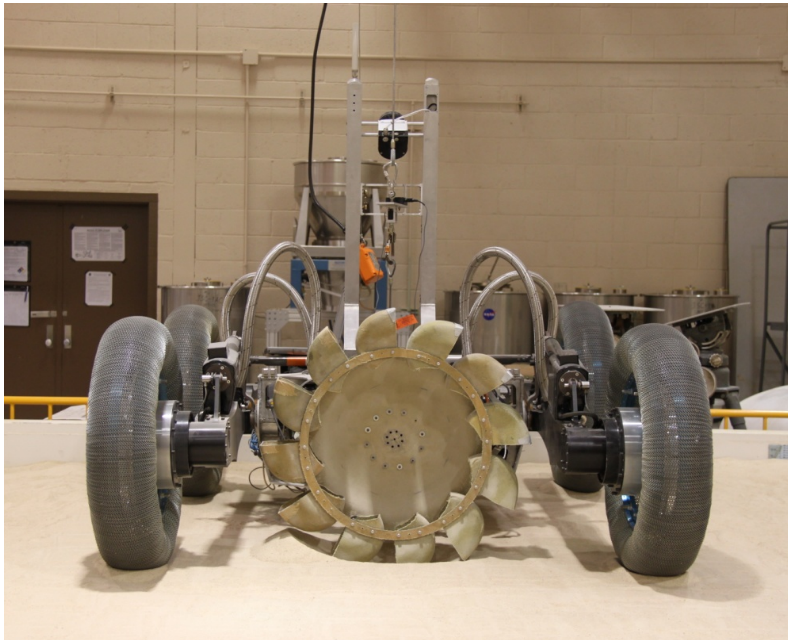
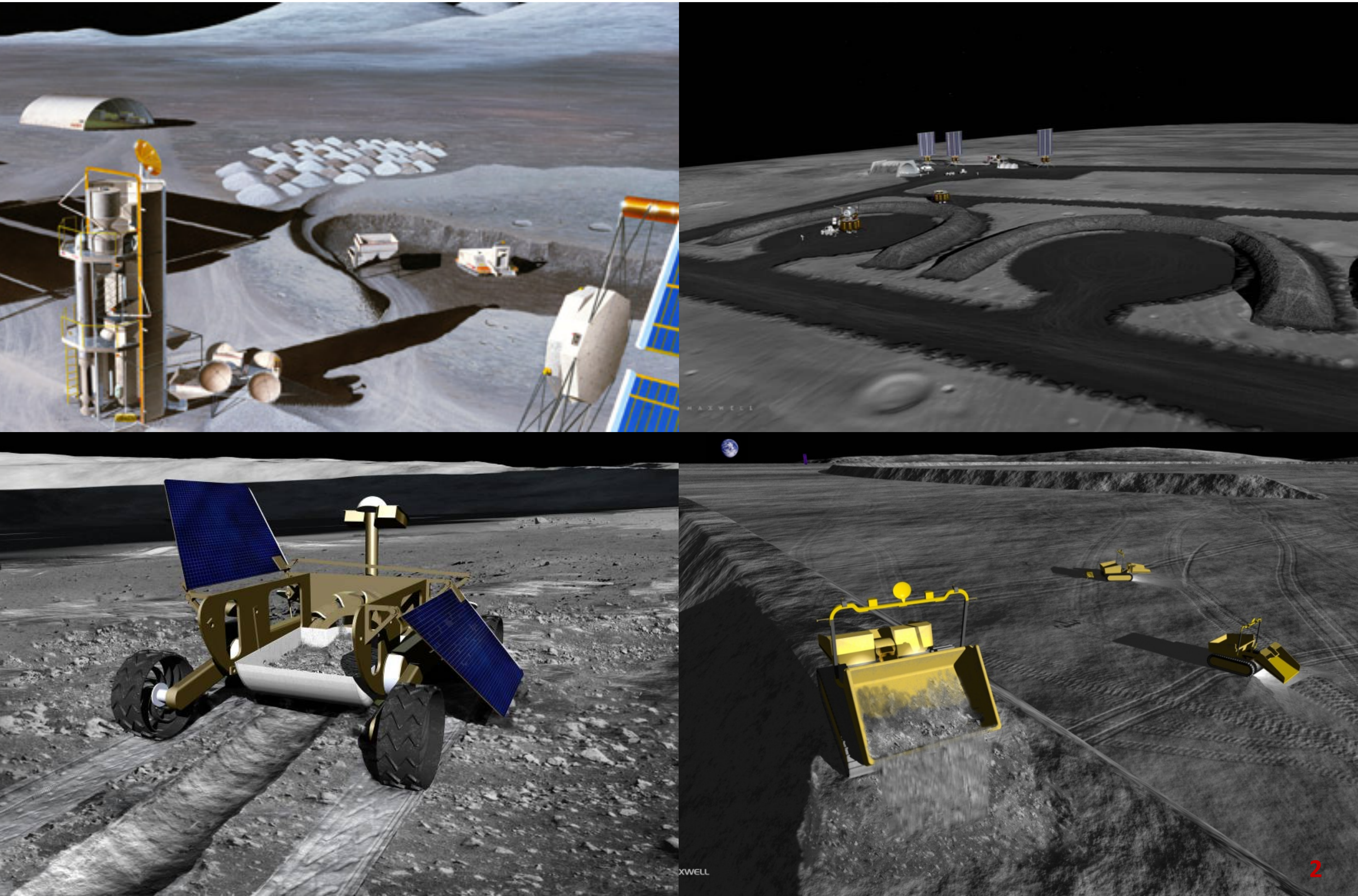
Considering Effects of Gravity on Planetary Excavators



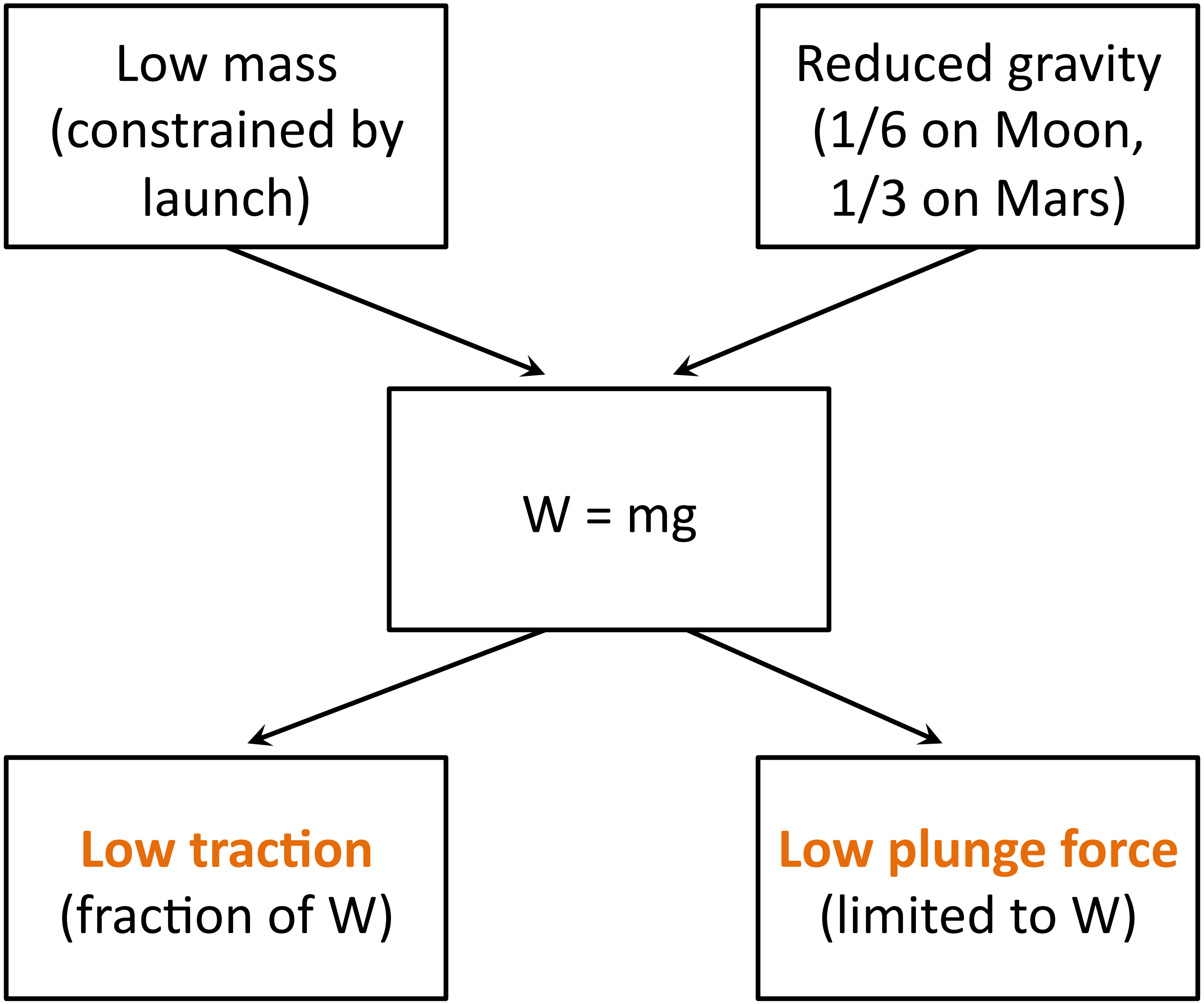
Krzysztof (Chris) Skonieczny
David S. Wettergreen

Carnegie Mellon
THE ROBOTICS INSTITUTE

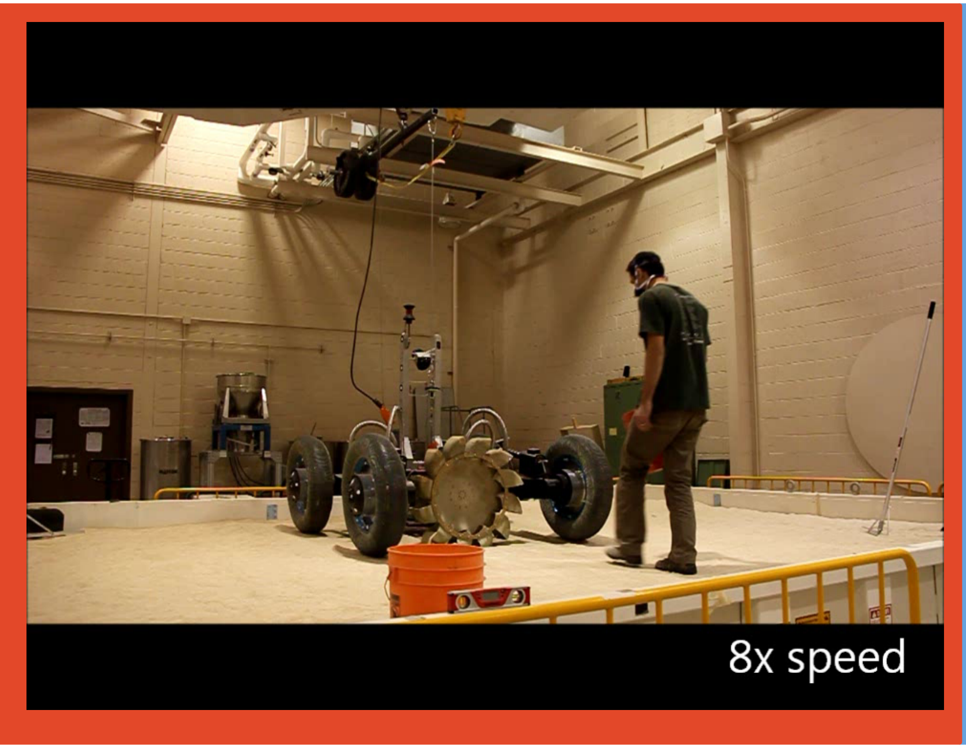
Planetary excavation sustains future exploration



