

COLDArm for Efficient Lunar Science and Site Characterization

**Jared Long-Fox¹, Robert Mueller², Eloise Marteau³,
Phillip Abel⁴, Daniel Britt¹, and Ryan McCormick³**

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¹University of Central Florida Department of Physics

²NASA Kennedy Space Center

³NASA Jet Propulsion Laboratory

⁴NASA Glenn Research Center

Introduction



- **Motivation**

- Time and energy are the most precious resources in lunar and planetary surface operations
- Having the capability to operate during the lunar night (~14 days) and in PSRs is key
 - Surviving the lunar night requires energy for heaters and electronics

- **Goals**

- Demonstrate the utility of a robotic arm that is capable of operating in the lunar night and in PSRs without heaters ($< -173\text{ }^{\circ}\text{C}$) by performing geotechnical site characterizations

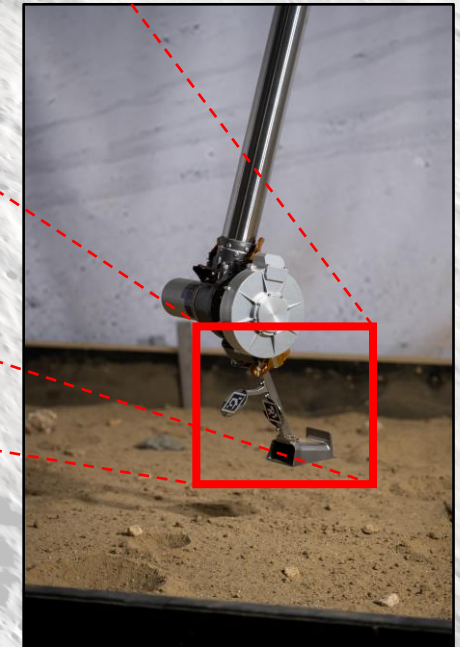
- **Impact**

- Successful demonstration of COLD Arm on the lunar surface will enable highly efficient lunar and planetary exploration, ISRU, and infrastructure development

COLDArm Hardware

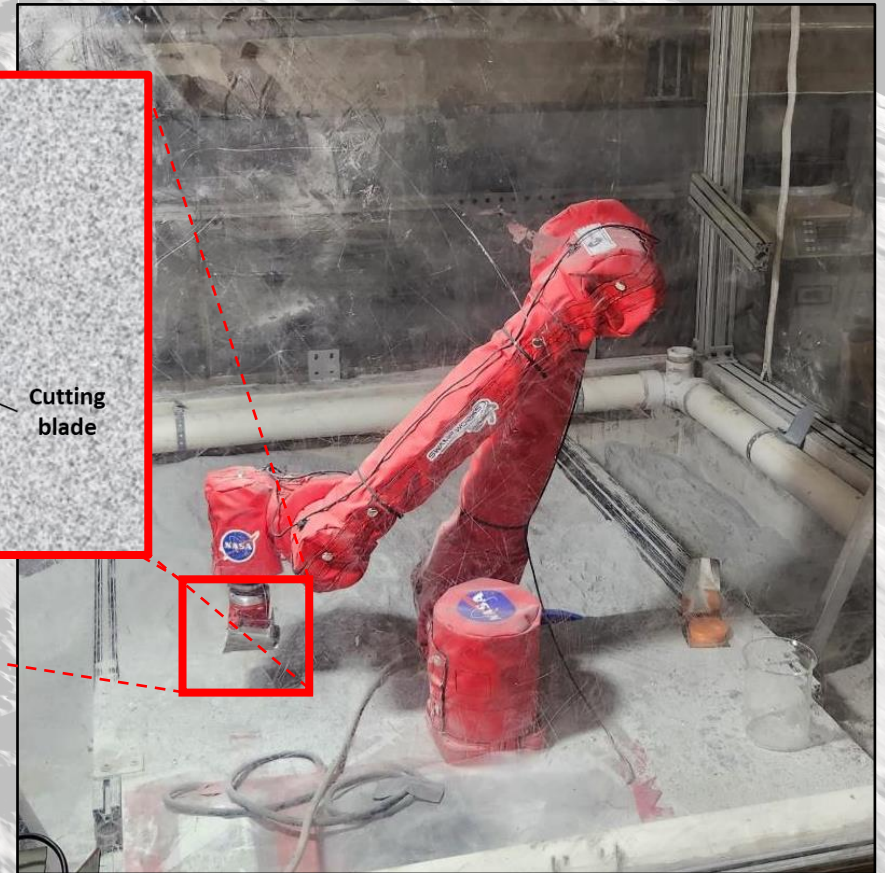
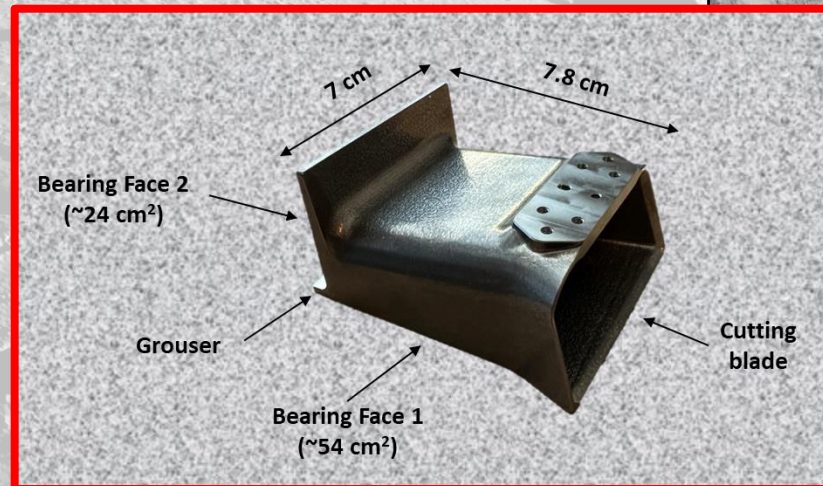


