Quantifying the Need for Advanced Computational Tools for Lunar Excavation Analysis

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Introduction

- Infrastructure development and ISRU on the lunar surface will require thousands of tons of lunar regolith → efficiency is key
- Excavation force reduction
  - Percussive [1] and vibratory [2]
  - Return on investment must be enough to justify the extra power and equipment complexity
- Computational models must enable comparison of different scoop, tool path, and force reduction methods [3], power requirements, and efficiency

Methods

- Excavation force and percussion motor power draw data from [1]; replica Surveyor III SMSS scoop, JSC-1A simulant
- Analytical Modeling
  - Static, medium RD, 70° rake angle, 5 mm/s speed
  - 2D Reece's Fundamental Equation of Earthmoving (FEE) [4]
    - Predict excavation forces based on known regolith/simulant properties (forward model)
    - Predict regolith/simulant properties from measured excavation forces (inverse model)
- Excavation Efficiency (force vs power)
  - Varying percussive BPM, high RD, 70° rake angle, 5 mm/s speed

2D Reece's Fundamental Equation of Earthmoving

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

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

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

$$N_q = \frac{\cot(\rho) + \cot(\beta)}{\cos(\rho+\delta) + (\sin(\rho+\delta)\cot(\beta+\phi))}$$

where F is excavation force, w is scoop width, d is scooping depth, γ is density, Q is surcharge load, ϕ is angle of internal friction, δ is angle of external friction, ρ is rake angle, and β is shear plane failure angle

Analytical Modeling

Parameter	Assumed Value
$c_{d=30,50,70mm}$ (Pa)	819.46, 755.03, 713.88 [5]
$\phi_{d=30,50,70mm}$ (°)	44.42, 43.67, 43.16 [5]
$\delta_{d=30,50,70mm}$ (°)	29.47, 29.11, 28.77 (0.67ϕ)
$\beta_{d=30,50,70mm}$ (°)	33.00, 35.00, 37.00 [1]

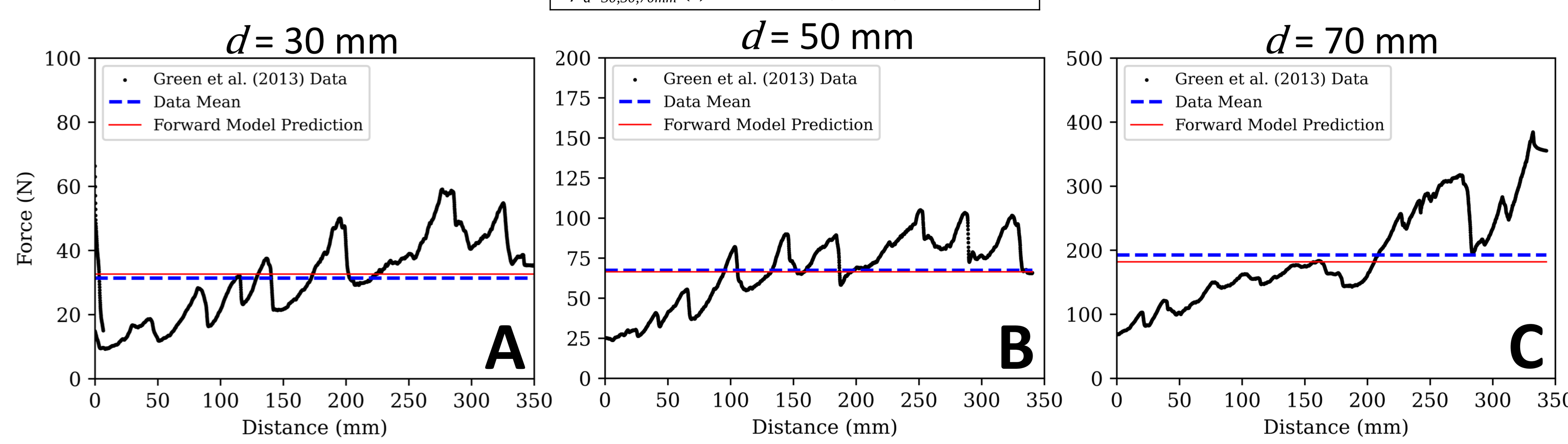
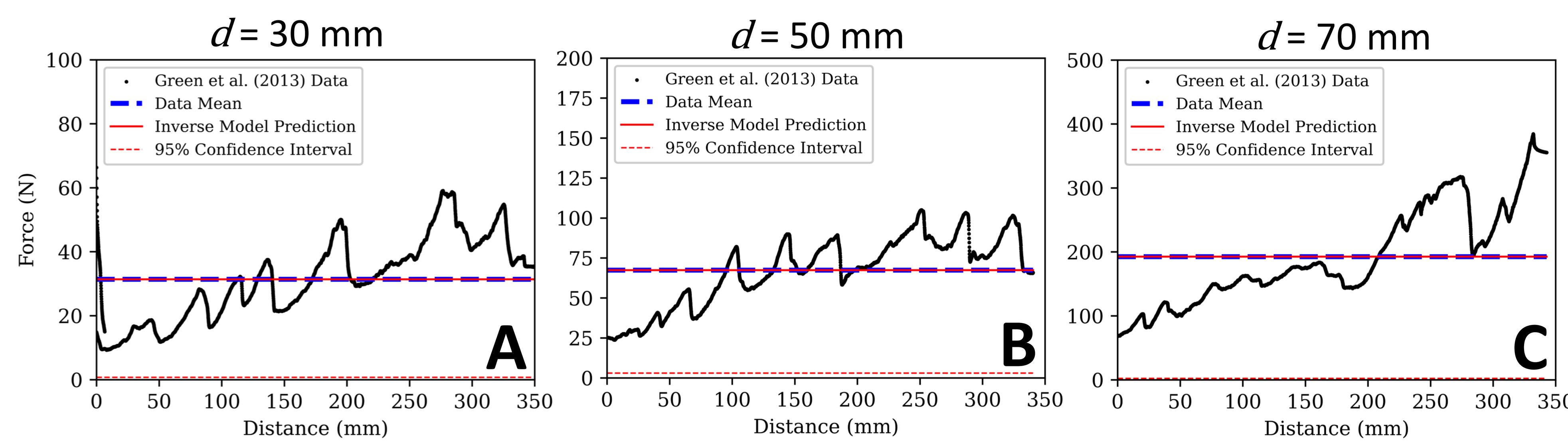