Challenges of planetary excavation



Continuous excavation excels in reduced gravity



Traction is often used to achieve excavation

Continuous excavators

Terrestrial mobile excavators

Discrete excavators

Bucket-wheel trencher

Bucket-chain trencher

Elevating scraper

Open-bowl scraper

Front-end loader

Bulldozer

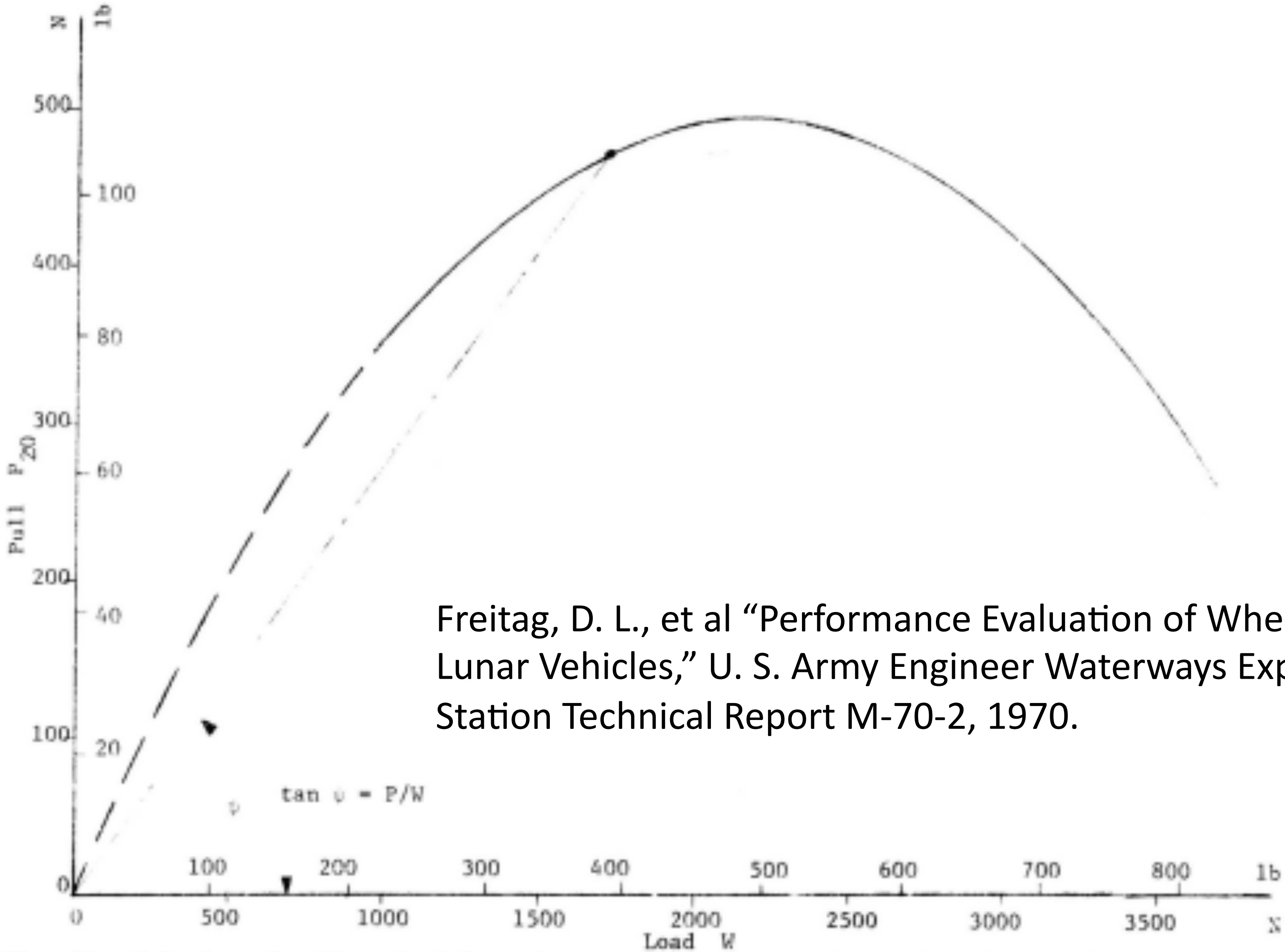
Planetary excavator prototypes

How should we test proposed planetary excavators?

- We want to make sure $DP_{20} > F_{ex}$

- If we only test this with a full mass vehicle in 1 g, we are implicitly assuming:
  - $DP_{20}\,(1/6\ g_{Earth}) \approx 1/6\ DP_{20}\,(g_{Earth})$
  - $F_{ex}\,(1/6\ g_{Earth}) \approx 1/6\ F_{ex}\,(g_{Earth})$

DP_{20} scales approx. linearly with load (W) in constant g

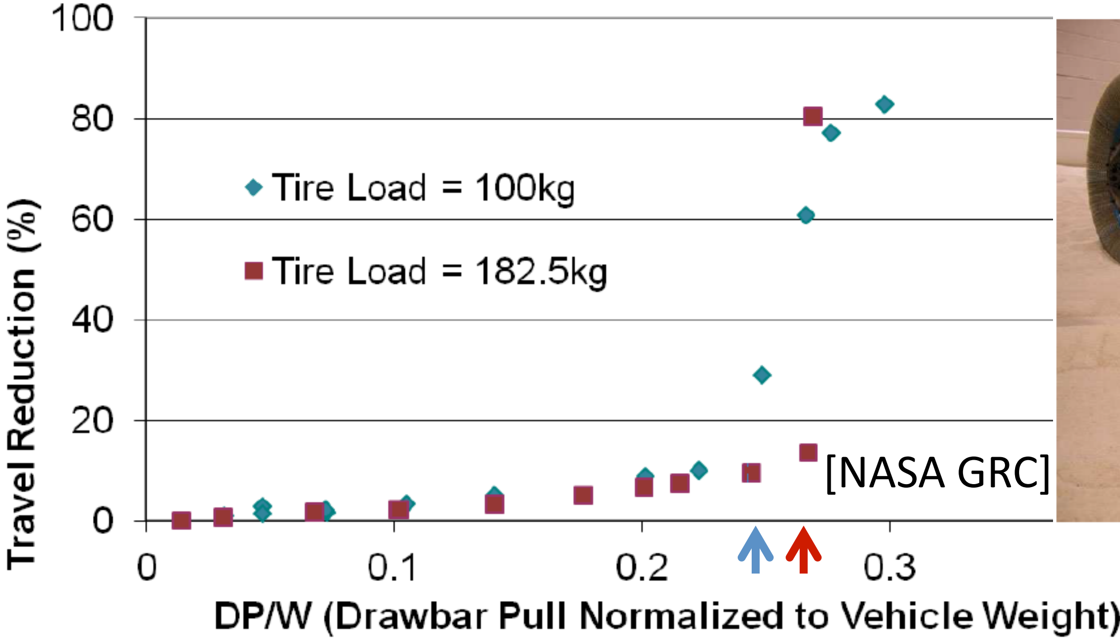


Freitag, D. L., et al "Performance Evaluation of Wheels for Lunar Vehicles," U. S. Army Engineer Waterways Experiment Station Technical Report M-70-2, 1970.

Fig. 46. Relation of pull to load for a heavily loaded pneumatic wheel on dense, air-dry Yuma sand

DP_{20} for changes in W vs. changes in g

- DP_{20}/W approximately constant at lower W (constant g)



[NASA GRC]

DP_{20} for changes in W vs. changes in g

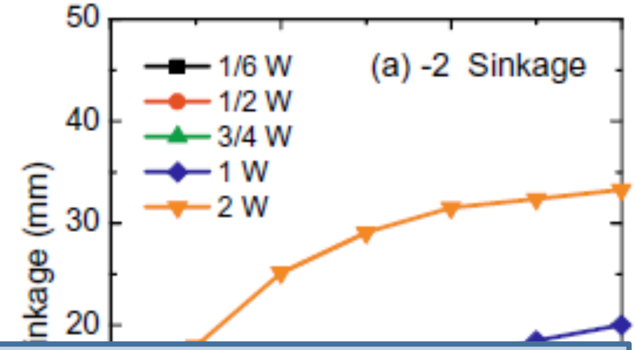
- DP_{20}/W approximately constant at lower W (constant g)

  Drawbar pull = Thrust – Resistance

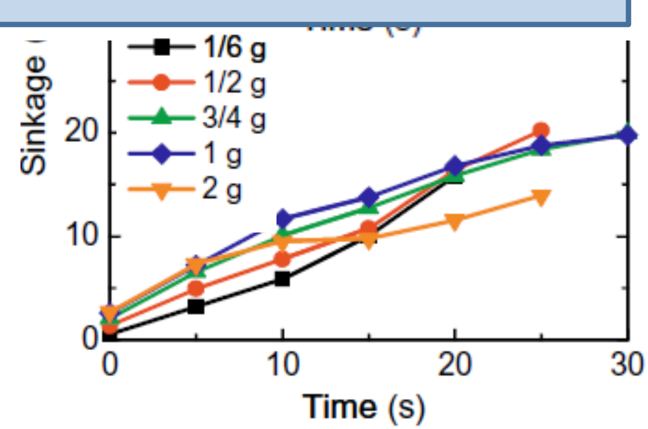
  With lower W, we get lower Thrust

  With lower W, we get reduced sinkage,

  and thus lower Resistance



Assuming $DP_{20}\ (1/6\ g_{Earth}) \approx 1/6\ DP_{20}\ (g_{Earth})$
is an over-optimistic estimate of planetary mobility



- DP_{20}/W lower at lower g

  With lower g, we get lower Thrust

  No equivalent reduction in sinkage,

  No equivalent reduction in Resistance

Kobayashi, T, et al, “Mobility performance of a rigid wheel in low gravity environments,” J Terramechanics, 2010.

F_{ex} for changes in g

- $F_{ex}\,(1/6\; g_{Earth}) = \{1/6\; F_{ex}\,(g_{Earth})\;,\; F_{ex}\,(g_{Earth})\;\}$

Boles, W. W. et al, “Excavation forces in reduced gravity environment,” J Aerospace Eng., 1997.

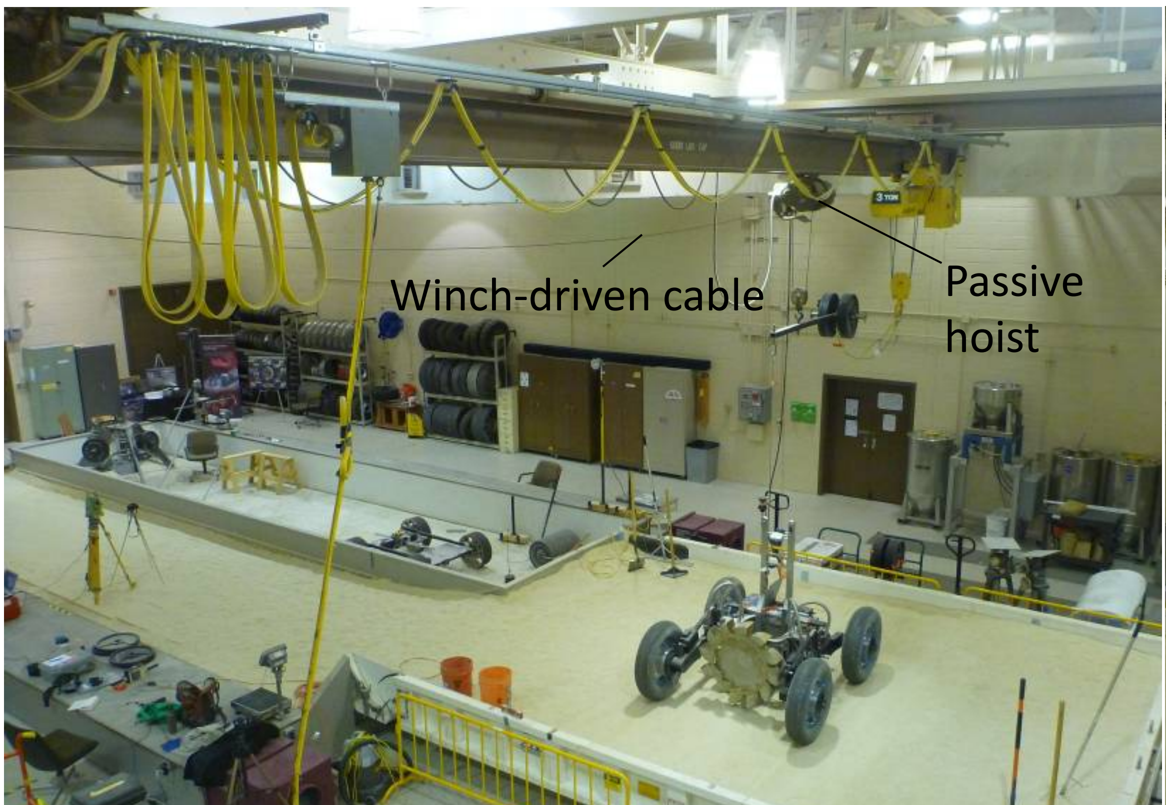
Assuming $F_{ex}(1/6\; g_{Earth}) \approx 1/6\; F_{ex}\,(g_{Earth})$
is the most optimistic estimate of planetary excavation forces