- **Arm**
 - 4 Degree of Freedom (DoF)
 - ~2 m reach
 - 50 N tip load
 - 63.5 Nm joint torque
 - Bulk metallic glass (BMG) joint actuators
- **Sensors and Payload**
 - 6 DoF force-torque sensor (FTS) at the end of the arm
 - ± 2 N force resolution
 - ± 0.5 Nm horizontal torque resolution
 - ± 0.1 Nm vertical force resolution
 - ~1 kg tool payload
 - 2 stereo cameras mounted on lander
 - ± 1 mm positional accuracy based on fiducial targets on the End Effector



Site Characterization at KSC

- UR10 robotic arm, 6 DoF FTS, COLD Arm Scoop
- LHS-1B simulant
- Experiments
 - Angle of Repose
 - Pressure-Sinkage
 - Shear
 - Excavation
- Software developed to estimate geotechnical parameters from experimental data under SSERVI collab.





Angle of Repose

- **Goal**

- **Measure the angle of repose of material**

- Provides a good first-pass overview of material properties to inform exploration efforts, tool paths for subsequent experiments, and gives a view of the shallow subsurface

- **Methods**

- **5 piles, 6 scoops each**

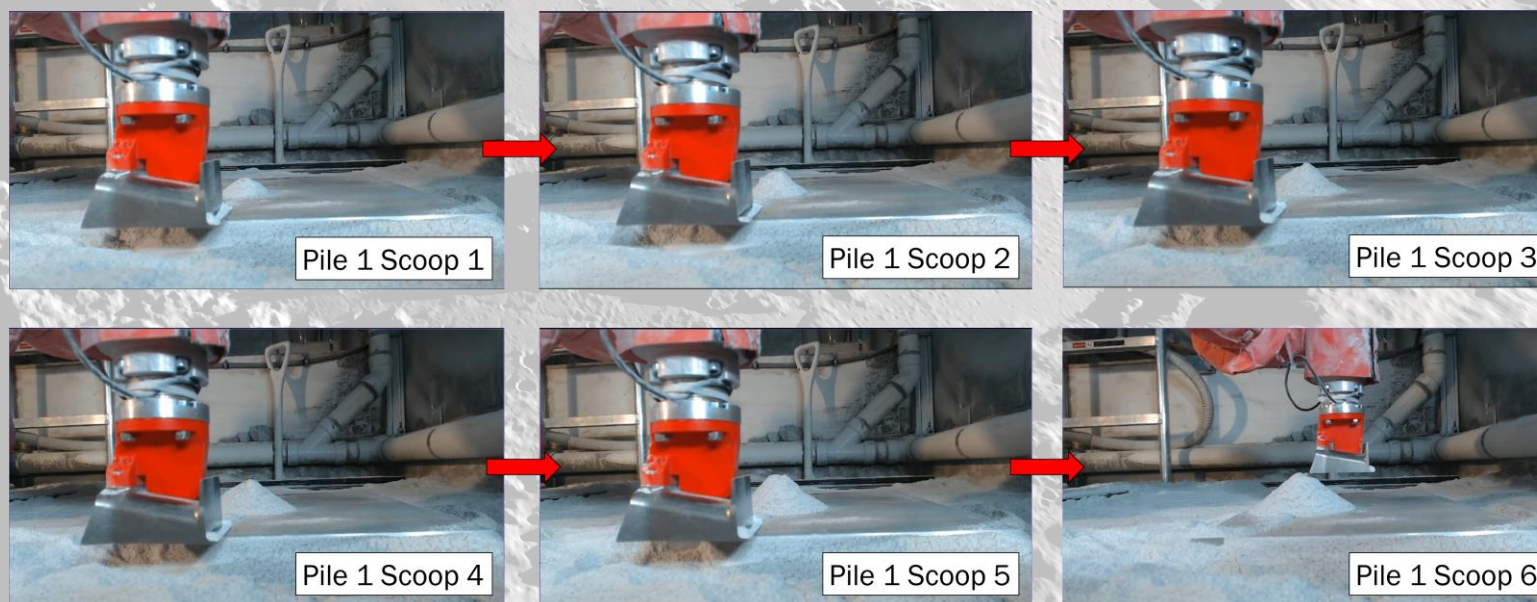
- Measure angle as each pile builds
 - Angle of Repose is sensitive to amount of material in the pile (~200+ g for consistency)

- **ImageJ used to process images**

- Profilometer, 3D scanner, or stereo cameras during mission enable same measurements

Angle of Repose

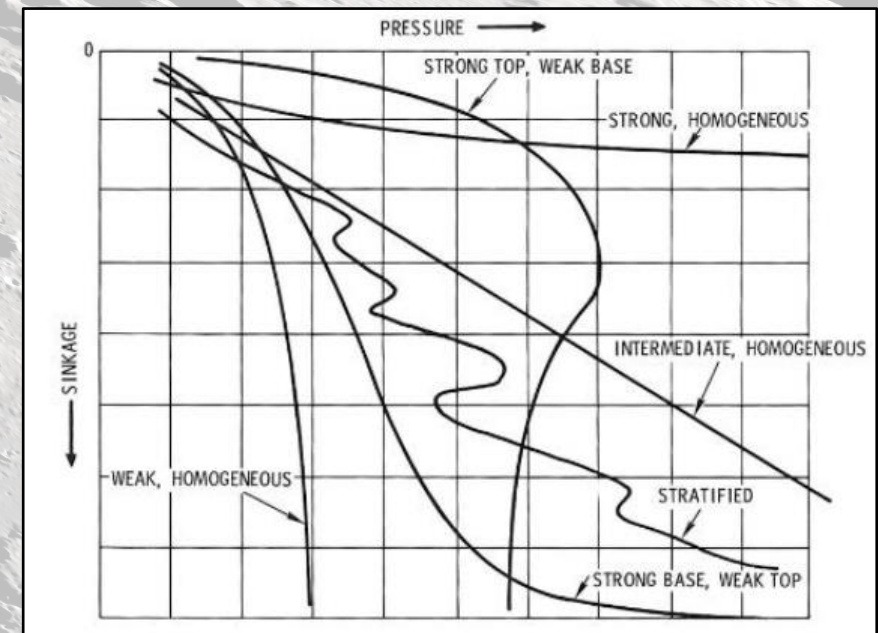
- Angle of Repose of LHS-1 simulant measured here is $38.72 \pm 3.70^\circ$ (95% conf.) is consistent with the published value $41.2 \pm 8.1^\circ$ (95% conf., Long-Fox et al., 2023)
 - Standard deviation decreased with each scoop added to the pile (5 piles, 6 scoops in each)
 - follows expected trend of increased consistency with more material



