cont'd

- Scientific investigation
 - Petrology, geology, origin of soil, volatile and atmospheric history, radiation record, impact record, search for organisms
 - Access to geologic units
 - Access to volatiles
 - Sample collection for return to Earth

Requirements, Cont'd

- *In Situ* engineering investigations
 - Geotechnical characterization
 - Plume/soil interaction measurement *in situ*
 - Test ISRU and excavation techniques
 - Test subsurface sounding techniques

Instruments & Measurements for Moon

- No further lunar sample return needs were anticipated
- Volatiles
- Regolith physical characteristics *in situ*
- Particle characteristics *in situ*:
 - Magnetic, Electrical,
 - Spectrometers to get chemical composition, specific gravity, data on glass/basalt/metallic deposition/etc.
- Meteoritic in-fall
- Solar wind in-fall

Instruments & Measurements for **Lunar Volatiles**

- Where, how much, how concentrated?
- Support development of physical models for
 - stability in the regolith
 - transport in the regolith
- Help in the interpretation of remote sensing measurements
- Associated lab studies are needed to support the measurement and modeling efforts

Instruments & Measurements for
Lunar Regolith Properties *In Situ*

- Basic flow index properties to support ISRU
- Near subsurface rock abundance and size distribution for excavation & construction sites
- Cone penetration (deep)
- Sounding tools

Instruments & Measurements for Mars

- Volatiles
 - H₂ and O₂ detection
 - Infrared
 - Raman spectroscopy
 - X-ray / Gamma-ray spectroscopy
 - Volatiles released when disturbing regolith
 - Bore hole tool to test characteristics of volatiles
 - Measurements that support physical modeling development of volatile transport in the regolith
 - Needs definition!
 - Questions raised: What measurements of the Martian permafrost currently exist? Is it localized in the polar regions or more ubiquitous?

Instruments & Measurements for Mars

- Regolith individual particle characteristics
 - Measured at the surface and in a column to some depth TBD (which requires excavation to extract samples)
 - Measurements:
 - Size distribution
 - Catalog of shapes
 - Electrical charge
 - Electrical conductivity
 - Thermal conductivity
 - Magnetic properties
 - Mineralogy
 - Hardness/crushing characteristics

Instruments & Measurements for Mars

- Regolith physical characteristics at the surface
 - Soil cohesion
 - Soil density before and after volatiles are expelled thermally
 - And likewise porosity
 - Uniaxial compression test equipment for use robotically
 - Bearing capacity
 - Material stiffness
 - One of the index tests of shear strength
 - It is generally agreed that the index tests are difficult to extrapolate or interpret apart from an existing base of experience, which does not yet exist for Martian soil
 - Yet a measurement of this sort is so basic that it must be done
 - Electrical resistivity

Instruments & Measurements for Mars

- Subsurface regolith physical characteristics as a function of depth
 - Soil cohesion
 - Soil density / porosity
 - before and after volatiles are expelled thermally
 - Bearing capacity
 - Material stiffness
 - One of the index tests of shear strength
 - Cone penetration (deep)
 - Bore hole tools for *in situ* mechanical testing (versus retrieving sample from bore hole to surface)
 - Specific energy of excavation / boring
 - Subsurface rock abundance and size distribution
 - Characterization of layering in the regolith
 - Including depth to bedrock
 - Sounding tools
 - Electrical resistivity
 - These support excavation (especially at water sources) and construction activities
 - Robotic, self-propelled submersible exploring device to go beneath surface (a mole)

Instruments & Measurements for Mars

- Soil/tire interaction characteristics
 - Measurements:
 - rolling resistance (the torque that soil applies to a rolling wheel while driving)
 - traction test (torque required to spin a wheel while the rover is held stationary)
 - shape/size of the resulting wheel ruts while driving normally.
 - Not just at the dust pockets and dunes, but also on the consolidated soil surfaces where we may do most of the driving.
 - These will probably be measured routinely on all Mars rovers as a "freebie" during the missions, but we might need a scaled-up test to support larger rovers that will come later
 - Also, should examine landing site to possibly obtain ultimate bearing pressure
 - ISRU excavation will require hauling larger loads (soil/ice payload) than what we have ever hauled in the past. Therefore these measurements are needed to properly design rover wheels, avoiding energy-wasteful designs and minimizing risks.

