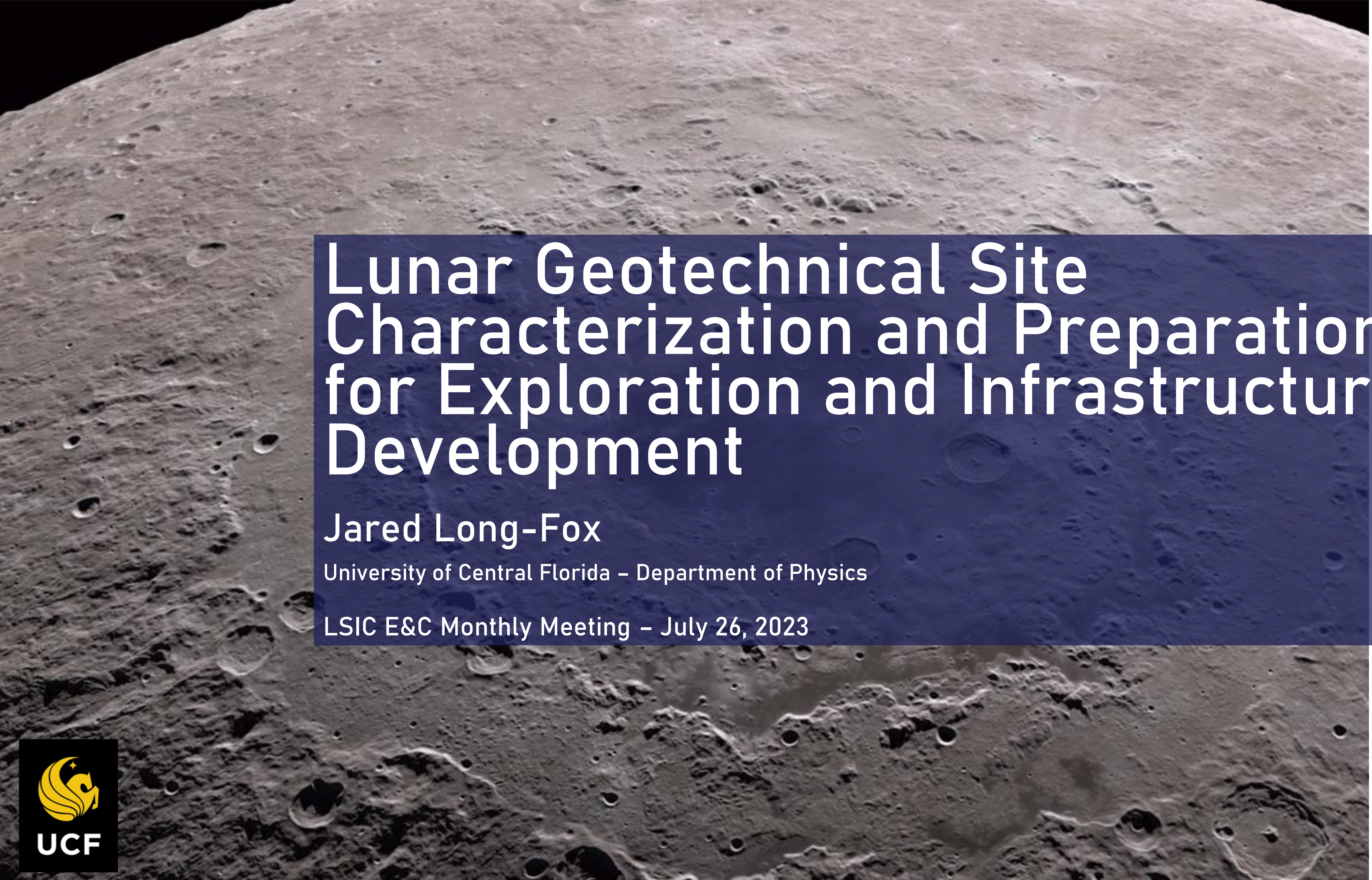

Lunar Geotechnical Site Characterization and Preparation for Exploration and Infrastructure Development

Jared Long-Fox

University of Central Florida – Department of Physics

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Introduction

- Sustainable lunar permanence relies on:
  - Safe and efficient interactions with planetary surfaces (landing, roving, infrastructure development)
  - Utilization of local resources
- Regolith will be the primary feedstock for infrastructure development and *in situ* resource utilization (ISRU)
  - Site-specific physical and chemical properties that are very different from Earth
  - Extreme environment – reduced gravity, no atmosphere (and related effects), and limited energy resources