Pressure-Sinkage



- **Goal**
 - Measure the relationship between applied pressure and resulting sinkage
 - Inform on site-specific trafficability and bearing capacity
- **Methods**
 - Use COLD Arm scoop Large Surface (Bearing Face 1) and Small Surface (Bearing Face 2) to push straight down on simulant; record force and displacement
 - Markov Chain Monte Carlo parameter estimations



Pressure-sinkage profiles and interpretations of strength with depth. From Salman and Kiss (2019)

Pressure-Sinkage



- Bekker (1956) model of pressure-sinkage:

- $P = \left(\frac{k_c}{b} + k_\phi \right) (z^n)$

- Reece (1965) model of pressure-sinkage:

- $P = (k_c + bk_\phi) \left(\frac{z}{b} \right)^n$

- Commonly used in terrestrial evaluations of bearing capacity and pressure-sinkage

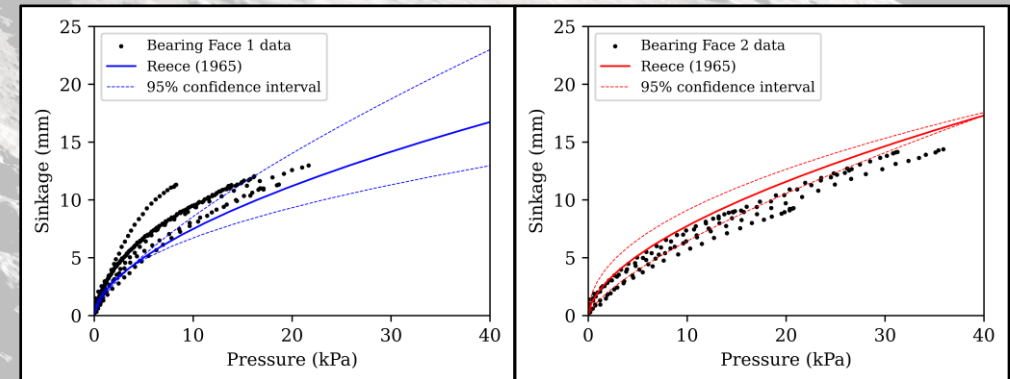
- Need to estimate k_c , k_ϕ , $n \rightarrow$ requires the use of two different sized bearing plates

- Inputs

- Pressure (P), sinkage (z), plate width (b)

- Outputs

- k_c , k_ϕ , and n with respective uncertainties



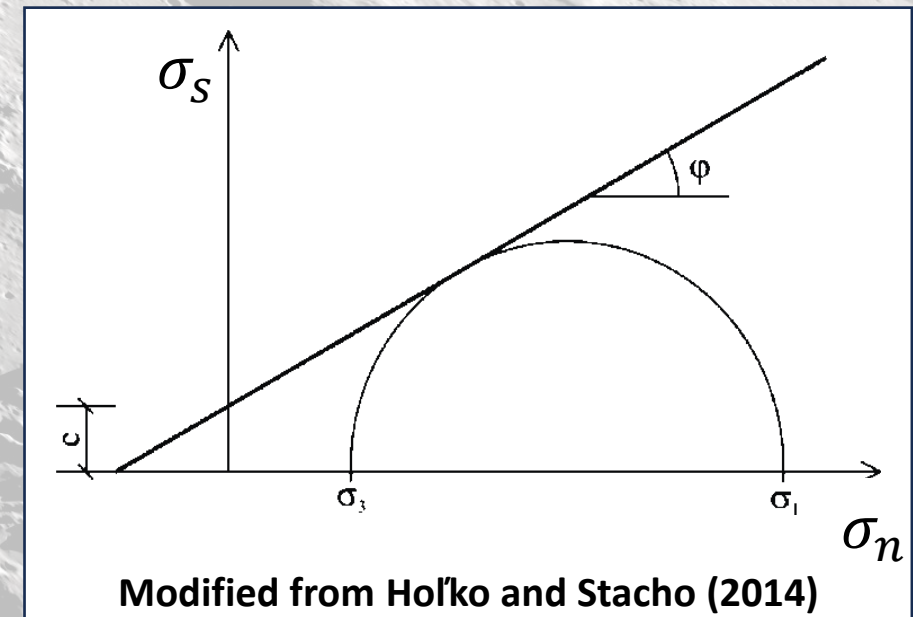
k_c	$-151.49 \pm \begin{matrix} 624.43 \\ 170.22 \end{matrix}$
k_ϕ	$7734.10 \pm \begin{matrix} 19042.84 \\ 5600.04 \end{matrix}$
n	$1.56 \pm \begin{matrix} 0.36 \\ 0.30 \end{matrix}$