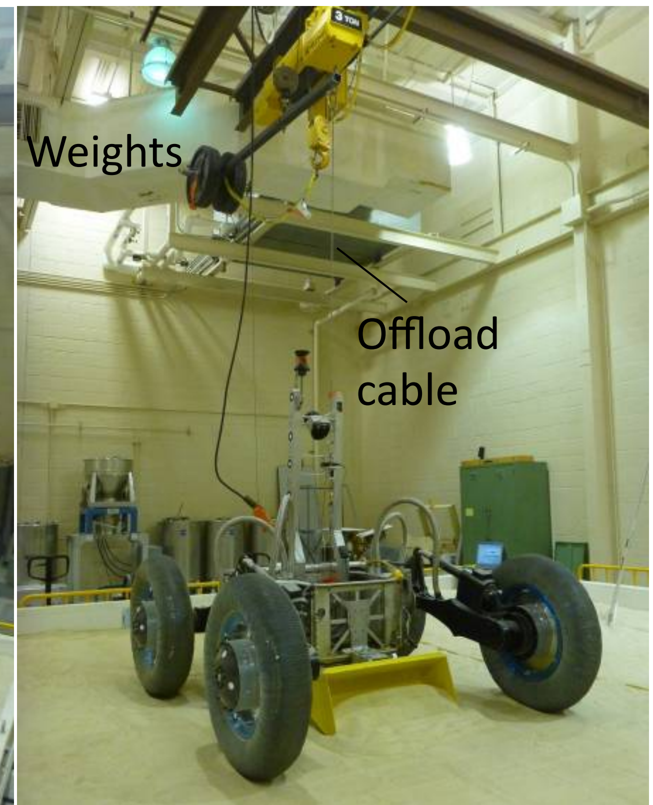
	Testing in 1 g	Gravity offload testing
Mobility	Over-optimistic	Over-optimistic
Excavation forces	Most optimistic	Most pessimistic

- Gravity offload testing a more balanced approach than 1 g testing

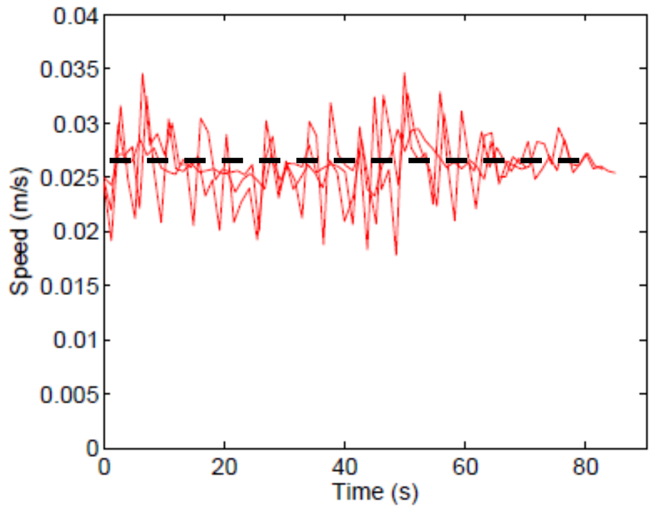
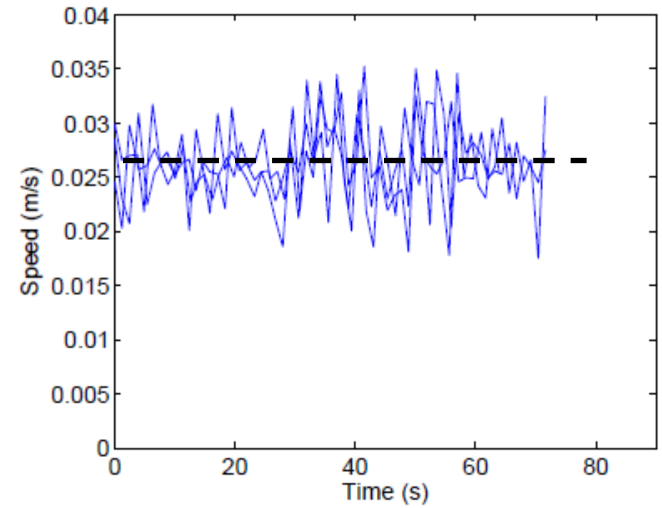
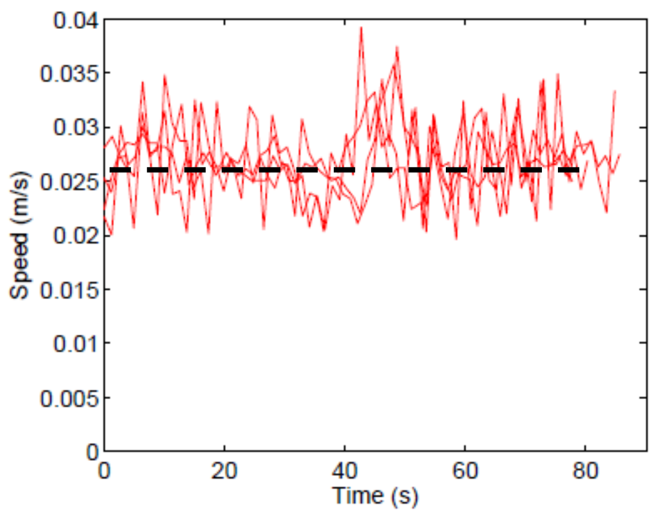
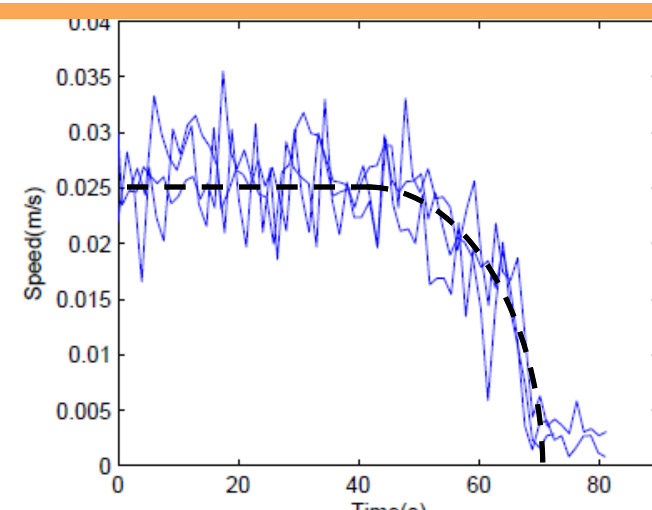
Gravity offloaded excavation experiments

- First laboratory experiments to test excavation with 5/6 of robot weight offloaded
- Conducted at NASA Glenn Research Center's SLOPE lab





Mobility impeded for lightweight discrete excavation

	Continuous excavation	Discrete excavation
1 g		
Offloaded to 1/6 g		

Continuous excavation excels when weight is limited

Offloaded discrete excavation collects little payload

Excavation in Earth gravity

45-50 kg collected

Excavation with gravity offload

15-20 kg collected

Conclusions

- Gravity offload testing is a more balanced method of testing proposed planetary excavators than testing full mass systems in 1 g

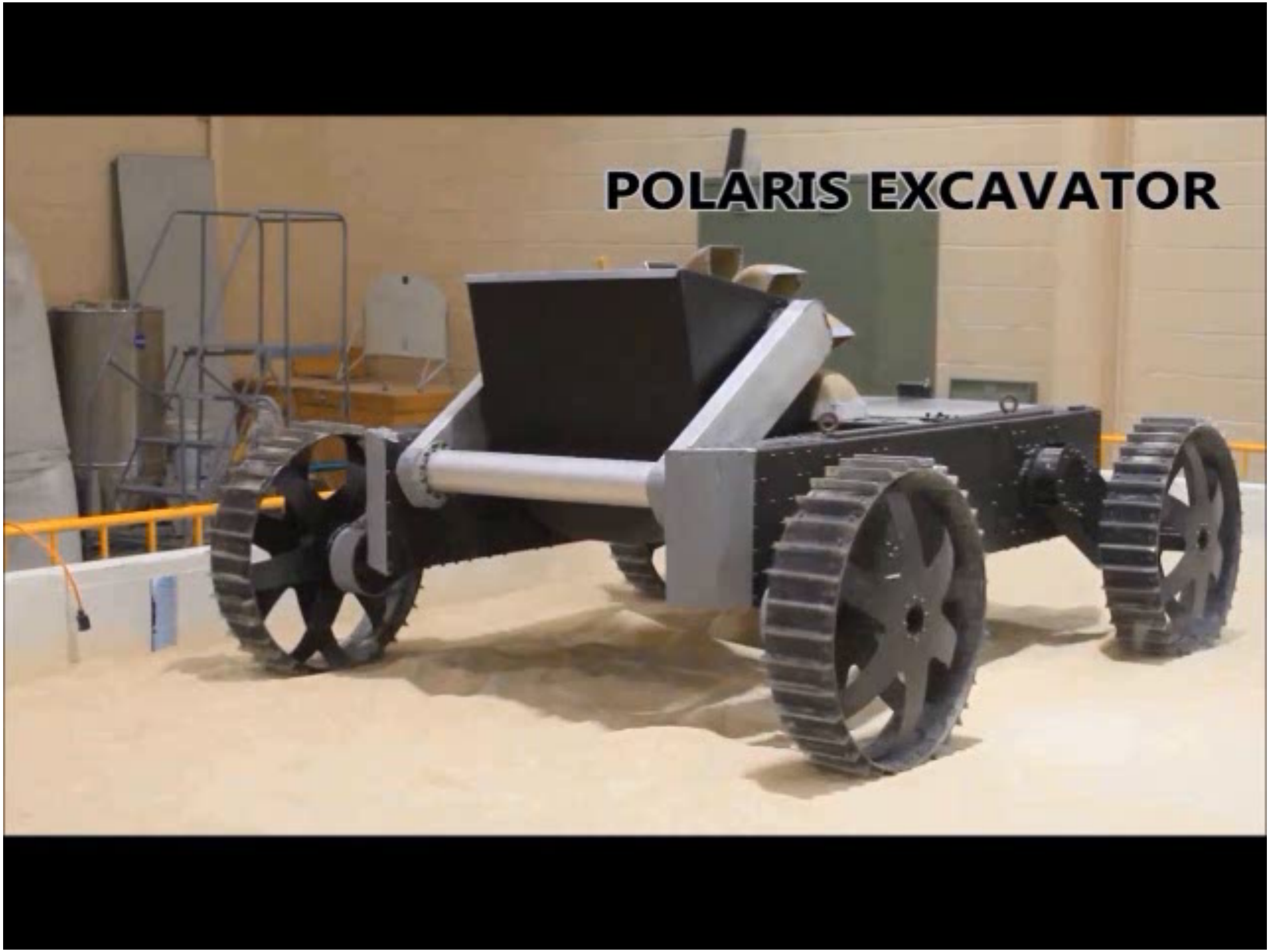
- Continuous excavators are better suited than discrete excavators to maintain productivity and mobility in lightweight operations

- Analytical framework can predict the effectiveness of various lightweight excavators

Acknowledgements:

Colin Creager, NASA Glenn Research Center / Rob Mueller, NASA Kennedy Space Center / Phil Metzger, (NASA Kennedy Space Center) / Astrobotic Technology Inc.