Instruments & Measurements for Mars

- Differential settlement of regolith
 - Measure stiffness of the soil
 - Measure/assess magnitude of settlement that may occur over the operational life of surface assets at the proposed landing site, considering maximum expected mechanical loading and maximum expected subsurface volatilization through thermal loading (e.g. by a nuclear reactor).
 - Affects heavy asset stability and upright posture
 - Affects the mechanical stress and leakage at asset interconnections (such as with interconnected habitation modules)
 - Note that the hardware gets heavier as geomaterials are added and as consumables are produced and stored.
 - Note that upright posture may be important for some ISRU processing hardware to ensure proper flow of materials.

Instruments & Measurements for Mars

- Basic flow index properties
 - Needed for design of ISRU processes
 - Measure for raw geomaterials and also for processed geomaterials
-

Rocket exhaust interaction for Mars

- Porosity at the surface and down to 1 meter
- Properties of any distinct features of layering
- Rock and pebble distribution embedded in the soil
- Depth and spatial variation in the quantity of loose (migrating) material in the region of the landing site
- Depth to bedrock at the actual planned landing site
- The presence of large boulders or bedrock just beneath the surface is also of critical importance
 - would probably enhance the fluidization of overlying soil

Sample return from the intended Mars landing sites?

- Divergent opinions on whether this is justifiable or necessary
- For geotechnical characterization, some prefer *in situ* measurements
- To fully understand physical and mechanical properties (dilatancy, strength, stiffness), samples are needed to augment the *in situ* measurements
 - It is possible to measure these properties remotely ***if*** we develop autonomous methods.
 - Technology advances required
 - Credibility
 - Low mass
 - Common instruments
- The needs on the 10-15 year horizon argue for some return samples from key sites to support mechanical properties modeling
- Lack of return samples will shift more burden to mission instruments.

Some Basic Research Directions

- Approach from a multi-scale perspective
 - Both discrete and continuum
 - Relevant forces at each scale
 - Catalog lunar particle shapes for use in modeling
 - Learn how to reconstruct and scale-up using new gravity and pressure conditions
 - Realistic lunar conditions
 - Realistic Martian conditions
- Will disturbed material be loosened or compacted over time by
 - Barometric pumping
 - Thermal cycling
- Behavior of water & ice on soils
 - Volatile diffusion & freezing seasonally
 - Will volatile dynamics loosen or compact soil over time?
 - Geophysical flows: wet or dry?

Modeling is needed

- Soil modeling is economical
 - U.S. Army, John Deere, and Caterpillar all use it
 - Controls cost: validate design before bending metal
 - Extends limited test program to all expected cases
 - Far more necessary for ET soils where experimental results and actual tests are vastly less accessible

Why didn't we need this for Apollo or Viking?

- Soil modeling was just a minor scientific objective (for the most part)
- Minor regolith modeling was needed for bearing capacity beneath spacecraft and for minor cratering effects
- By contrast, the Exploration Initiative depends upon soil handling equipment to enable the overall mission!
- Lessons learned in Apollo: more soil mechanics needed to make hardware designs functional
- How much more so when the entire mission depends upon it!
- See comparison table (next page)

Comparison of Geotechnical Requirements in Apollo/Viking versus Exploration Initiative