Long-Fox et al. (2023)
LPSC abstract

Shear



- **Goal**
 - Estimate Mohr-Coulomb parameters of cohesion (c) and angle of internal friction (φ) (key geotechnical parameters for prediction of regolith behavior)
- **Methods (Testing Ongoing)**
 - Pseudo-direct shear test
 - Apply normal load with Bearing Face 2
 - Translate horizontally to shear regolith while maintaining normal load
 - Repeat multiple times at different normal loads
 - Mohr-Coulomb linear fit
 - $\sigma_s = \sigma_n \tan(\varphi) + c$



The logo for COLD Arm features the word "COLD" in blue and "Arm" in grey, with a stylized robotic arm integrated into the letter "A". The arm is blue and grey, with a blue gripper at the end. The background is a light grey gradient.

- To measure excavation forces to provide information on geotechnical properties (e.g., compaction and shear strength) and provide characterization of subsurface stratigraphy

- Use COLDArm scoop to excavate in different simulant densities, different rake angles, and different cutting depths
- Develop computational models to predict geotechnical properties from excavation data



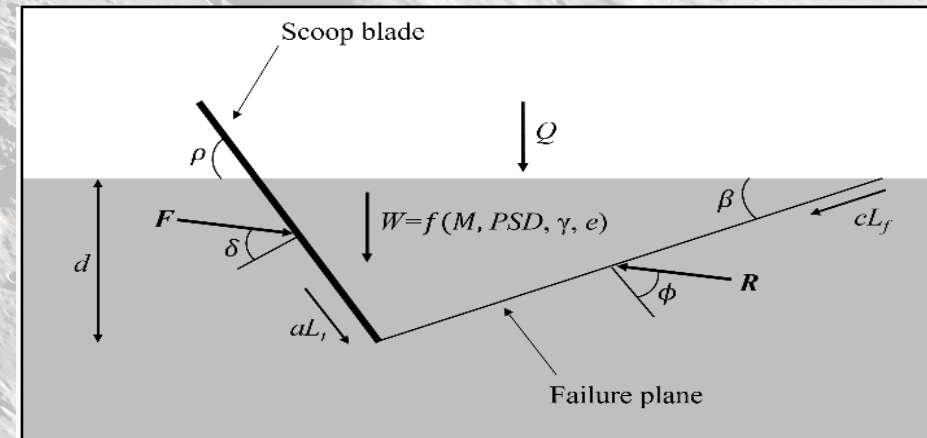
Excavation



- **Reece's Fundamental Equation of Earthmoving (2D; Reece, 1964)**

- $F = w[cdN_c + \gamma d^2 N_\gamma + QdN_q]$
 - d is cutting depth
 - w is scoop width
 - Q is surcharge load (depth and density)
 - N_c, N_γ, N_q are dimensionless "N factors"

- $$N_c = \frac{1 + (\cot(\beta) \cot(\beta + \phi))}{[\cos(\rho + \delta) + (\sin(\rho + \delta) \cot(\beta + \phi))]}$$
- $$N_\gamma = \frac{\cot(\rho) + \cot(\beta)}{2[\cos(\rho + \delta) + (\sin(\rho + \delta) \cot(\beta + \phi))]}$$
- $$N_q = \frac{\cot(\rho) + \cot(\beta)}{\cos(\rho + \delta) + (\sin(\rho + \delta) \cot(\beta + \phi))}$$

