Quantifying the Need for Advanced Computational Tools for Lunar Excavation Analysis. J. M. Long-Fox[1], R. P. Mueller[2], K. A. Zacny[3], and D. T. Britt[1], [1]University of Central Florida Department of Physics (4111 Libra Drive Room 430, Orlando, FL 32816; jared.long-fox@ucf.edu), [2]NASA Kennedy Space Center Swamp Works, Merritt Island, FL 32923, [3]Honeybee Robotics, 2408 Lincoln Ave, Altadena, CA 91001.

Introduction: Infrastructure development on the lunar surface will require thousands of tons of lunar regolith, and the extreme conditions on the lunar surface demand efficient and reliable methods of regolith acquisition. Percussive excavation has been experimentally shown to significantly reduce reaction forces during excavation as compared to conventional "static" excavation [1,2]. Implementing such force reduction methodologies during lunar surface excavation operations would allow for lower mass equipment with lower size and load capacity requirements; the return on investment of the power to run a motor to drive percussion must be enough to justify the extra power and equipment complexity. To develop hardware and CONOPS for planetary excavation, reliable computational models must be developed to enable comparison of different scoop, tool path, and force reduction configurations [3] and their resulting power requirements and efficiency curves. The work presented here uses data from [1,2] as a case study to establish metrics for force reduced excavation efficiency and evaluate a commonly used excavation force prediction model, Reece's Fundamental Equation of Earthmoving (FEE) [4], for use in lunar excavation CONOPS and hardware development efforts.

Efficiency Analysis: To define metrics of excavation efficiency, data from [1,2] are used, and further details of this evaluation are given in [5]. These experiments [1,2] used a replica Surveyor III SMSS scoop in a series of percussive excavation experiments that varied frequency, simulant (JSC-1A) density, and scooping depth. The relative cost (power draw) of percussive excavation is evaluated as a function of percussive frequency and scooping depth. Experiment data from [1,2] selected for use in this case study efficiency analysis sample a range of percussive frequencies (0-1750 beats per minute, BPM) and scooping depths (30, 50, and 70 mm) but all have the same speed (5 mm/s), high relative density (> 95%), and rake angle of 70°. Specifically, the ratio of motor power to total excavation force (W/N) and ratio of percent force reduction to percussion motor power (%/W) are calculated and fit with linear ($y = mx + b$) and exponential ($y = ae^{bx} + c$) functions and respectively. Excavation force per unit power as a function of percussive frequency and depth is shown in Figure 1 and percent force reduction per unit power vs frequency and depth is shown in Figure 2.

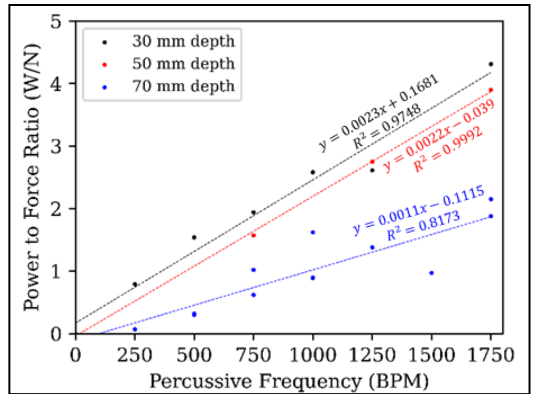

Figure 1. Percussive frequency vs power cost per total force during excavation.

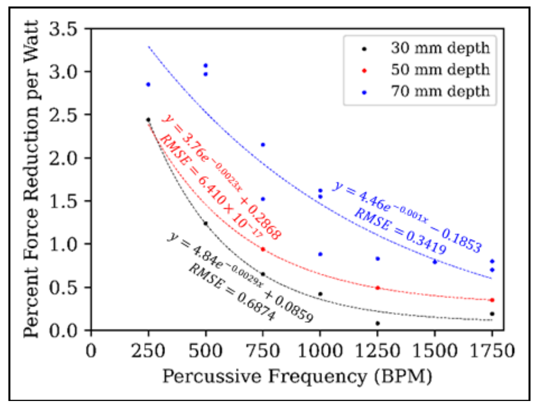

Figure 2. Percussive frequency vs. percent force reduction (compared to static excavation) per unit power.

Analytical Modeling:

Reece's FEE (Eq. 1) predicts excavation forces (F) as a function of scooping geometry (e.g., rake angle ρ, scoop width w, and depth d), material properties of the regolith and tool (cohesion c, angle of internal friction φ, angle of external friction δ, shear plane failure angle β, and surcharge load q) and dimensionless "N factors" N_c, N_γ, and N_q (Eq. 2, 3, and 4, respectively).

$$F = w\left[cdN_C + \gamma d^2 N_\gamma + qdN_q\right] \quad (1)$$

$$N_c = \frac{1+[\cot(\beta)\cot(\beta+\varphi)]}{\cos(\rho+\delta)+[\sin(\rho+\delta)\cot(\beta+\varphi)]} \quad (2)$$

$$N_\gamma = \frac{\cot(\rho)+\cot(\beta)}{2[\cos(\rho+\delta)+[\sin(\rho+\delta)\cot(\beta+\varphi)]]} \quad (3)$$

$$N_q = \frac{\cot(\rho)+\cot(\beta)}{\cos(\rho+\delta)+[\sin(\rho+\delta)\cot(\beta+\varphi)]} \quad (4)$$

