COLDArm Pressure-Sinkage Testing: Implications for Assessing Lunar Trafficability J. Long-Fox[1], R. Mueller[2], E. Bell[2], K. Dudzinski[3], B. Peacock[2], J. Gleeson[2], L. Sibille[4], R. McCormick[5], E. Marteau[5], D. Newell-Smith[5], P. Abel[6], [1]University of Central Florida Department of Physics (4111 Libra Drive Room 430, Orlando, FL 32816; jared.long-fox@ucf.edu) [2]Swamp Works, NASA Kennedy Space Center, Merritt Island, FL 32899, [3]University of Houston, 4800 Calhoun Rd, Houston, TX 77004, [4]Southeastern Universities Research Association (SURA), Washington D.C., [5]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, [6]NASA Glenn Research Center, 21000 Brookpark Rd., Cleveland, OH 44135

Introduction: The ability for regolith to support the movement of vehicles, known as trafficability, is commonly assessed using pressure-sinkage relationships [1]. Trafficability on the lunar surface is controlled by the site-specific physical properties of the regolith and the geometry and mass of the roving vehicle. Lunar regolith pressure-sinkage testing can be performed with standard exploration hardware (e.g., robotic arms with scoops) and will help define exploration routes and hazard zones for rovers and astronauts, as knowledge of the sinkage of a wheel in regolith helps constrain viable operating conditions for rovers. The objective of this study is to demonstrate the necessity of in situ testing and characterization of lunar regolith physical properties for exploration and infrastructure development activities.

Methods: Pressure-sinkage experiments were performed at NASA Kennedy Space Center (KSC) Swamp Works using Exolith Lab Simplified LHS-1 lunar highlands regolith simulant [2] and a Universal Robotics UR10 robotic arm which was outfitted with the COLDArm geotechnical scoop [3]. The scoop has two bearing faces, one with an area of ~54 cm^2 (Bearing Face 1) and one with an area of ~24 cm^2 (Bearing Face 2) [3]. The UR10 arm is programmed to press Bearing Face 1 and 2 into the fresh surface of the simulant (known density) a given distance and continuously monitoring the force.

The data obtained from this testing were used to estimate relevant parameters (and their uncertainties) of the Reece [1965] pressure-sinkage model [1]:

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

where P is pressure, k_c is a constant related to cohesion, b is plate width, k_ϕ is a constant related to friction, z is sinkage depth, and n is a dimensionless constant. To enable predictions of sinkage due to a given applied pressure (or vice versa), the k_c, k_ϕ, and n parameters estimated using least squares and Metropolis-Hastings Markov Chain Monte Carlo methods [4]; 95% confidence intervals of the estimated parameters are found using a series of F tests. The same parameter estimation algorithms are applied to published [5] predictions of rover wheel sinkage as a function of wheel size and rover mass based on remote sensing of lunar boulder tracks to calculate bearing capacity for the Resource Prospector (RP) rover and the Lunar Electric Rover (LER) [5]. The mass vs. sinkage curves for LER and RP were digitized to extract mass and sinkage predictions. See Figures 1 and 2 for plots of the digitized LER and RP data (black dots), respectively, and the best fit Reece [1965] model (green and orange lines). Based on these previously published lunar pressure-sinkage predictions [5], the contact area of the LER and RP wheels was based on the width of the wheels (30 cm and 15 cm, respectively), and the length of the contact area for both LER and RP was assumed to be 15 cm to satisfy analysis requirements in [4]. The sinkage curves in [5], as well as the results of analyses here are compared to results from the robotic arm-based testing performed at KSC to evaluate the differences between interpretations of regolith physical properties.

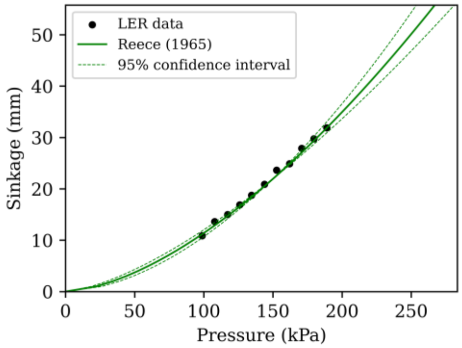

Figure 1. Reece [1965] best-fit model for the LER pressure-sinkage predictions from Bickel et al. [5].

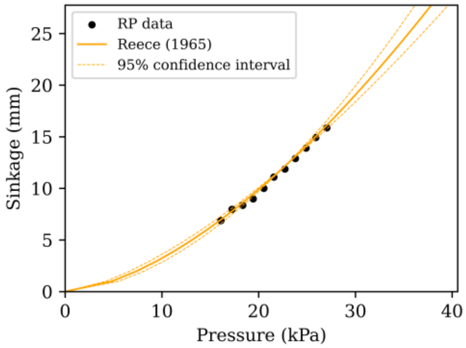

Figure 2. Reece [1965] best-fit model for the RP pressure-sinkage predictions from Bickel et al [5].

Results: Results of fitting the COLDArm Bearing Face 1 and 2 data (black dots) using the Reece [1965] model of pressure-sinkage [1] are shown in Figures 3 and 4 as blue and red lines, respectively. Table 1 gives parameter estimates and 95% confidence intervals for the COLDArm testing and remote sensing analysis from [5] shown in Figures 1 and 2.