Aspect of Soil Mechanics	Apollo/Viking	Exploration Initiative
Focus:	Early work focused on understanding bearing and stability of lander. Very simple statics problems. Later work included mobility and subsurface sampling.	Mission success depends critically on early geotechnical analysis: ISRU excavation and processing, ability to land, support larger habitats on a more complex regolith (with ices), mobility, personnel protection.
Mission-criticality:	Low: affected only a portion of the science objectives if the core sampler did not work; mobility safety margins limited the range of exploration (walk back criteria)	High: necessary for enabling the overall mission (ISRU excavation and processing, etc.)
When performed:	Most geotechnical analysis was done later for small end-item development in later missions. Static bearing strength and limited cratering analyses done early.	Extensive analysis and modeling needed during early design stages and for major systems validation of each spiral.
Scale of activity:	Minor: data analysis and small end-item development (e.g., soil core sampler)	Major: coordinate systems and element designs among multiple contractors. E.g., ISRU processing system design affects excavation system design depending upon geotechnical inputs.
Safety implications:	Little or none Respiration of dust and wear of suit seals and components began to be problems on the J missions (15-17)	Very high. Determines pass/fail certification of critical flight elements (such as ISRU -- e.g., ability to manufacture additional consumables in a contingency situation). Could result in failure of resource systems and crew health. Safety could limit crew mobility as in Apollo.
Lead time needed:	None. (Apollo lander and suits designed before Surveyor missions landed on moon.)	A decade or more to obtain in-situ data and develop engineering tools for hardware designers

Final flight validation by testing alone is not possible

- Difficulties testing on the target planet
- Too expensive
- Too slow to get there
- Difficult to troubleshoot
- No access to analyze failed hardware
- Difficulties testing in planetary atmospheric/thermal chambers
- Too expensive to do all tests there
- Too many parallel activities compared to number of chambers
- Gravity is a crucial parameter in soil mechanics
- Dimensions of chambers are limiting to many activities such as mobility (driving), excavation, drilling...

- Modeling is already standard practice to validate critical flight hardware
 - The only thing new for NASA is to apply it to soil

Cannot rely on hardware manufacturers to do their own modeling

- Flight certification is too critical to rely on contractor-derived soil models
 - NASA must determine the “gold standard” soil model
- Wasteful for every hardware manufacturer to reinvent wheel
 - should have a common database of soil modeling
 - Too hard for NASA to understand as many models as there are contractors – better to have one model that is well-understood
- Contractor will not want to assume risk for soil model of ET materials
 - Models not well-established in comparison with terrestrial models
 - Lack of experimental comparison in comparison with terrestrial practices
 - Mission success relies too critically upon correct model
- Soil modeling should spiral in development to match spirals of program
 - Requires central organization to manage multiple spiral inputs and multiple customer milestones, each spiral resulting in a program-approved set of models
 - Avoid a disorganized hodgepodge of activities from various organizations
 - Have organizational structure to incorporate lessons-learned from earlier missions into design and validation of later missions

Program Integration Needs

- Flow-up of in situ measurement requirements from hardware manufacturers
 - not timely to support robotic program development schedule
 - Need central modeling effort to specify in situ measurements and later deliver model to hardware designers
 - Mediating role
- Flow-down of model to hardware manufacturers
 - will not be timely unless model development begins now, even before actual architecture of program has been established

Granular Mechanics

- Fundamental problems with granular mechanics have not been explained yet (scaling to ET environment), but may be addressed seamlessly in an overall modeling effort



Army/
Industry
Terrestrial
Models

Develop Extraterrestrial Soil/Geomaterials Models

(Continuum, DEM,...)

Simulant
Experiments

Remote
Sensing

Granular
Physics
Research

In-Situ
Measurements

Sample
Return
Analysis &
Test ???

Lunar
Mission
Results

Mars Pre-
cursor mission
results

Models to
Experimenters

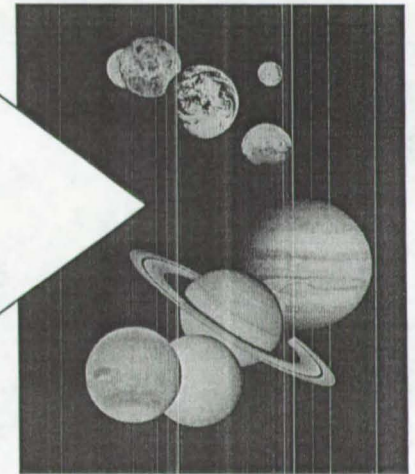
Rocket
Cratering
studies

Predictive
regolith
stability

Hardware
Designers

Models for
surface ops
simulations

Hardware
qualification
and final flight
certification



Moon, Mars,
asteroids, other
solar system bodies

Spinoff: better
knowledge of
terrestrial soil
mechanics and
granular physics