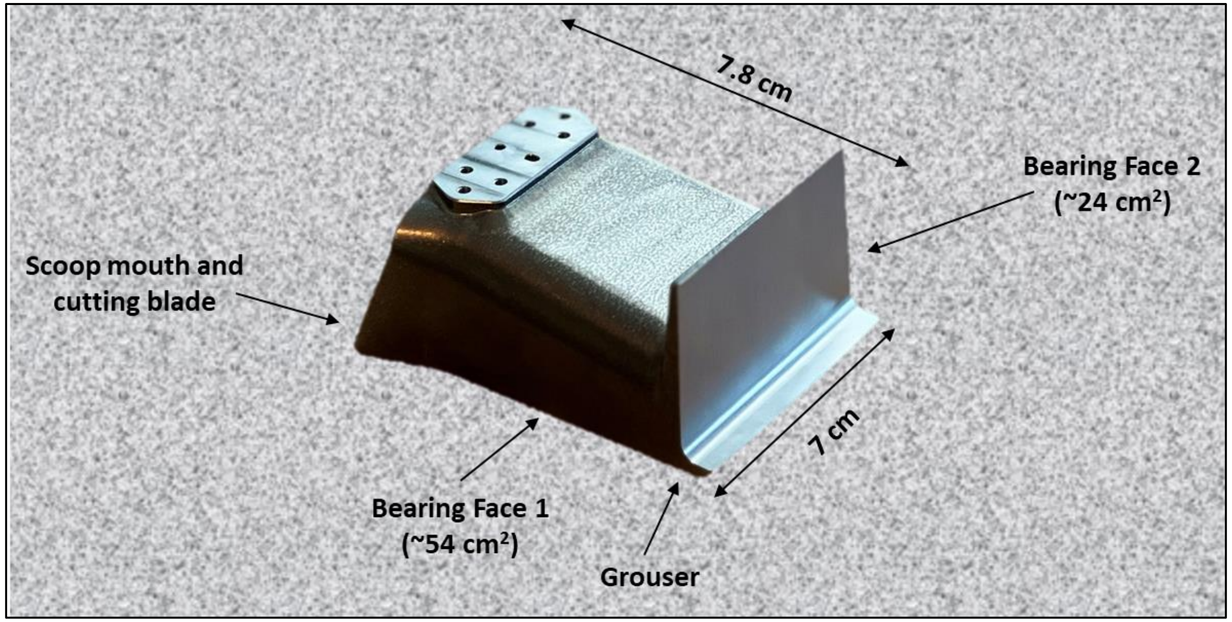
Image credit: NASA

The Need for Site Characterization and Preparation

- Terrestrial construction requires site characterization and specific preparation methods to bring the site into acceptable specs → need same for the Moon
    - Need to define "acceptable" for the lunar case
- Need to characterize *in situ* physical properties
    - Unlike what we deal with on Earth
    - Extreme environment
    - Site specific variations
- Should use simple, standard exploration tools and tests whenever possible
    - Borrow from terrestrial studies as able
    - Minimize mass → cheaper and more efficient launches and operations

Experimental Hardware

- COLDArm testing campaign at NASA KSC Swamp Works
  - Ground interaction data being collected using COLDArm geotechnical scoop
    - Force-torque sensor on UR10 arm
    - LHS-1B simulant



Site Characterization Experiments

- Angle of Repose
  - Provides a first-order look at the strength of the material you are working with
- Pressure-Sinkage
  - Provides information on bearing capacity and trafficability
  - Bernstein (1913), Bekker (1969), and Reece (1965)
- Shear
  - A fundamental quantity to characterize (e.g., Mohr-Coulomb relationship) – shear strength plays a part in nearly all other mechanical properties of regolith (including AoR)
- Excavation
  - Convolution of horizontal and vertical forces acting on regolith
  - Able to learn physical properties based on forces observed during excavation (more on this soon!)
- Materials
  - Need high-fidelity lunar regolith simulants

Site Characterization: Angle of Repose

- Gives insights into the high-level physical properties of regolith
  - Useful for initial explorations and characterizations
  - Not definitive enough for in-depth quantitative analyses of regolith mechanics

- With sufficient pre-flight testing, can inform on:
  - Volatile content
  - PSD
  - Composition

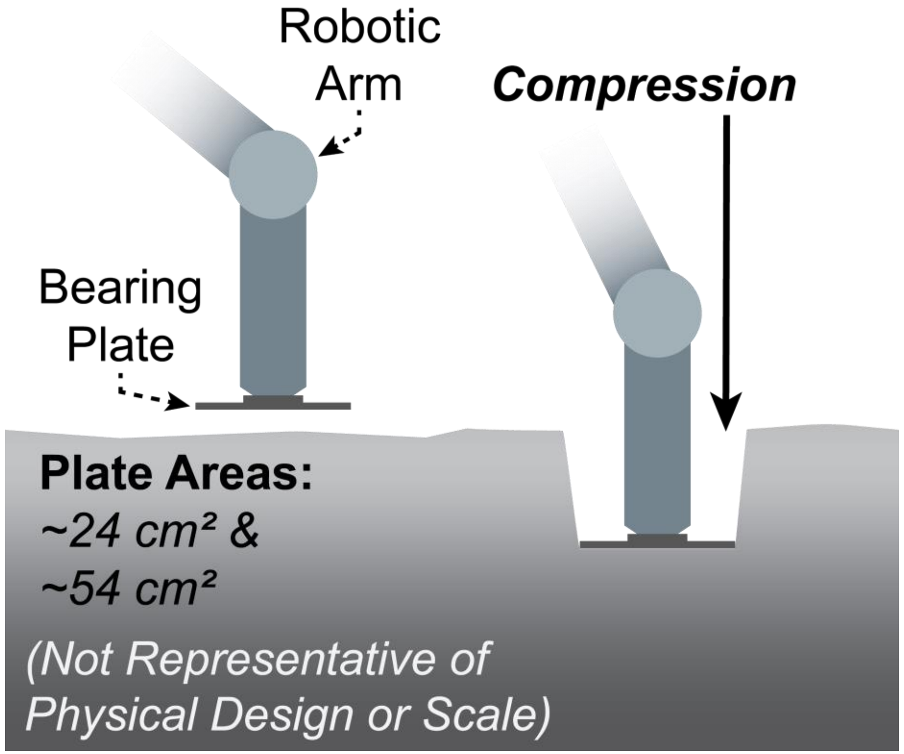
- Need sample piles above a given mass/volume because angle of repose is sample size-dependent