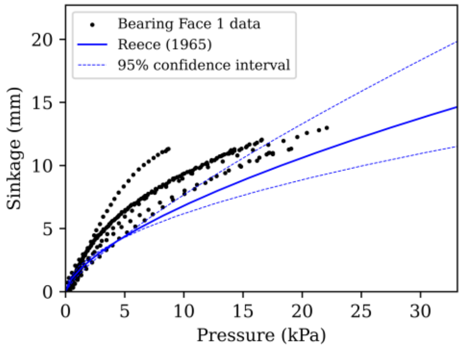

Figure 3. Reece [1965] best-fit model for the KSC COLDArm Bearing Face 1 pressure-sinkage data.

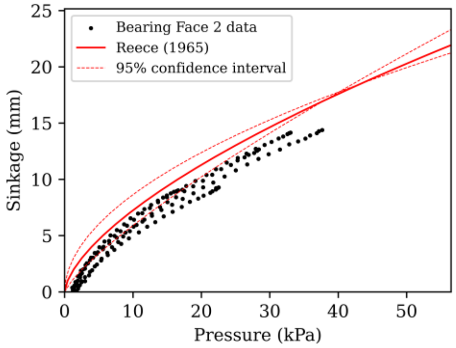

Figure 4. Reece [1965] best-fit model for the KSC COLDArm Bearing Face 2 pressure-sinkage data.

Table 1. Estimates (95% confidence) for Reece [1965] parameters for COLDArm data and Bickel et al. [5]

	COLDArm	**Remote Sensing [5]**
$\boldsymbol{k_c}$	$-151.49 \pm^{624.43}_{170.22}$	$-541.10 \pm^{85.66}_{73.35}$
$\boldsymbol{k_\phi}$	$7734.10 \pm^{19042.84}_{5600.04}$	$4323.85 \pm^{677.56}_{581.35}$
$\boldsymbol{n}$	$1.56 \pm^{0.36}_{0.30}$	$0.6185 \pm^{0.055}_{0.055}$

Discussion: The Reece [1965] fits of preliminary COLDArm Bearing Face 1 and 2 pressure-sinkage data underpredict and overpredict the measured data, respectively, but the overall shape of the curve is satisfactory. Misfits are attributed to the fact that the geotechnical properties of lunar regolith and simulants differ greatly from that of terrestrial soils (Reece [1965] is a terrestrial model); work is ongoing to develop more robust characterizations of *in situ* regolith pressure-sinkage relationships. The data from testing the COLDArm scoop show a steep increase in sinkage relative to applied pressure in the lower pressure ranges, and this indicates that the relatively uncompacted upper layers of simulant experience are more susceptible to compression [6]. This is a key finding for low-mass roving platforms aimed for lunar operations since lightweight rovers may need to contend with this upper "fluffy" layer on the lunar surface which has much different terramechanical properties than well-compacted regolith. The boulder track analyses [5] are not affected by this upper layer of low-density regolith due to the high mass of the objects causing the sinkage and hence provide a significantly different view of regolith pressure-sinkage relationships, as evidenced by the shape of the best-fit curves in Figures 1 and 2 as opposed to Figures 3 and 4. This difference highlights the necessity of on-site testing of lunar pressure-sinkage relationships for lunar road mapping, infrastructure site selection and exploration terrain hazard analysis.

Conclusions: Characterizing the pressure-sinkage relationships of lunar regolith during exploration and resource acquisition and utilization activities will help indicate areas suitable for travel for a wide range of rover masses, including increasingly common small, low-mass rovers (e.g. [7], [8]). The ability of COLDArm to withstand the extreme lunar environment without heaters offers the ability to perform vital site characterizations (including but not limited to pressure-sinkage) in permanently shadowed regions (PSRs) and throughout the lunar night, giving an increase in efficiency and lowering overall energy costs for exploration and *in situ* resource utilization (ISRU) efforts.

Acknowledgments: The work presented here was performed as part of the NASA Jet Propulsion Laboratory (JPL) and Motiv Space Systems COLDArm project at the NASA Kennedy Space Center (KSC) Swamp Works laboratory in collaboration with the University of Central Florida (UCF) Center for Lunar and Asteroid Surface Science (CLASS) node of the NASA Solar System Exploration Research Virtual Institute (SSERVI, NASA Cooperative Agreement 80NSSC19M0214).

References: [1] Reece, A. R. (1964), Land Locomotion Laboratory Report No. 8470. [2] Long-Fox et al. (2022) *NASA Exploration Science Forum*. [3] Backus, S. et al. (2021), LEAG. [4] Wong, J. Y. (1980), *J. Terramech.* 17. [5] Bickel, V. T. et al. (2019), *J. Geophys. Res.: Plan.* 124. [6] Salman, N. D. and Kiss, P. (2019), DOI:10.21791/IJEMS.2019.1.24. [7] NASA CADRE,https://www.nasa.gov/directorates/spacetech/game_changing_development/projects/CADRE. [8] Tallaksen, A. P. et al. (2017), LEAG.