Polaris: A productive planetary excavator



Future Work

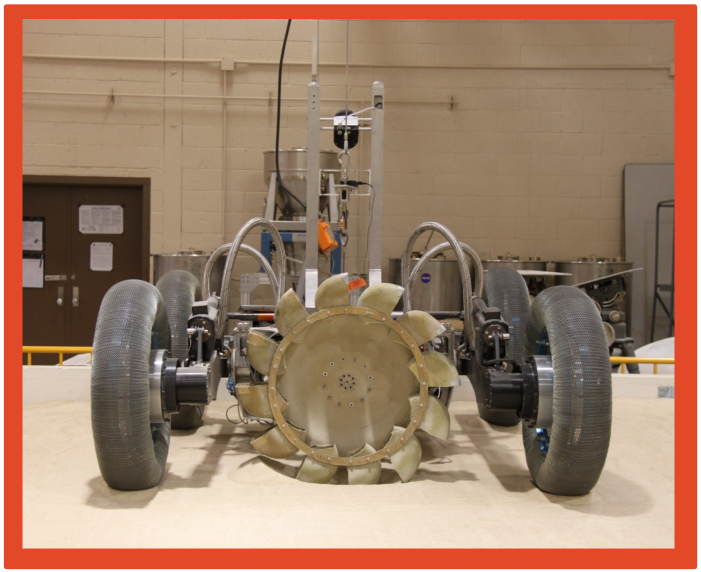
Future site of 16-storey controlled-g drop tower?

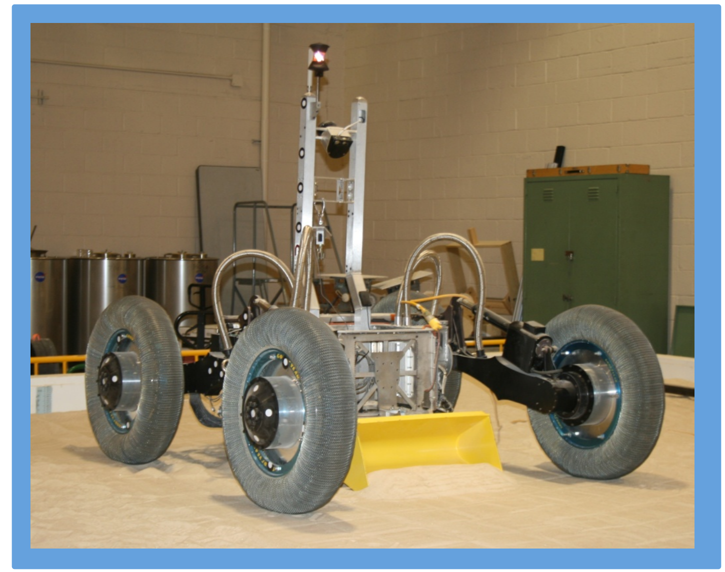
Thank you! Questions?

kskoniec@encs.concordia.ca

Predicting lightweight numbers

- Excavation performance and mobility can be predicted for Scarab with bucket-wheel and front-loader bucket





Wheel and tool characterization experiments $\rightarrow$ $\widetilde{T}, \widetilde{F}_{0,cont}, \widetilde{F}'_{disc}$ $\rightarrow$ L

Predicted "lightweight numbers"

- Details of the analytical framework for predicting the effectiveness of excavators in lightweight (i.e. low g) operations is outlined in my PhD thesis.

	Continuous excavation	Discrete excavation
$1\ g$	$L = 60\text{-}130$	$L = 2\text{-}4$
$1/6\ g$	$L = 10\text{-}20$	$\boldsymbol{L = 0.3\text{-}0.7}$ *

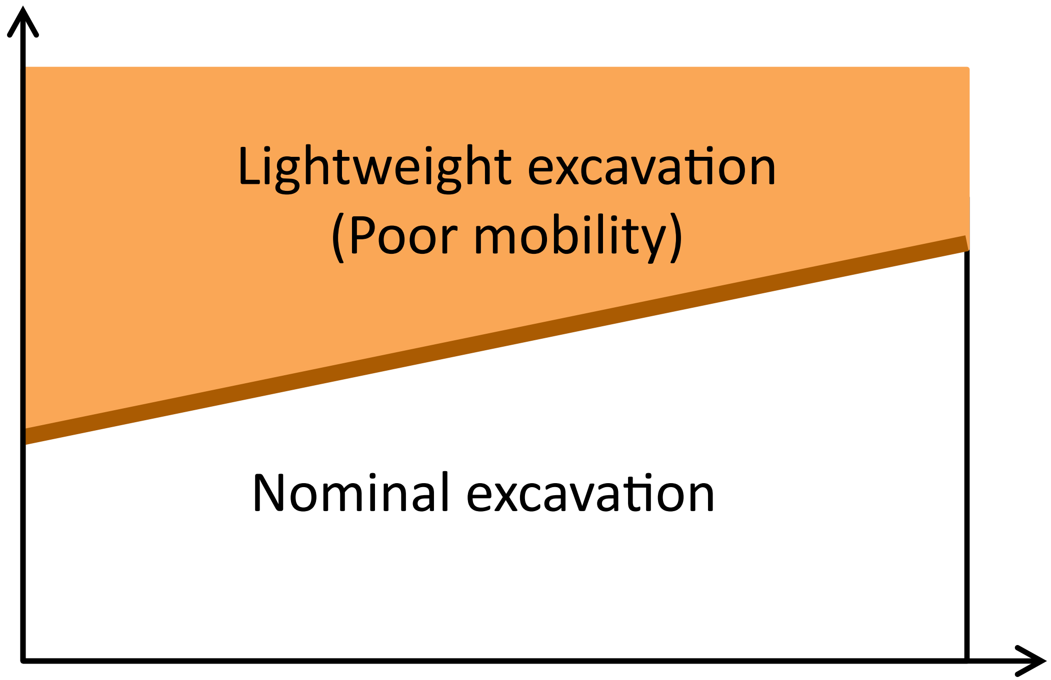
$^{*}L < 1 \rightarrow$ Operation below lightweight threshold, where excavator mobility is impeded

Skonieczny, K, "Lightweight Robotic Excavation," Carnegie Mellon University, PhD thesis CMU-RI-TR-13-09. 2013.

When is an excavator too light to dig productively?

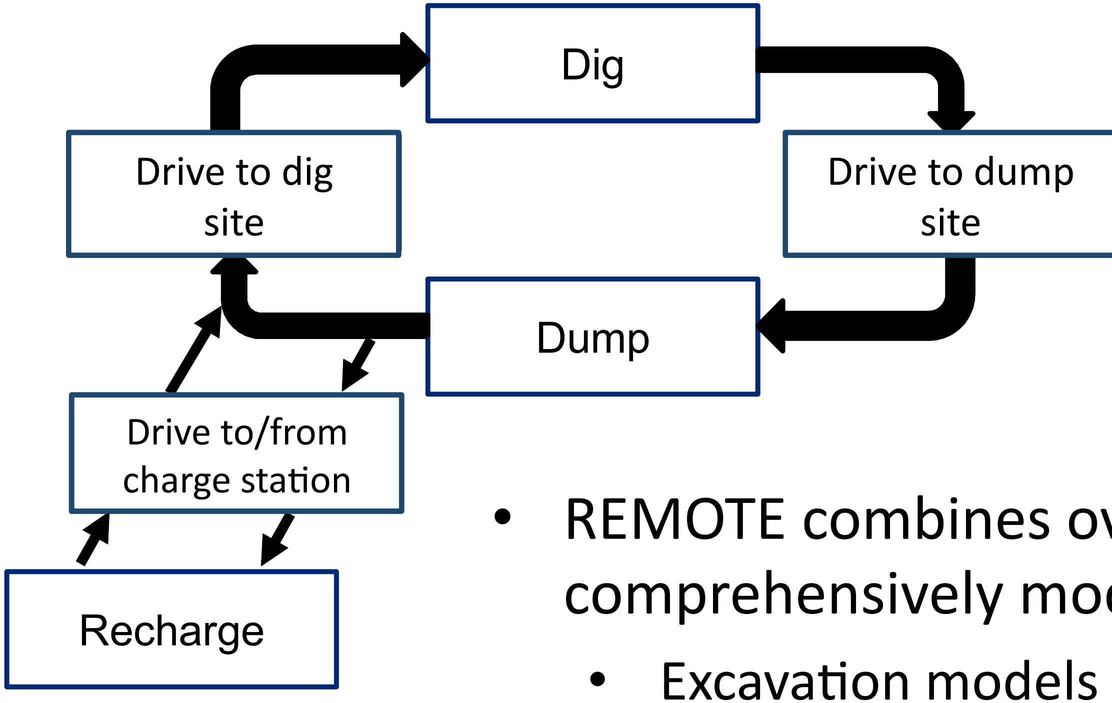
- Analytical modeling and experimental characterization distill into a single non-dimensional "lightweight number," L, that predicts excavator performance for a given g

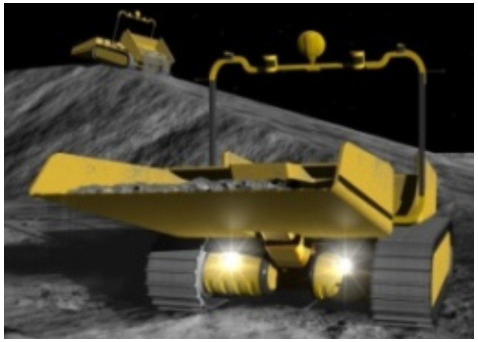
- Lightweight number analysis predicts continuous excavators perform better in low gravity than discrete excavators



REMOTE: Regolith Excavation, MObility & Tooling Environment

- REMOTE sensitivity analysis distinguishes those parameters that govern productivity and merit deeper investigation