Site Characterization: Pressure-Sinkage

- Pressure-sinkage relationships inform on bearing capacity and tractive capabilities of the regolith
  - The ability to predict rover performance and safety factors in infrastructure development as a function of regolith properties is key

- Provides information on:
  - Relative compaction of local regolith for exploration and infrastructure development safety
  - Moisture and volatile content [Long-Fox et al., 2022]

- Models of pressure-sinkage
  - Bernstein (1913): $p = kz^n$
  - Bekker (1969): $p = \left(\frac{k_c}{b} + k_\phi\right) z^n$
  - Reece (1965): $p = \left(ck_c + \gamma b k_\phi\right) \left(\frac{z}{b}\right)^n$

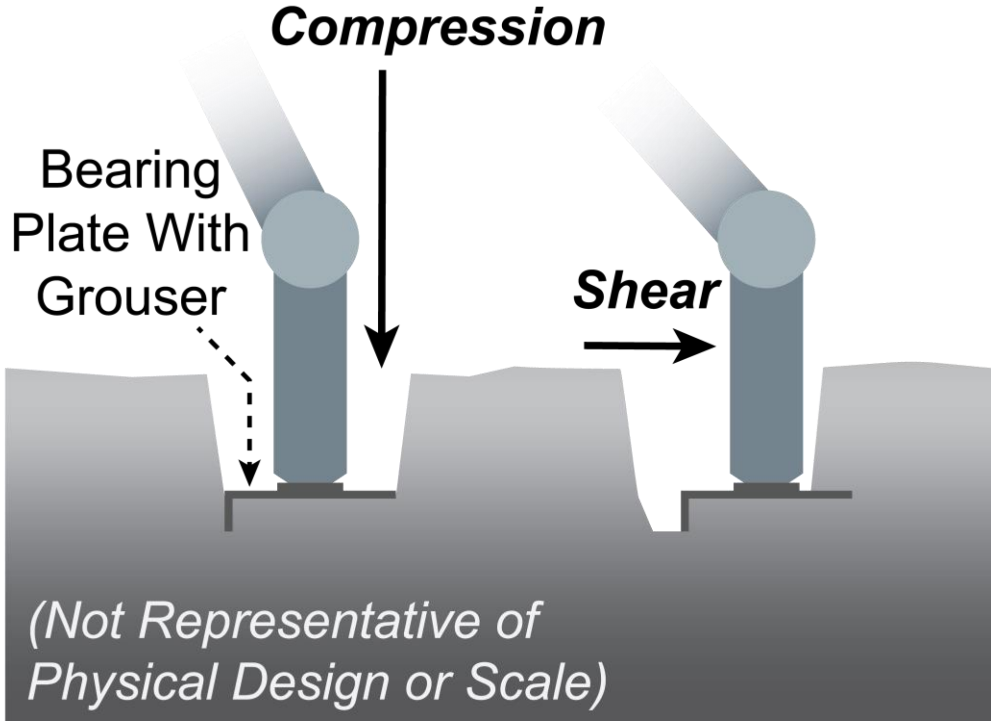


Site Characterization: Shear

- Shear strength is a fundamental property that determines bulk regolith behavior
    - Affected by relative state of compaction
    - Volatile content is expected to cause variations in shear strength
    - Sensitive to PSD and mineralogy

- Provides information on:
    - Traction
    - Load bearing capabilities
    - Material handling