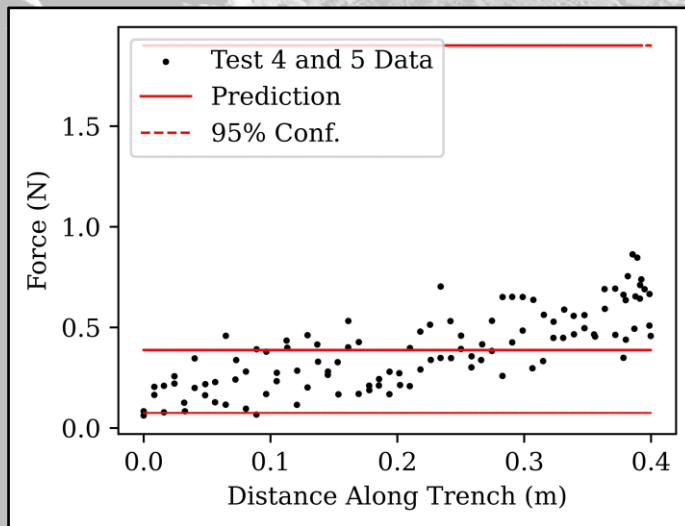


Modified from McKyes (1985)

Excavation



• Reece's FEE Preliminary Results (Testing Ongoing)



LHS-1B simulant at $\sim 1.4 \text{ g/cm}^3$

2.5 mm cutting depth

5° rake angle

$$c = 314.30 \pm \frac{263.83}{236.16} \text{ Pa (95% conf.)}$$

$$\varphi = 18.75 \pm \frac{37.14}{16.00}^\circ \text{ (95% conf.)}$$

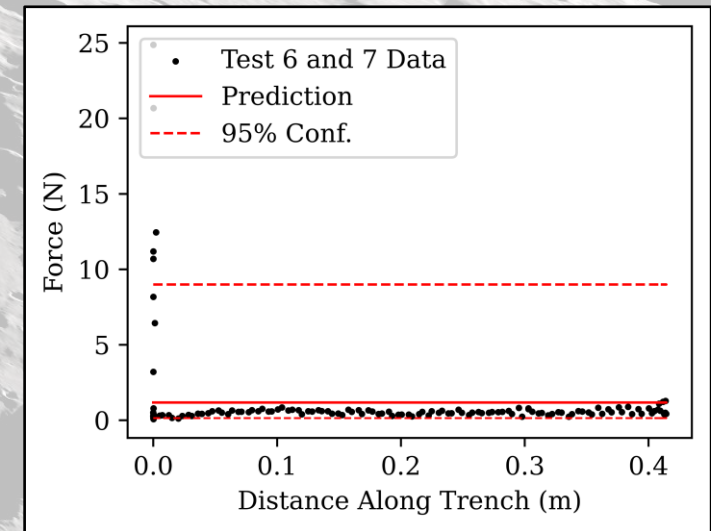


LHS-1B – Long-Fox et al. (2022)

NESF abstract

$$c = 341 \pm 37 \text{ Pa}$$

$$\varphi = 27.81 \pm 4.99^\circ$$



LHS-1B simulant at $\sim 1.4 \text{ g/cm}^3$

5 mm cutting depth

15° rake angle

$$c = 374.89 \pm \frac{307.42}{300.27} \text{ Pa (95% conf.)}$$

$$\varphi = 42.97 \pm \frac{17.11}{41.67}^\circ \text{ (95% conf.)}$$

Conclusions and Future Work



- **Robotic arm testing with the COLDArm scoop:**
 - Can accurately measure Angle of Repose
 - Informs on and offers predictions of lunar and planetary trafficability and bearing capacity from pressure-sinkage tests
 - Is expected to be able to estimate cohesion and angle of internal friction from pseudo-direct shear tests
 - Shows promise in predicting cohesion and angle of internal friction from excavation force data
- **Next steps**
 - Perform each experiment in different (relative) densities to discern trends between amount of compaction and geotechnical parameter estimations
 - Compare to actual lunar data collected during COLDArm lunar flight mission

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Thank you – *ad lunam!*

Questions? Feel free to reach out!

Email: jared.long-fox@ucf.edu

LinkedIn: <https://www.linkedin.com/in/jaredlongfox/>

ResearchGate: <https://www.researchgate.net/profile/Jared-Long-Fox>