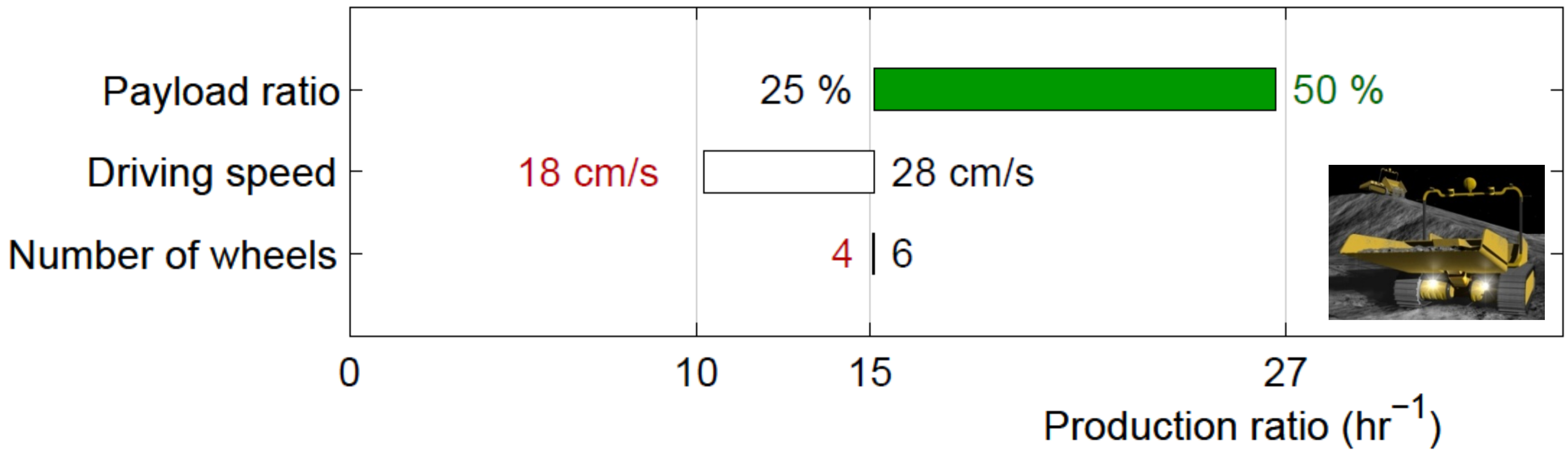




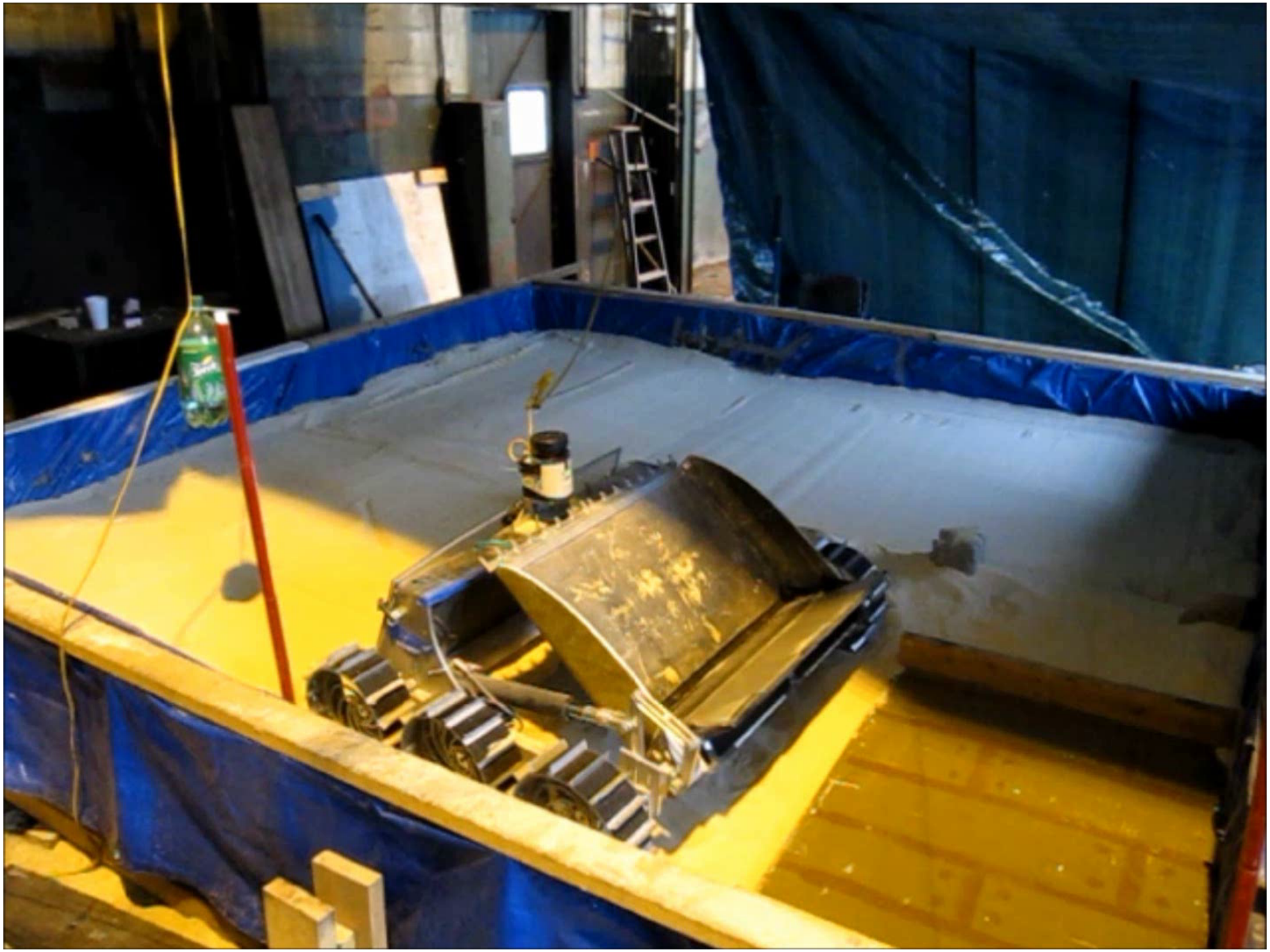
- REMOTE combines over 25 parameters to comprehensively model excavation tasks:
  - Excavation models [Luth-Wismer, Balovnev]
  - Traction model [Bekker-Wong]
  - Driving and power parameters

Modeled sensitivity analysis

- Payload ratio and driving speed govern productivity of small excavators

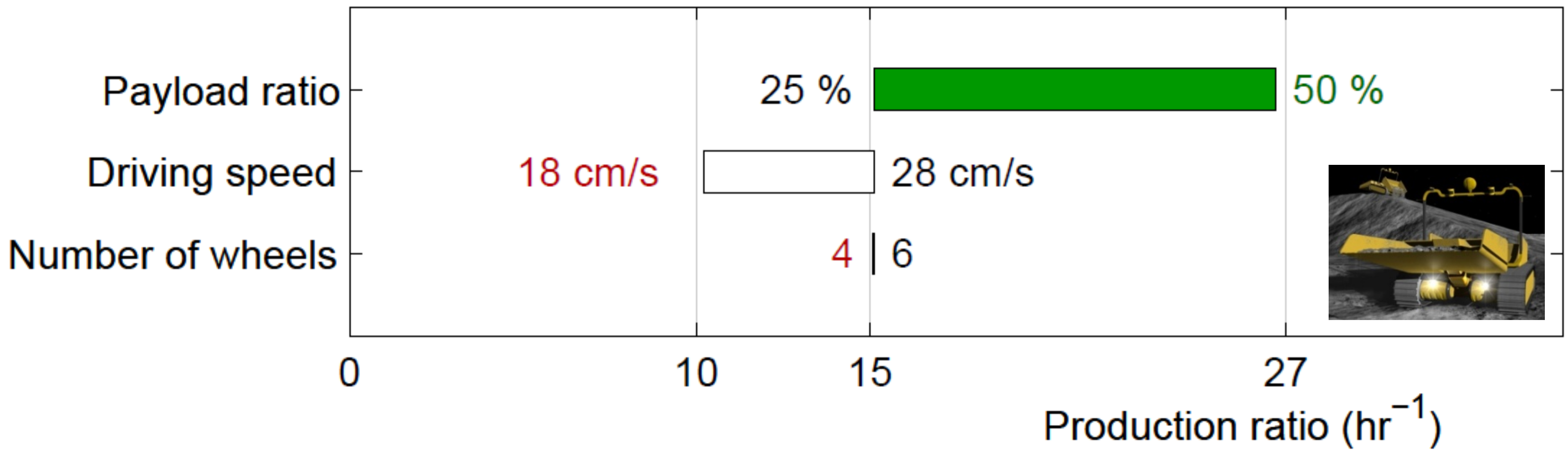


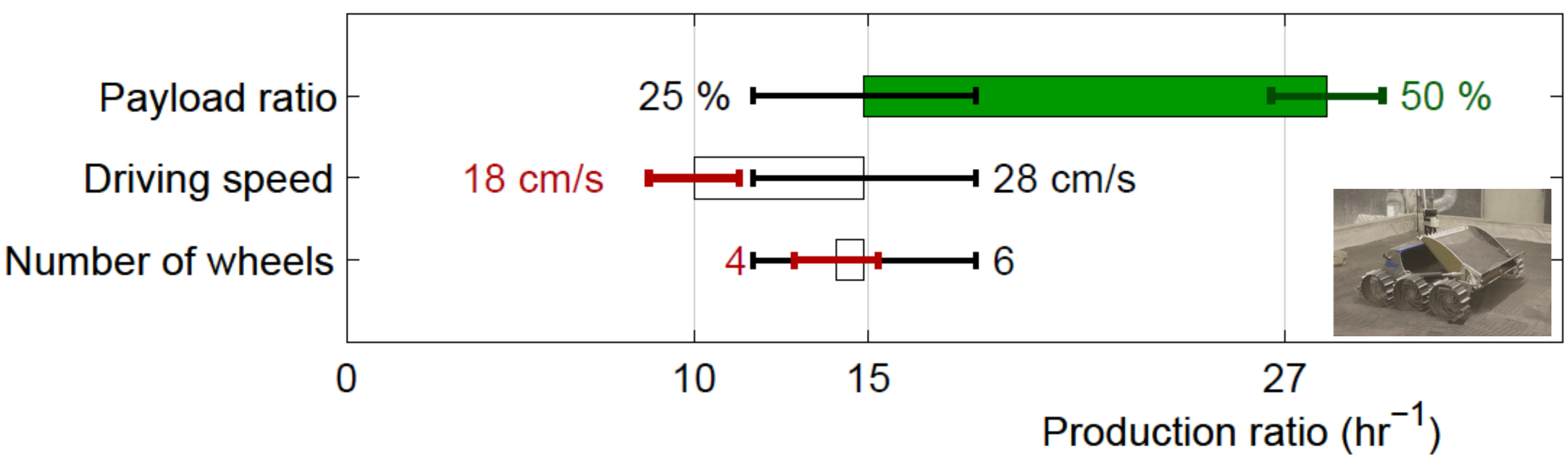
Experiments with a small scraper



Comparing experimental and modeled sensitivity

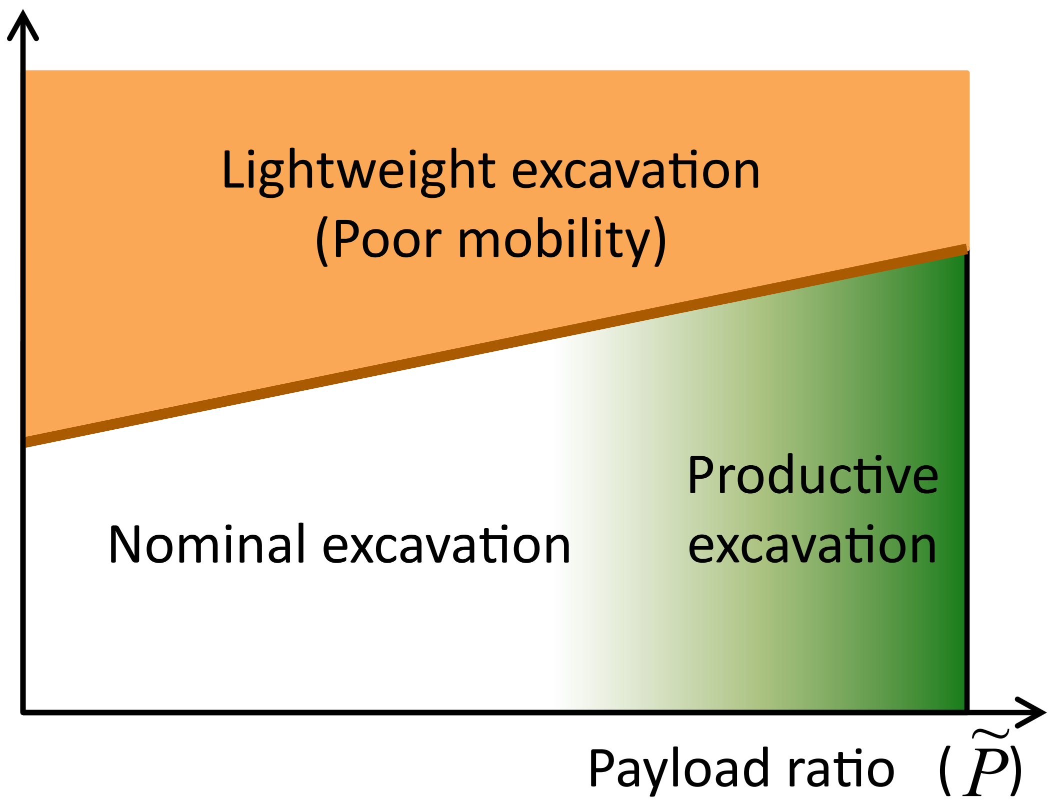
- Experiments confirm results predicted by model, but both model and experiments assume nominal mobility during digging