- Mohr-Coulomb model of shear strength
    - $\tau_s = \sigma_n \tan(\phi) + c$

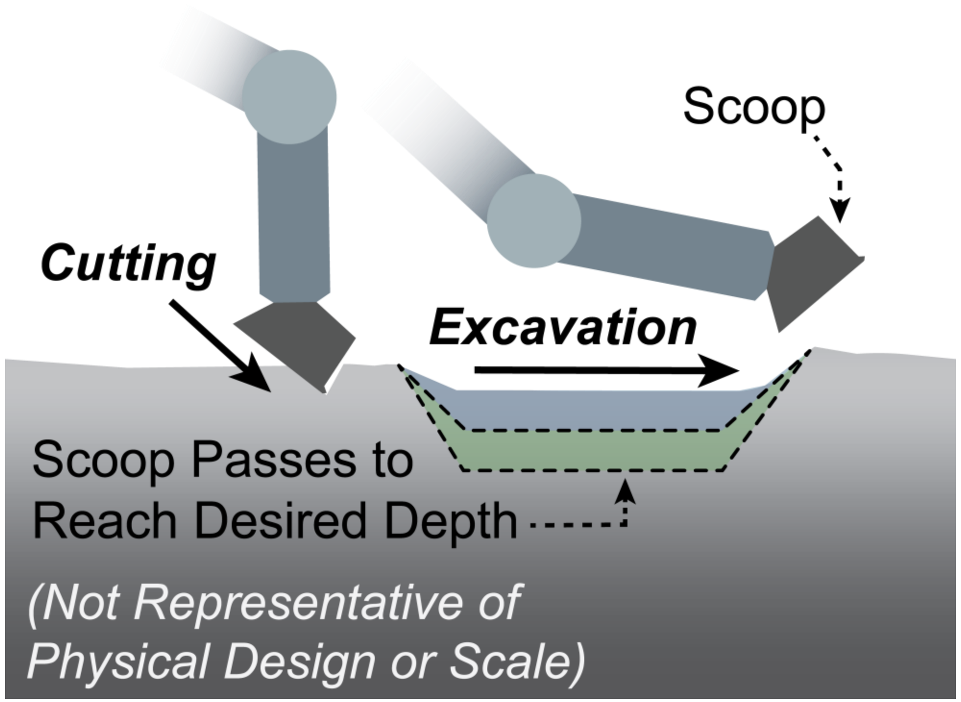


Site Characterization: Excavation

- Excavation is a convolution of horizontal and vertical forces acting on the regolith
  - Shear
  - Compression

- Forces required for excavation are a function of many material properties (e.g., density, porosity, cohesion, frictional constants,...)

- Desirable to be able to estimate material properties during excavation
  - Will allow adaption to changing regolith conditions



(Not Representative of Physical Design or Scale)

Excavation: Analytical Modeling

- COLDArm excavation data being modeled with simple analytical models (2D Reece's Fundamental Equation of Earthmoving – Reece, 1964)
- Estimating relevant properties of materials being excavated:
  - Cohesion (c)
  - Angle of internal friction (ϕ)
  - Shear plane failure angle (β)
  - Angle of external friction (δ)
- Markov Chain Monte Carlo (MCMC) for parameter estimations and F-tests for 2σ confidence intervals

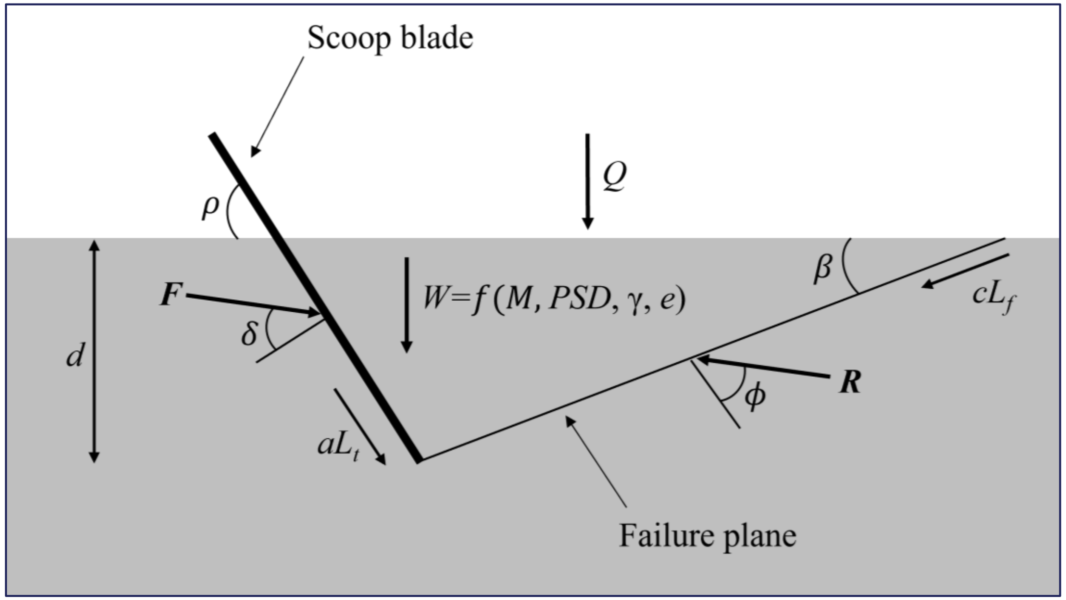
$$F = w\left[cdN_c + \gamma d^2 N_\gamma + QdN_q\right]$$

w is scoop width

d is cutting depth

N_c, N_γ, N_q are dimensionless "N factors"