Here, the predictive capabilities of Reece's FEE are evaluated as a forward model (input known/assumed parameter values to predict forces) and an inverse model (predict parameter values from input excavation force data). Data used are from three experiments of [1,2] with varying depth with excavation speed of 5 mm/s and ρ = 70°. Only static excavation force data is considered here since this is what Reece's FEE is intended to simulate. If Reece's FEE can offer reliable predictions, it can be used in lunar excavation planning and analysis. The density of the simulant in each test was 47% to 54% RD (1.743 to 1.775 g/cm^3, "medium RD") [1,2]. Parameter values for forward models are given in Table 1.

Table 1. Forward model input parameter values.

Parameter	Assumed Value
$c_{d=30,50,70mm}$ (Pa)	819.46, 755.03, 713.88 [7]
$\varphi_{d=30,50,70mm}$ (°)	44.42, 43.67, 43.16 [7]
$\delta_{d=30,50,70mm}$ (°)	29.47, 29.11, 28.77 (0.67φ)
$\beta_{d=30,50,70mm}$ (°)	33, 35, 37 [1,2]

Inverse models used a Markov Chain Monte Carlo (MCMC) technique detailed in [6] to find a best-fit set of parameter values that describe the given data. The forward and inverse model fits to the data from [1,2] are given in Figure 3, and the best fit parameter estimations from the inverse model are given in Table 2.

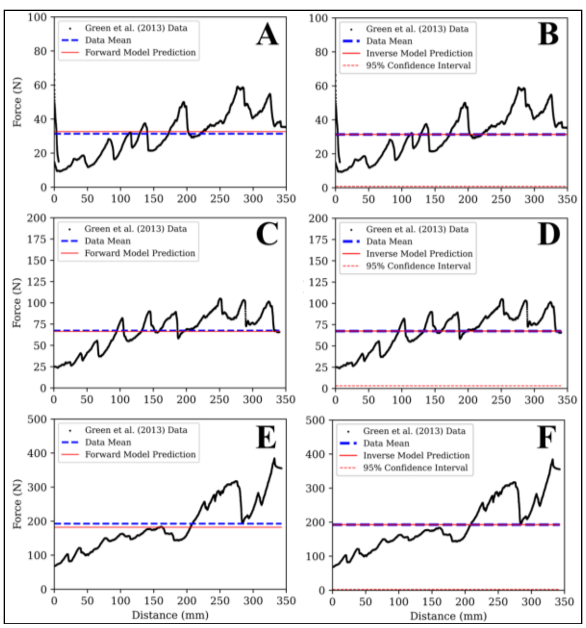

Figure 3. d = 30 mm forward **(A)** and inverse **(B)** model best fits, d = 50 mm forward **(C)** and inverse **(D)** model best fits, and d = 70 mm forward **(E)** and inverse **(F)** model best fits. Upper confidence intervals of the inverse models are above the maximum force value of each plot.

Table 3. MCMC inverse model parameter estimates (2σ uncertainty) compared to the expected values.

Parameter	Estimated Value	Expected Value
d = 30 mm		
c (Pa)	$1425.65 \pm^{1818.14}_{1393.72}$	819.46 [5]
φ (°)	$40.61 \pm^{34.77}_{37.70}$	44.42 [5]
δ (°)	$39.64 \pm^{25.67}_{38.81}$	29.47 (0.67φ)
β (°)	$17.92 \pm^{55.83}_{17.20}$	33.00
d = 50 mm		
c (Pa)	$649.34 \pm^{2153.72}_{649.07}$	755.03 [5]
φ (°)	$47.50 \pm^{27.65}_{46.76}$	43.67 [5]
δ (°)	$40.98 \pm^{40.97}_{40.69}$	29.11 (0.67φ)
β (°)	$6.64 \pm^{72.64}_{6.04}$	35.00
d = 70 mm		
c (Pa)	$1868.17 \pm^{1686.39}_{1794.53}$	713.88 [5]
φ (°)	$33.59 \pm^{41.27}_{26.99}$	43.16 [5]
δ (°)	$40.54 \pm^{40.015}_{39.59}$	28.77 (0.67φ)
β (°)	$31.64 \pm^{33.04}_{30.84}$	28.77

Discussion and Conclusions: The efficiency analysis here shows that the power cost per force of excavation is directly proportional to percussive frequencies (Figure 1) and that there are diminishing returns with increased percussive frequency (Figure 2). The general trends and considerations are expected to be true for any force-reduced excavation, not just the configuration used in [1,2]. The forward model parameter values given in Table 1 fit the mean values of the data well, but the inverse model results (Table 2) show that solutions to Reece's FEE are highly nonunique and have very wide confidence intervals. The failure to produce reliable parameter estimations is also expected for other analytical excavation force prediction models and hence, these models are not able to evaluate efficiency or be used in tool path planning or hardware design. Taken together, the results here show that more advanced computational models are needed to be able to design equipment, define tool paths, and analyze excavation power budgets; this is the subject of ongoing work.

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