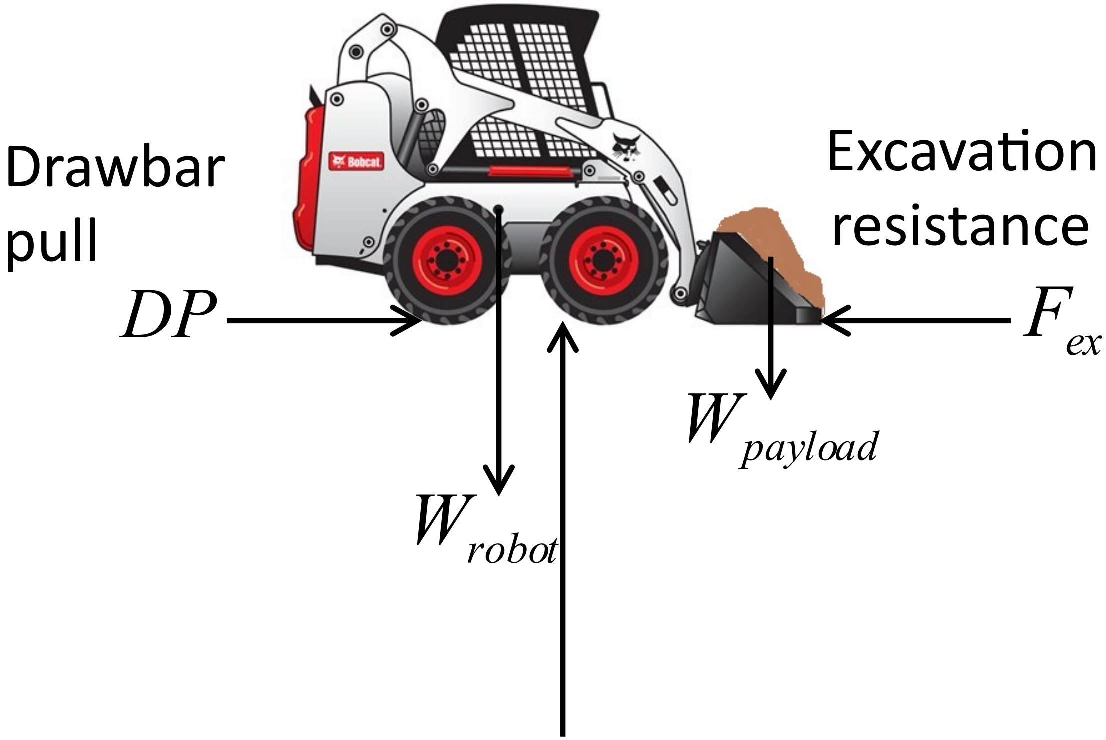
Payload ratio governs productivity for small excavators

- Payload ratio is a good predictor of productivity



- Can high payload ratio be achieved without crossing into the regime of lightweight excavation?

Forces acting on an excavating robot



$$W = W_{robot} + W_{payload}$$

- Operating too lightweight if:

$$F_{ex} > DP_{20}$$

Payload ratio:

$$\tilde{P} = \frac{W_{payload}}{W_{robot}}$$

Excavation resistance coeff.:

$$\tilde{F} = \frac{F_{ex}}{W_{robot}}$$

Traction coefficient:

$$\tilde{T} = \frac{DP_{20}}{W}$$

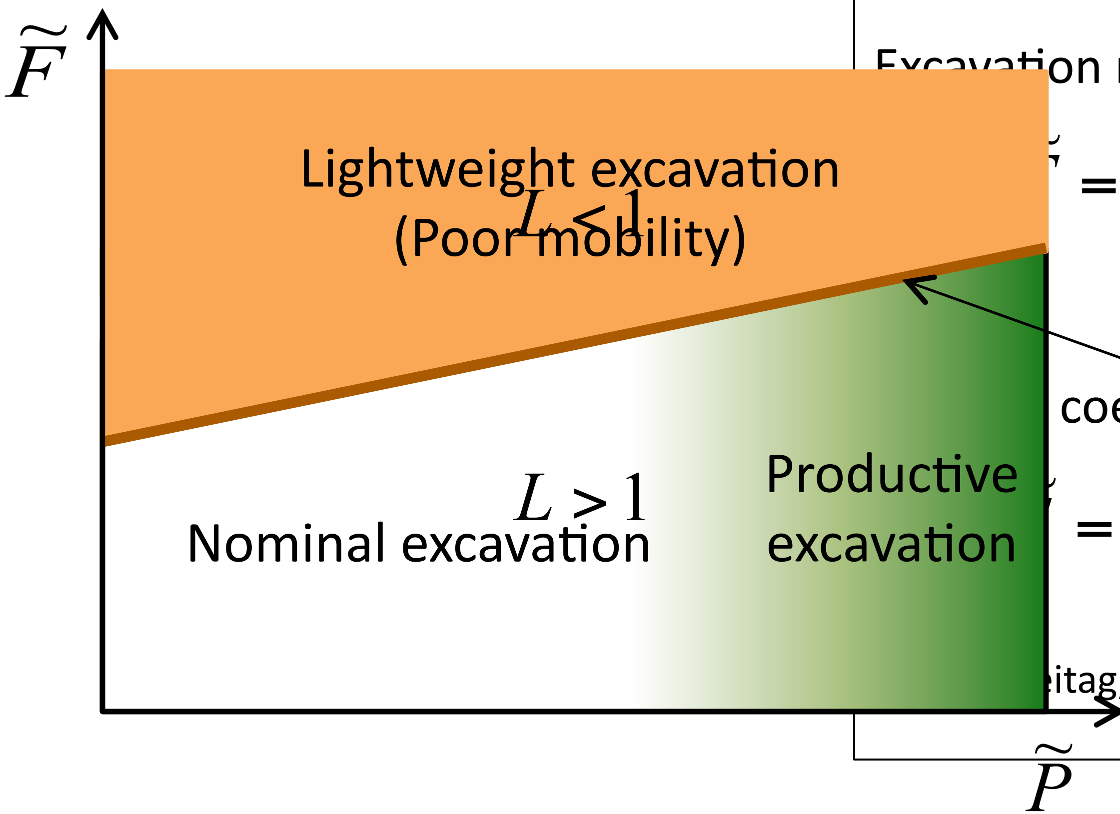
[Freitag, 1970; Wong, 2012]

The lightweight threshold

- Operating too lightweight if:

$$F_{ex} > DP_{20}$$

$$\tilde{F} > \tilde{T}\left(1 + \tilde{P}\right)$$



$$L \equiv \frac{\tilde{T}\left(1 + \tilde{P}\right)}{\tilde{F}}$$

Payload ratio:

$$\tilde{P} = \frac{W_{payload}}{W_{robot}}$$

Excavation resistance coeff.:

$$\tilde{F} = \frac{F_{ex}}{W_{robot}}$$

coefficient:

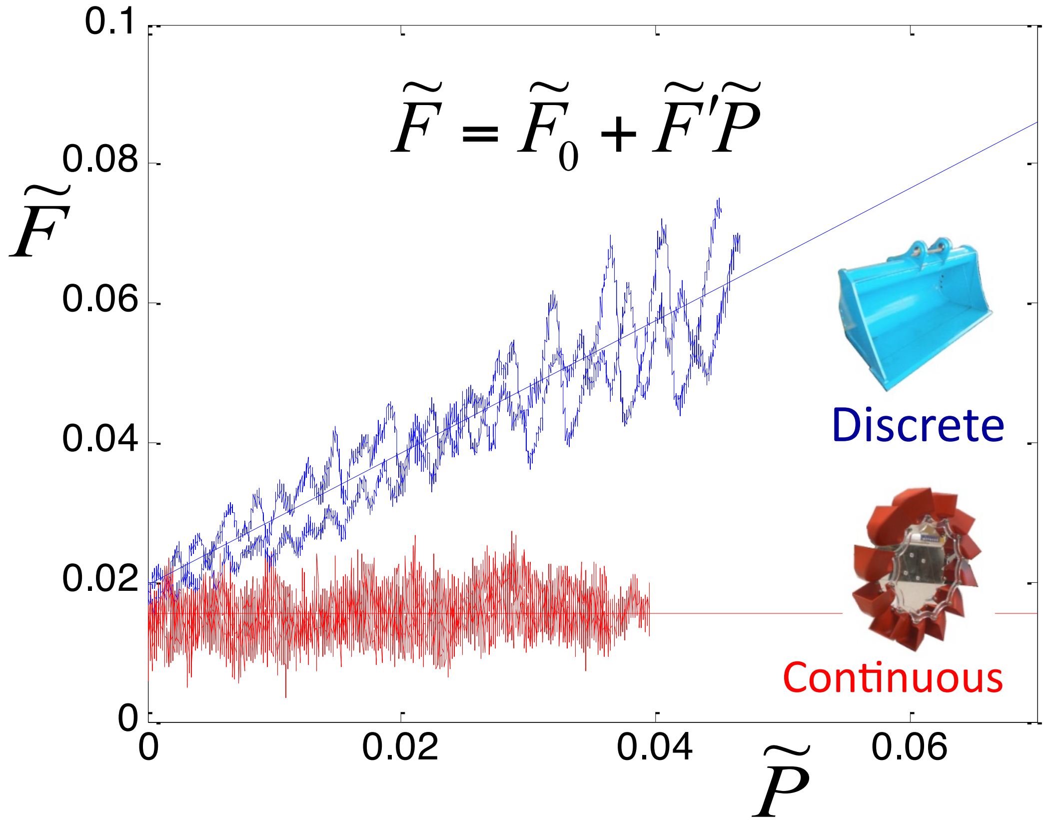
$$\tilde{T} = \frac{DP_{20}}{W}$$

…itag, 1970; Wong, 2012]

Continuous and discrete lightweight numbers

- $\widetilde{F}(\widetilde{P})$ can be approximated linearly:

$$L = \frac{\widetilde{T}\left(1+\widetilde{P}\right)}{\widetilde{F}_0 + \widetilde{F}'\widetilde{P}}$$

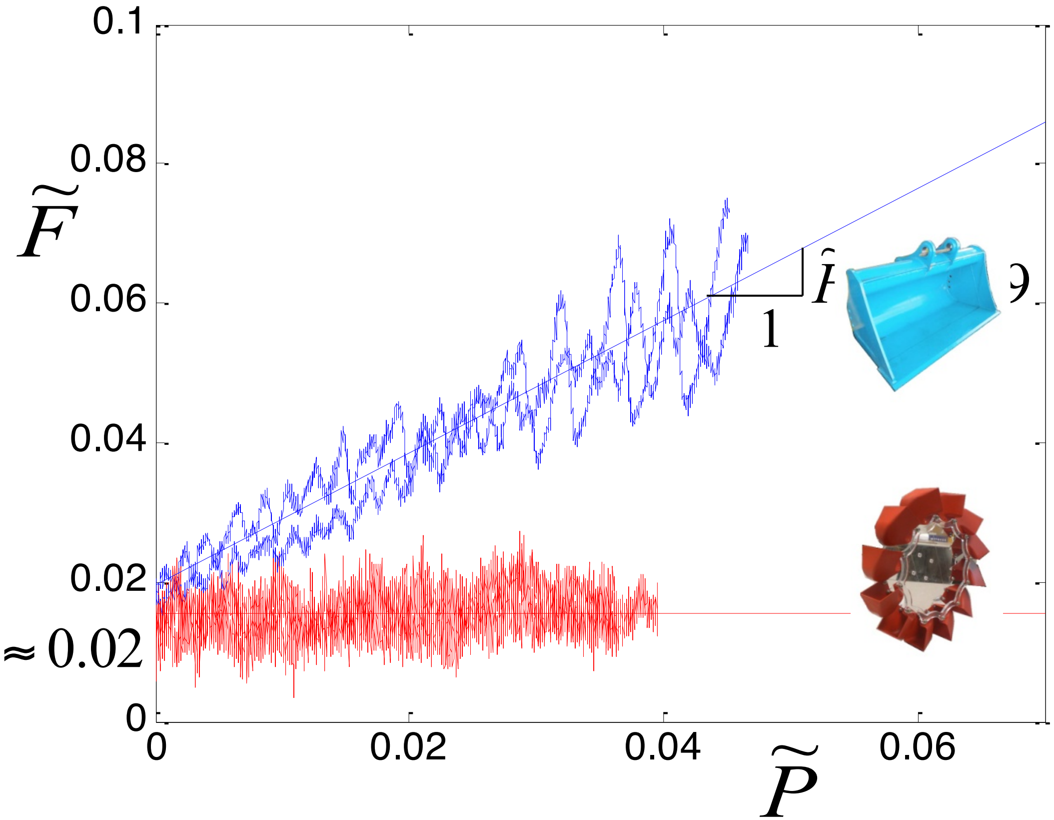


$$\lim_{\widetilde{P}\to\infty}\left(L_{disc}\right) = \frac{\widetilde{T}}{\widetilde{F}'_{disc}}$$