Q is surcharge load

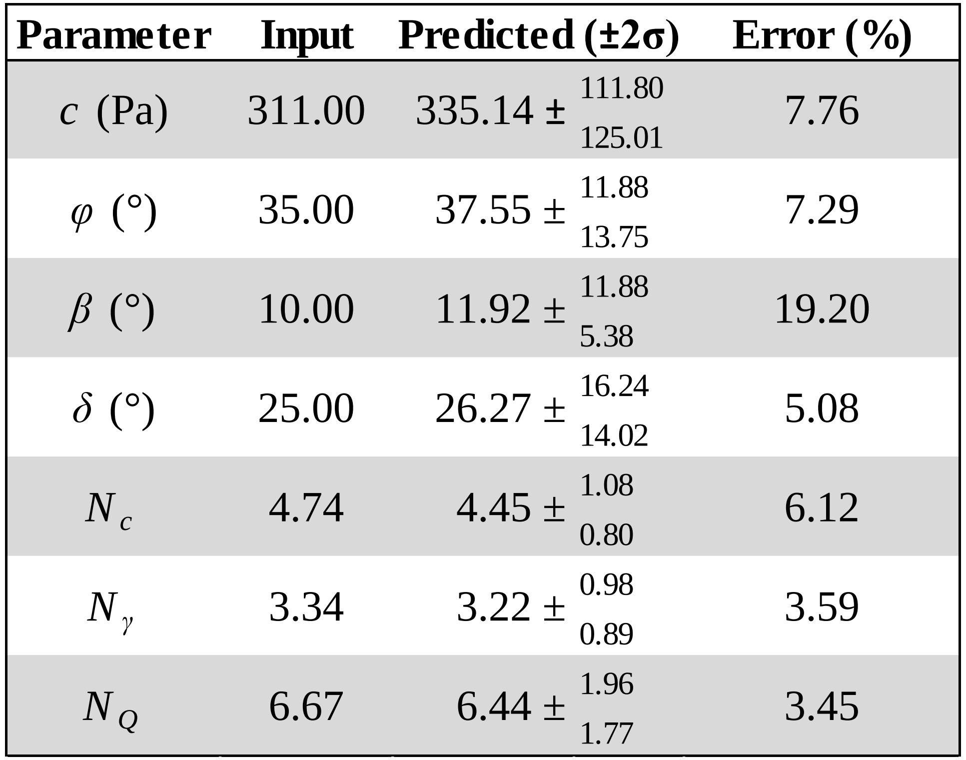


Modified from McKyes (1985)

Excavation: Analytical Modeling

- COLDArm excavation testing starting late Summer 2023

- Recovery Test
  - Generate synthetic data using Reece's Fundamental Equation of Earthmoving with known input parameters (10% Gaussian noise added)
  - Run MCMC model to see if algorithm can predict synthetic data
    - 10 adaptations of 1,000 samples each to "home in" on best-fit set of parameter values
  - Reece's FEE provides a suitable first-order set of parameter estimations



Parameter	**Input**	**Predicted (±2σ)**	**Error (%)**
c (Pa)	311.00	$335.14 \pm^{111.80}_{125.01}$	7.76
φ (°)	35.00	$37.55 \pm^{11.88}_{13.75}$	7.29
β (°)	10.00	$11.92 \pm^{11.88}_{5.38}$	19.20
δ (°)	25.00	$26.27 \pm^{16.24}_{14.02}$	5.08
N_c	4.74	$4.45 \pm^{1.08}_{0.80}$	6.12
N_γ	3.34	$3.22 \pm^{0.98}_{0.89}$	3.59
N_Q	6.67	$6.44 \pm^{1.96}_{1.77}$	3.45