Figure 1. Forward model predictions of data from [1] for excavation speeds of 5 mm/s, rake angle of 70°, and depths of **(A)** 30 mm, **(B)** 50 mm, and **(C)** 70 mm using Reece's FEE and given input parameter values.



(A)

Parameter	Estimated Value	Expected Value
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 [1]

(B)

Parameter	Estimated Value	Expected Value
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 [1]

(C)

Parameter	Estimated Value	Expected Value
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 (°)	$31.64 \pm^{33.04}_{30.84}$	37.00 [1]

Figure 2. Inverse model predictions and uncertainties of model parameters based on data from [1] for excavation speeds of 5 mm/s, rake angle of 70°, and depths of **(A)** 30 mm, **(B)** 50 mm, and **(C)** 70 mm.

Metrics of Excavation Efficiency

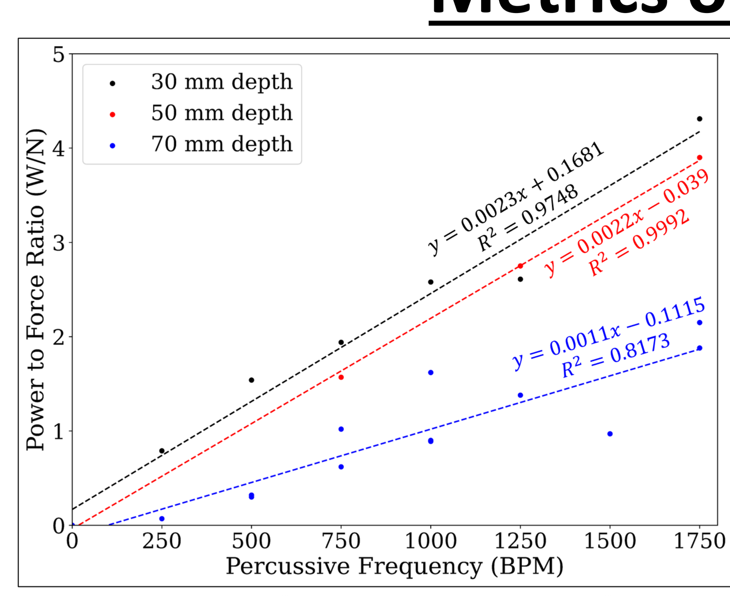


Figure 3. Linear fits to percussive frequency vs percussion motor power expended per unit excavation force during excavation of high relative density JSC-1A with a replica Surveyor III SMSS scoop at 30, 50, and 70 mm digging depths; data from [1].

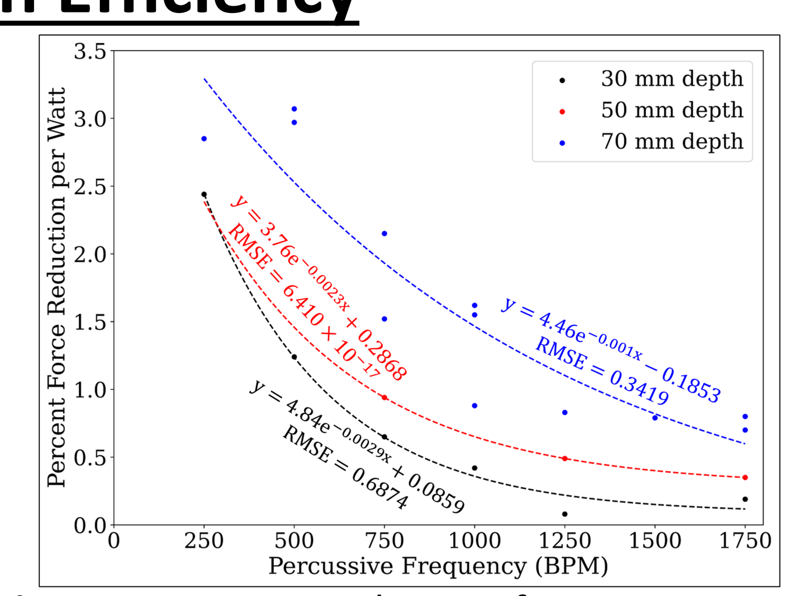


Figure 4. Exponential curve fits to percussive frequency vs percent force reduction per watt expended by percussion motor during excavation of high relative density JSC-1A with a replica Surveyor III SMSS scoop at 30, 50, and 70 mm digging depths; data from [1].

Discussion

- Standard analytical models are not suitable for lunar and planetary excavation analysis
  - Forward models offer good predictions; inverse modeling reveals ill-resolved parameter space → not reliable
  - Not able to be used for tool path development, equipment design, power budget analysis, etc.
- Efficiency analysis shows:
  - Power cost per unit force is linearly proportional to percussive frequency
  - Percent force reduction per unit power expended has diminishing returns → can be optimized
  - General trends expected to hold for other scenarios (regolith, equipment)

Conclusion

- More advanced computational models are needed for planetary excavation hardware design, CONOPS development, and power budget analysis
  - Subject of ongoing work

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References

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