$$\min\left(L_{cont}\right) = \frac{\widetilde{T}}{\widetilde{F}_{0,cont}}$$

Continuous and discrete lightweight numbers

$$\widetilde{F}'_{disc} >> \widetilde{F}_{0,cont} \longrightarrow \min(L_{disc}) < \min(L_{cont})$$



$$\widetilde{F}_{0,cont} \approx 0.02$$

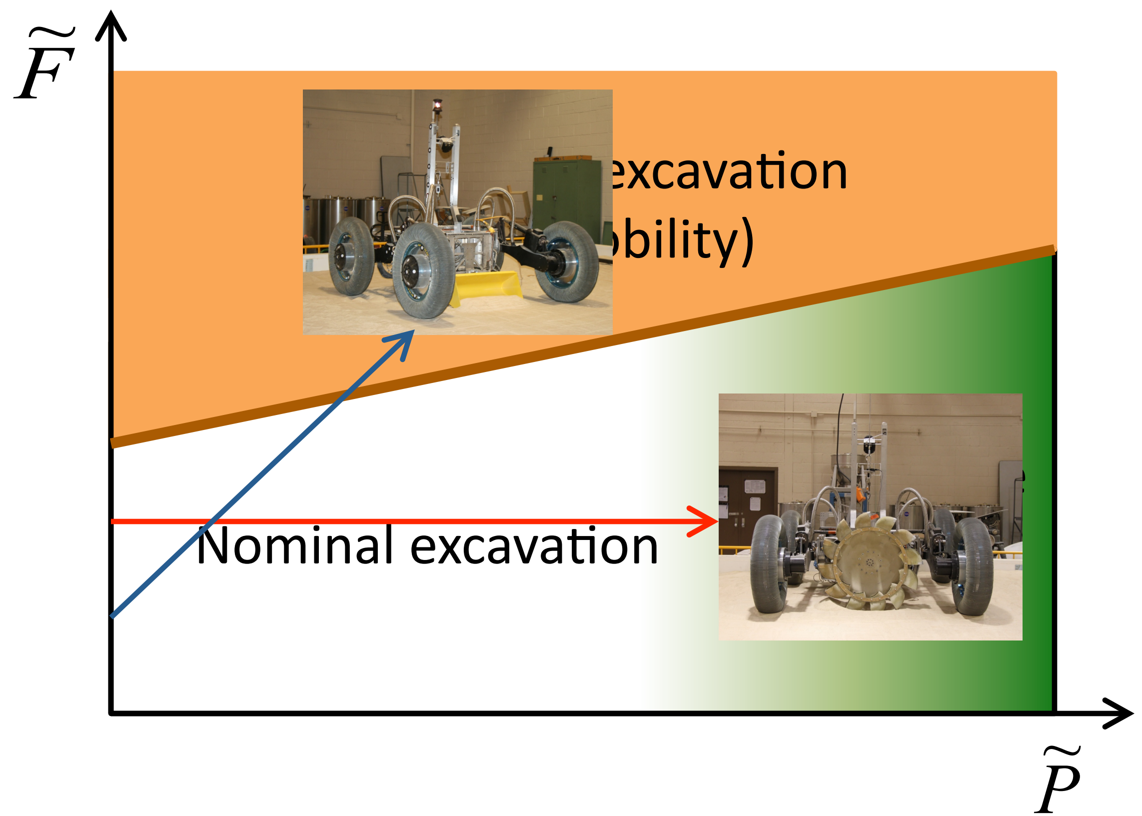
$$\min(L_{disc}) = \frac{\widetilde{T}}{\widetilde{F}'_{disc}}$$

$$\min(L_{cont}) = \frac{\widetilde{T}}{\widetilde{F}_{0,cont}}$$

At equivalent production, continuous excavation is less likely to impede mobility

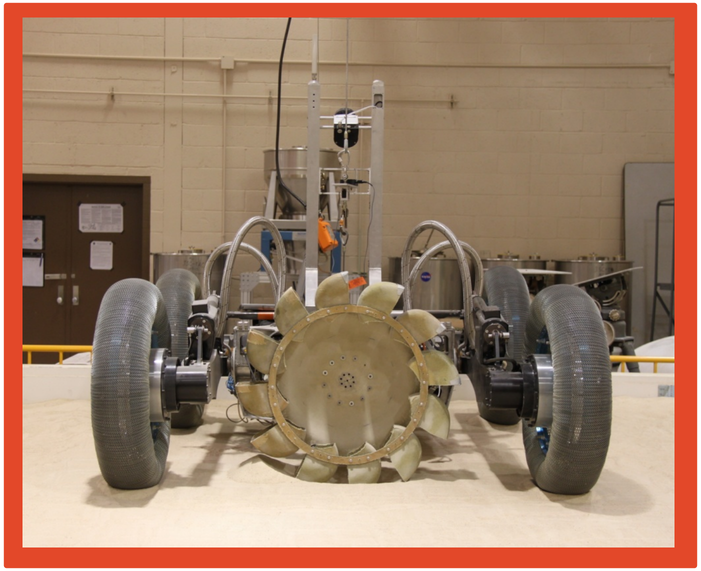
Continuous excavation outperforms discrete

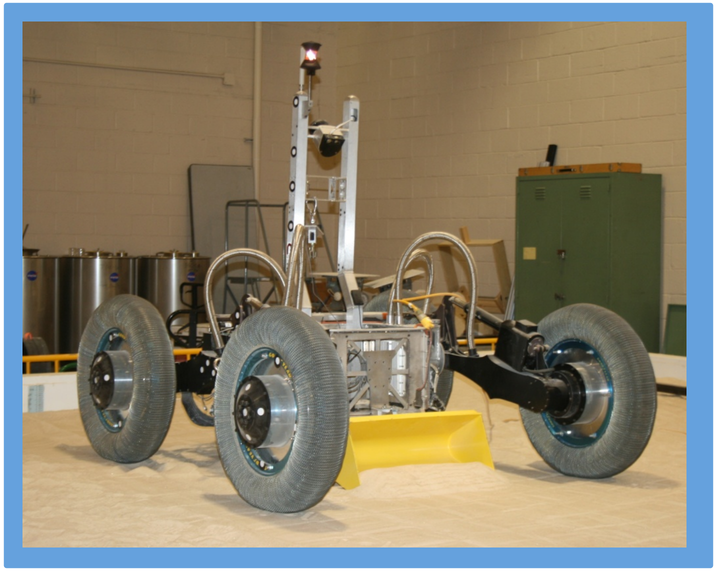
- At equivalent productivity, discrete excavator is more likely to cross into the lightweight excavation regime



Predicting lightweight numbers

- Excavation performance and mobility can be predicted for Scarab with bucket-wheel and front-loader bucket

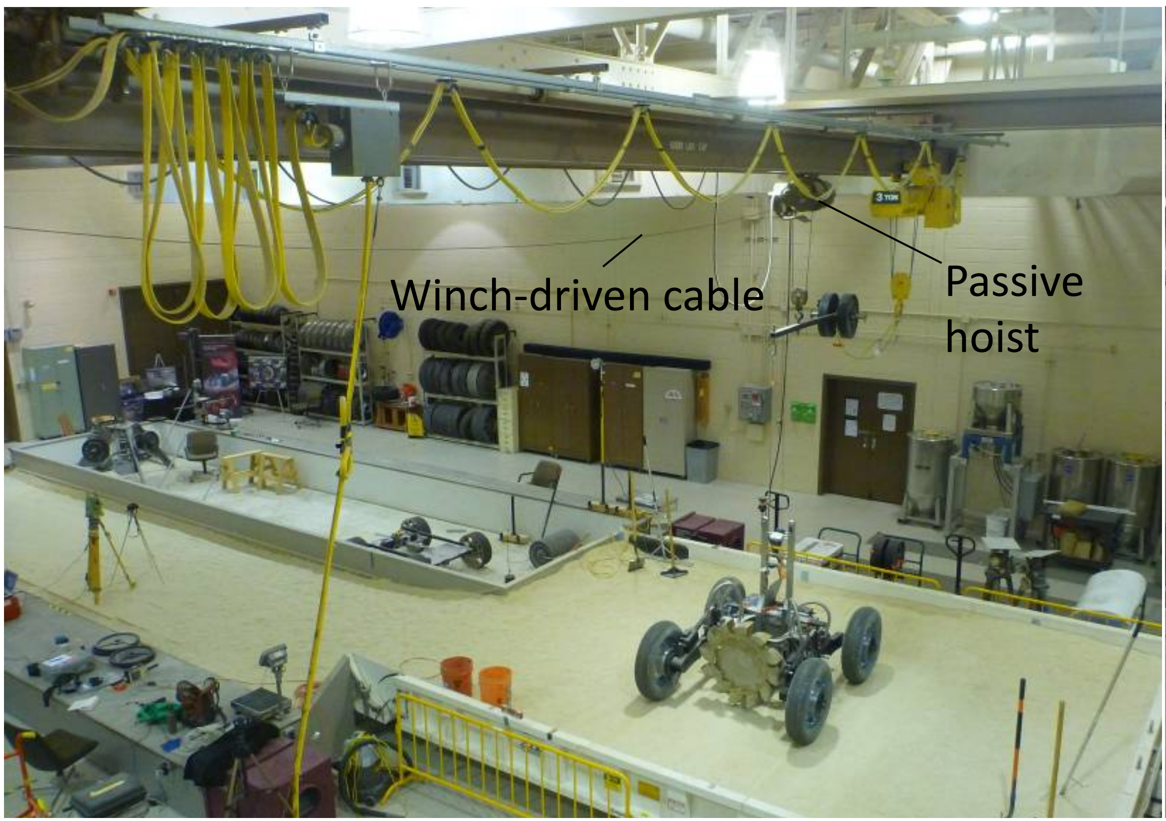


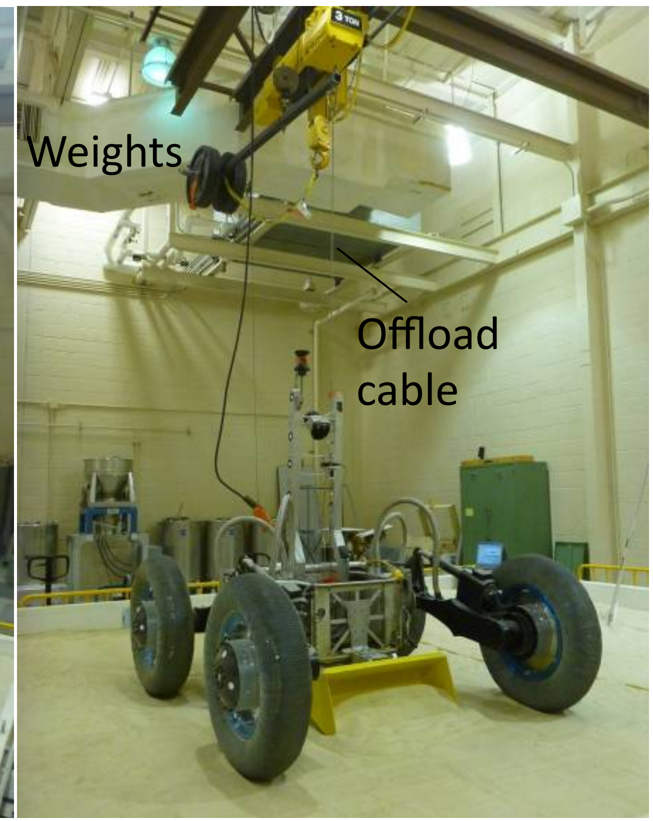


Wheel and tool characterization experiments	→	$\widetilde{T}, \widetilde{F}_{0,cont}, \widetilde{F}'_{disc}$	→	L

Gravity offloaded excavation experiments

- Reduced gravity has detrimental effects on both excavation resistance [Boles, 1997] and traction [Kobayashi, 2010]
- Reduced/offloaded gravity lowers L
- First laboratory experiments to test excavation with 5/6 of robot weight offloaded