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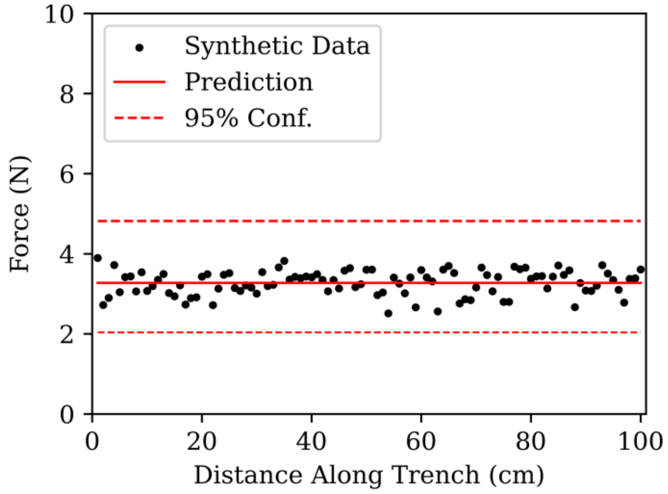
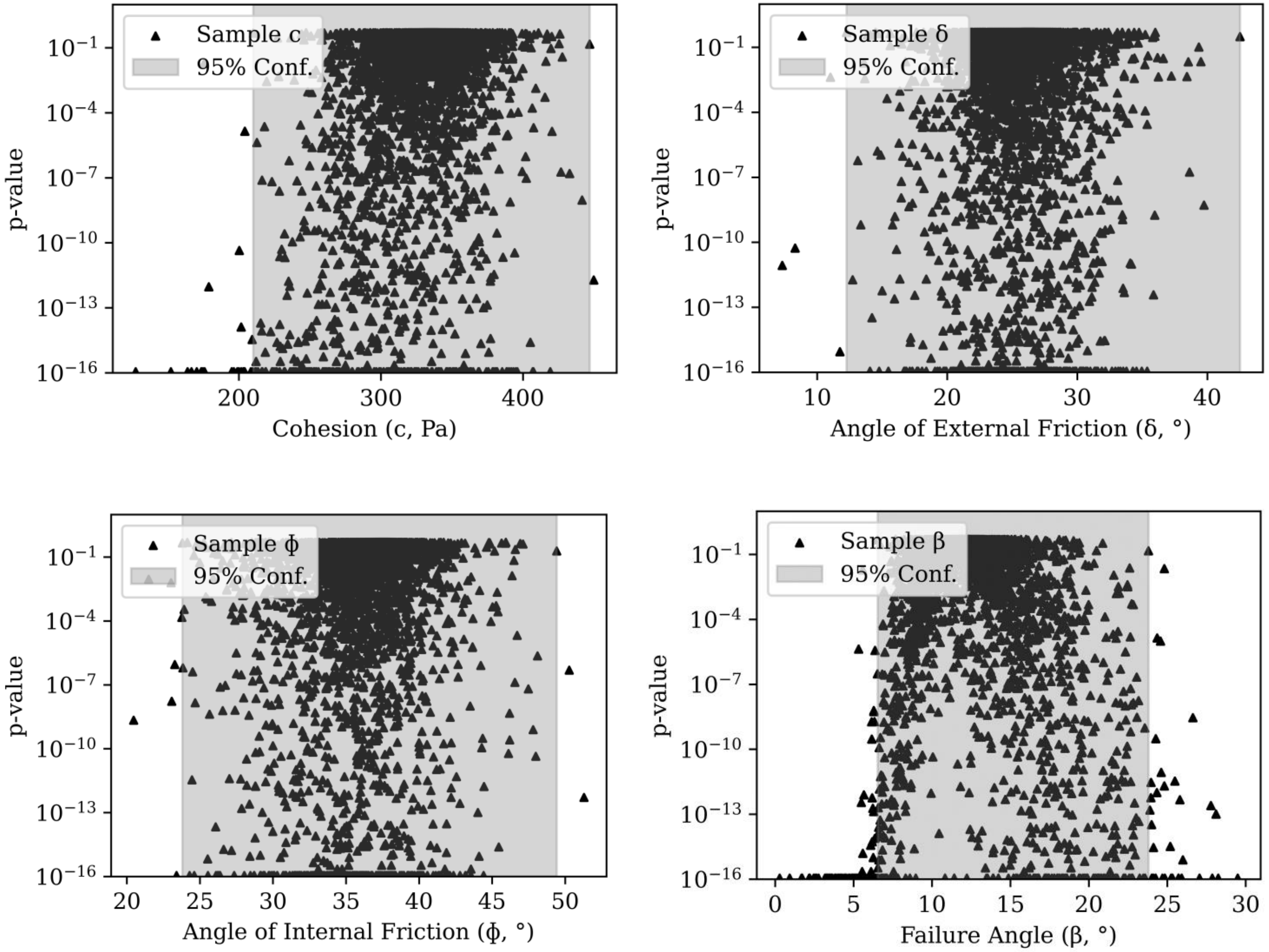
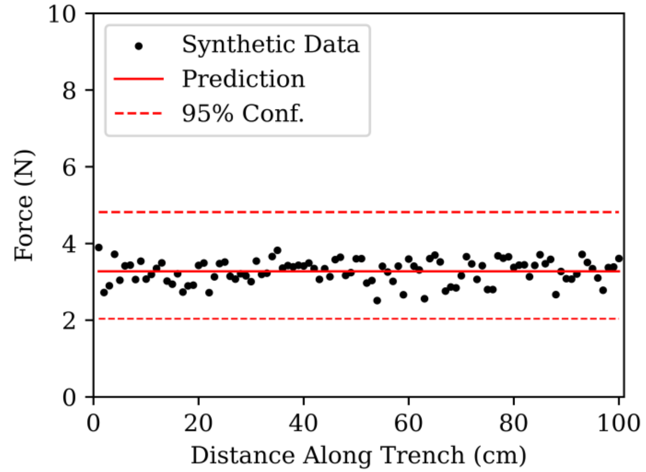


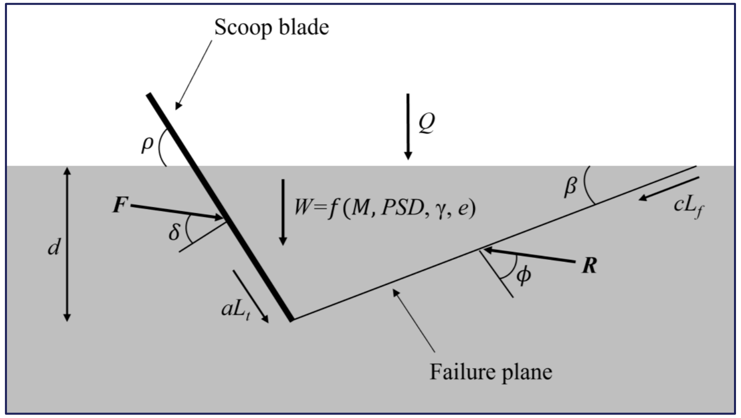


Excavation: Analytical Modeling

- Analytical models of excavation are overly simplistic
  - Homogeneity of materials
  - Flat free surface
  - Unrealistic tool geometry
  - Lack of environmental effects
  - Spurious empirical calibration coefficients
  - Unable to incorporate force reduction directly into model

- Need realistic models that can incorporate 3D distributions of material properties, uneven topography, and force reduction methods





Modified from McKyes (1985)

To fully describe a quantitative estimate, you need: 1) A measure of central tendency; 2) a sense of uncertainty; 3) rigorous analysis of assumptions and biases

Excavation: The Need for Force Reduction

- Need ways to reduce the reaction force needed for raw material acquisition during excavation due to challenging material properties and environment:
  - High cohesion and dilative nature of regolith
  - Reduced gravity (1/6 g on the Moon)
  - Launch mass budgets

- Experimental work in force reduction is showing good results, but none of these efforts have developed predictive capabilities
  - Vibration [Rezich et al., 2021]
  - Percussion [Green et al., 2013]

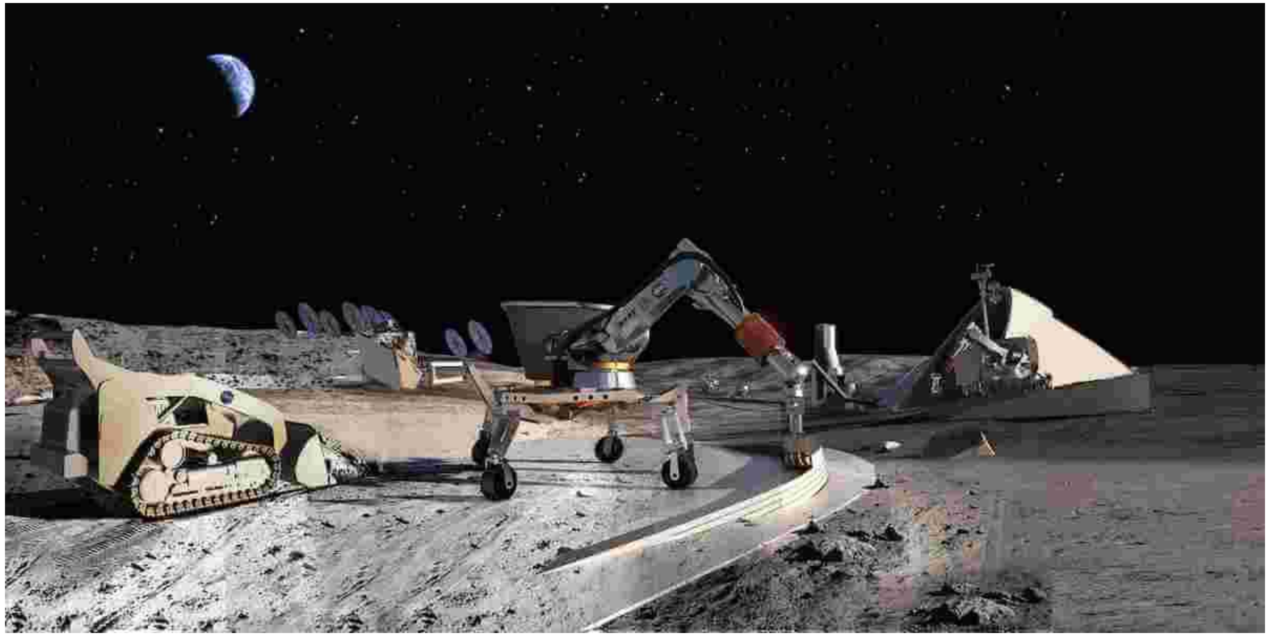


Image credit: Contour Crafting

Excavation: Numerical Modeling

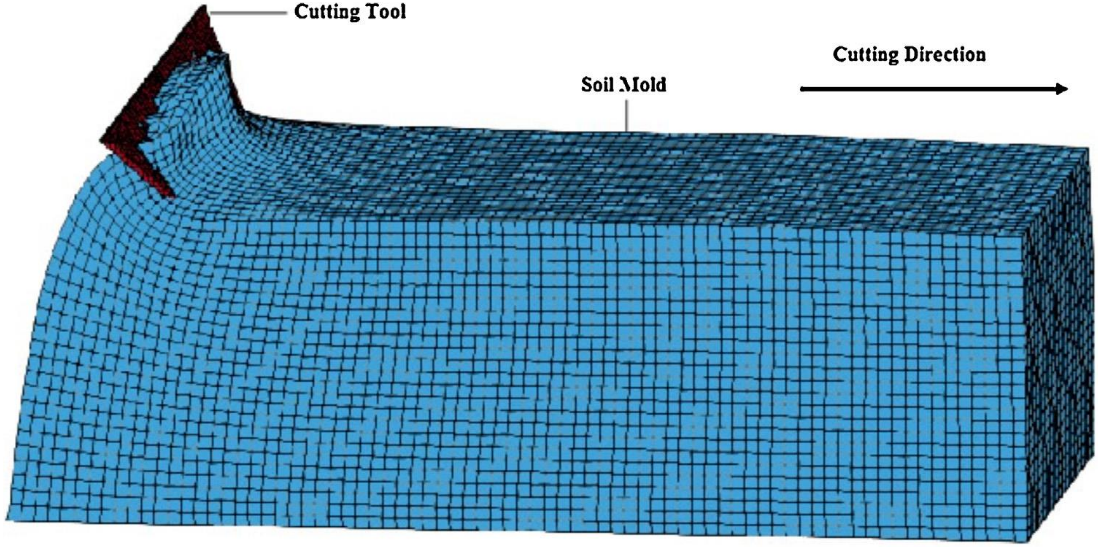
- Numerical models allow for fewer simplifying assumptions compared to analytical models
    - CAD-based tool geometries allow testing of prototype hardware and allow for better mission planning
    - Arbitrary 3D domain geometries and material property distributions
    - Can prescribe various loadings such as vibration, percussion, and more
    - Multiphysics

- Finite element models (FEMs)
    - Continuum-based
    - Coupled Eulerian-Lagrangian treats regolith as a highly deformable solid being manipulated by a rigid tool
    - Often used in modeling soil-tool and soil-wheel interactions on Earth [Tagar et al., 2015]

- Discrete element models (DEMs)
    - Discontinuous, independently moving particles
    - Represents regolith as individual grains interacting with each other and tools/wheels
    - Becoming more common, but granular mechanics is extremely complex and hence difficult to describe computationally.

Excavation: Numerical Modeling

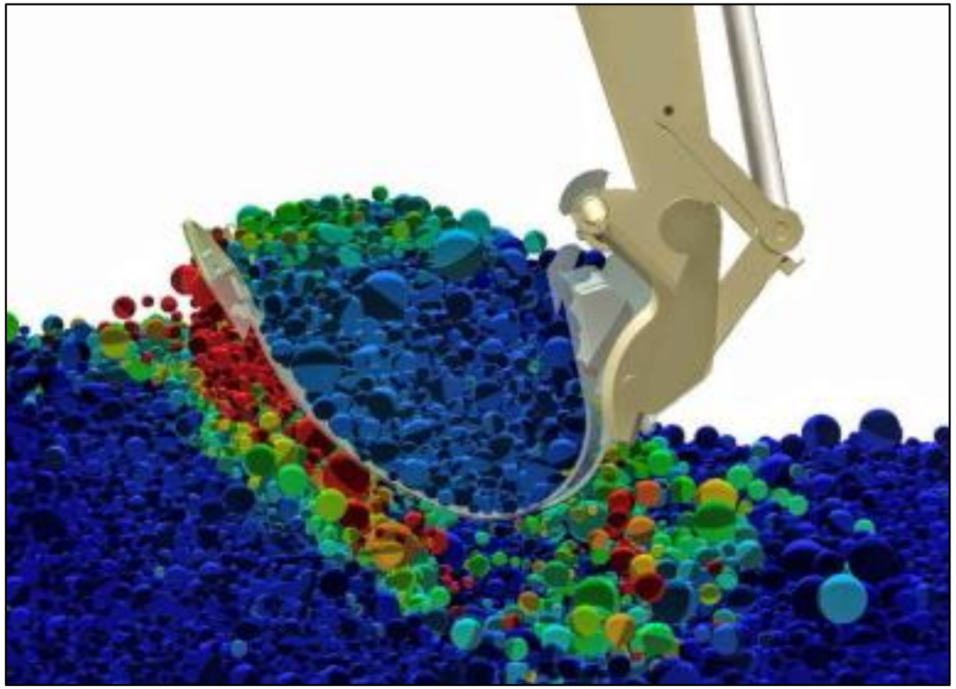
- FEMs are established, well-understood formulations that have been applied to modeling of terrestrial geological media in multiple fields for many years
- The representation of granular regolith as a solid or fluid-like material is inaccurate, but may capture bulk behavior suitably
  - What are the limitations of this approximation of net mechanical behavior specifically in the lunar case?



From Tagar et al. (2015)

Excavation: Numerical Modeling

- DEMs are computationally complex and the fledgling field of granular mechanics is still ill-resolved compared to the solid and/or fluid-like mechanics of FEMs
  - Difficult to fully capture all the physics [Schmulevich, 2010]
    - Different simulations require different material property calibrations- no reliable methods to determine which
  - Very computationally expensive
  - Do not handle wide PSDs well
    - Particle size distribution is the most important aspect of regolith for simulants to replicate [Sibille et al., 2006]
    - Planetary regolith generally has PSDs than span 7 or 8 orders of magnitude…



From Coetzee et al. (2017)

Future Work and Products

- Collect COLDArm excavation data (no force reduction)
  - Ingest into analytical models for parameter estimations → first-pass approximations of physical properties during excavation
  - Provides baseline data

- Develop percussive and vibratory excavation testing hardware
  - COLDArm scoop
  - Surveyor replica scoop

- Develop experiment arrays and perform experiments to collect data
  - Compare force reduction methodologies
  - Compare modeling methods (analytical vs. FEM vs. DEM)

- Develop and calibrate FEMs and DEMs
  - Statistically compare efficiency and accuracy of calibrated model predictions relative to experimental data
  - Calibration workflows and calibrated models will be new tools we can use to plan safe and efficient excavation operations planning

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Questions?

jared.long-fox@ucf.edu