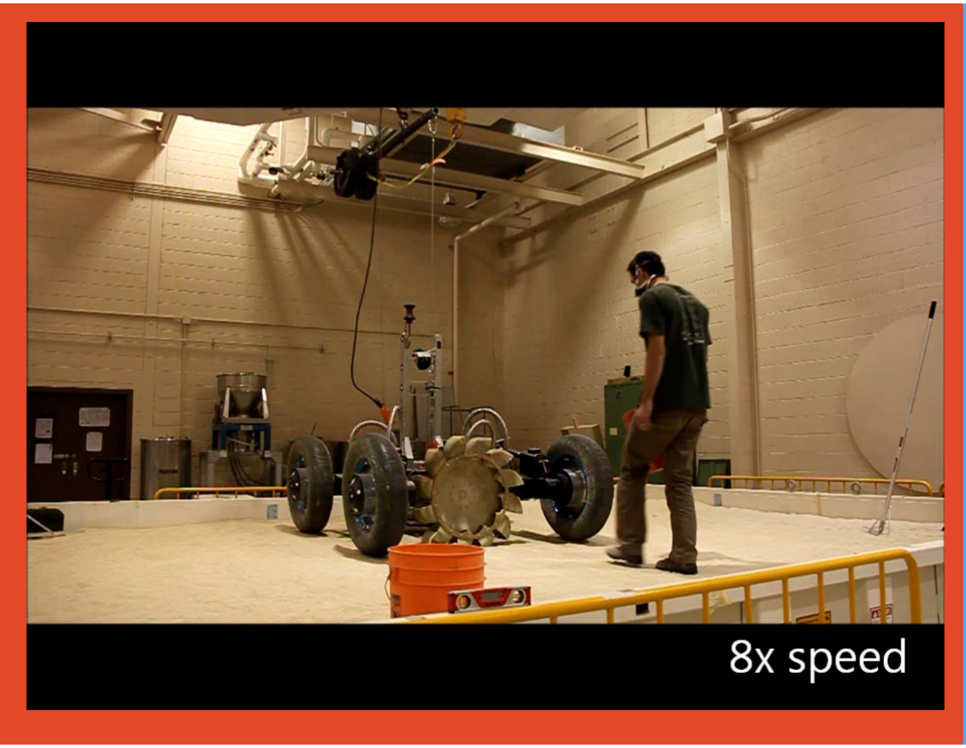




Gravity offloaded excavation experiments

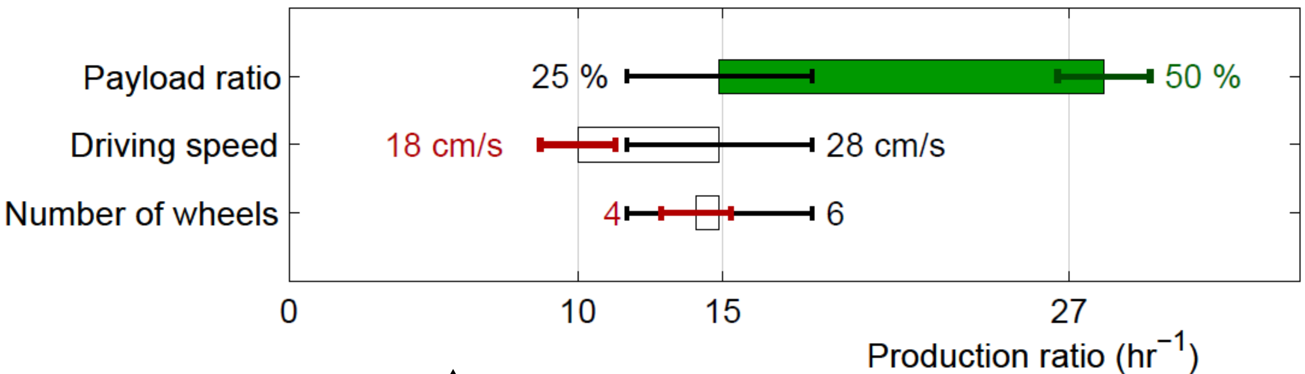
- Continuous excavation unhindered in gravity offload

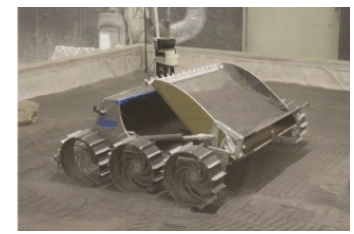
- Discrete excavation stalls robot with minimal payload collected

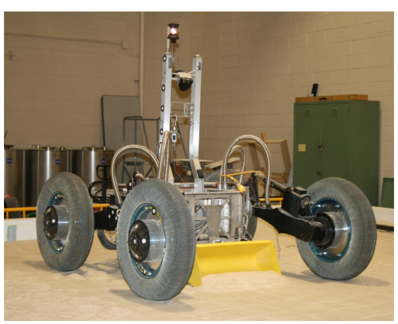


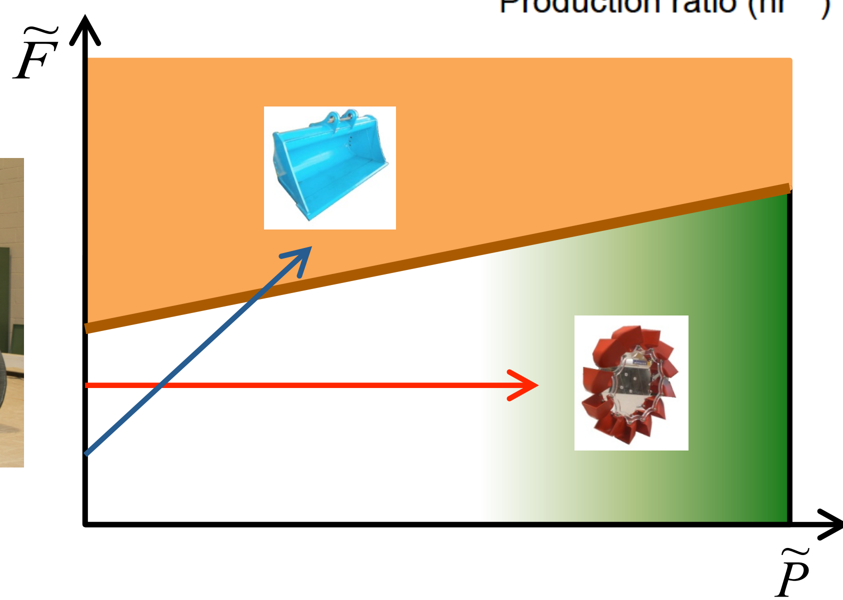
Planetary excavator design principles

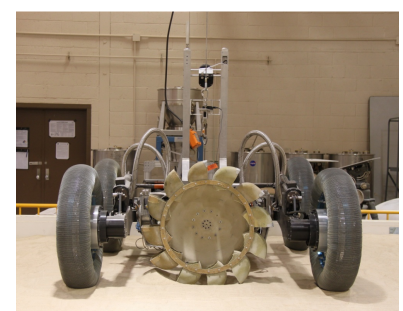
1. High payload ratio ($\widetilde{P}$)
2. High driving speed (v_d)
3. Continuous excavation



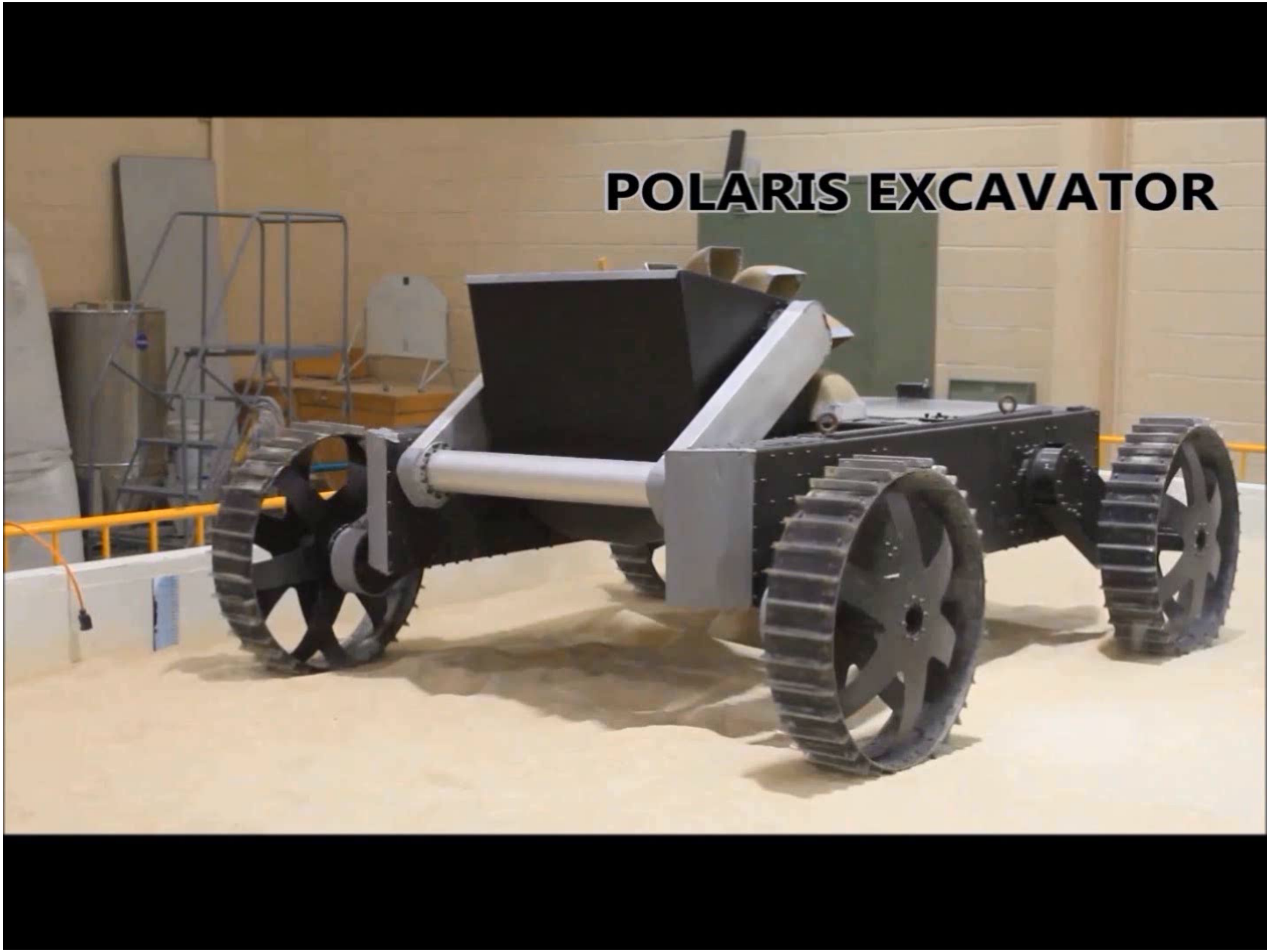




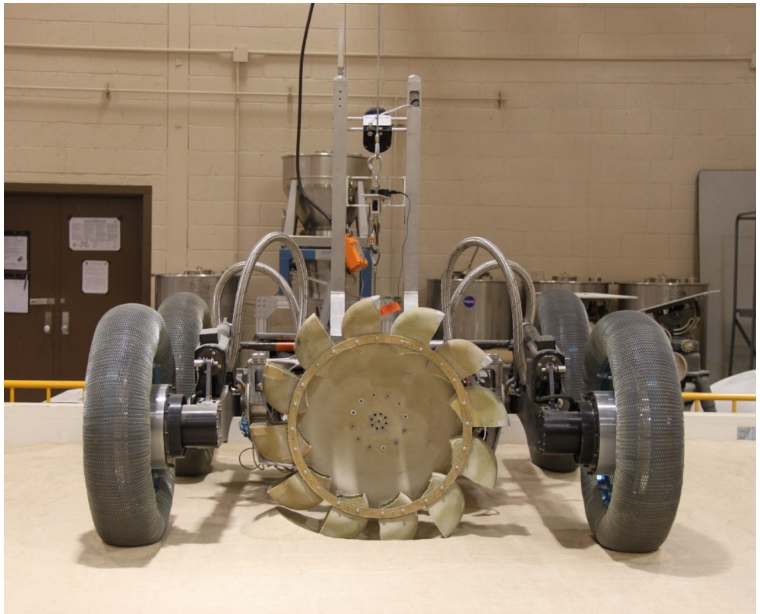


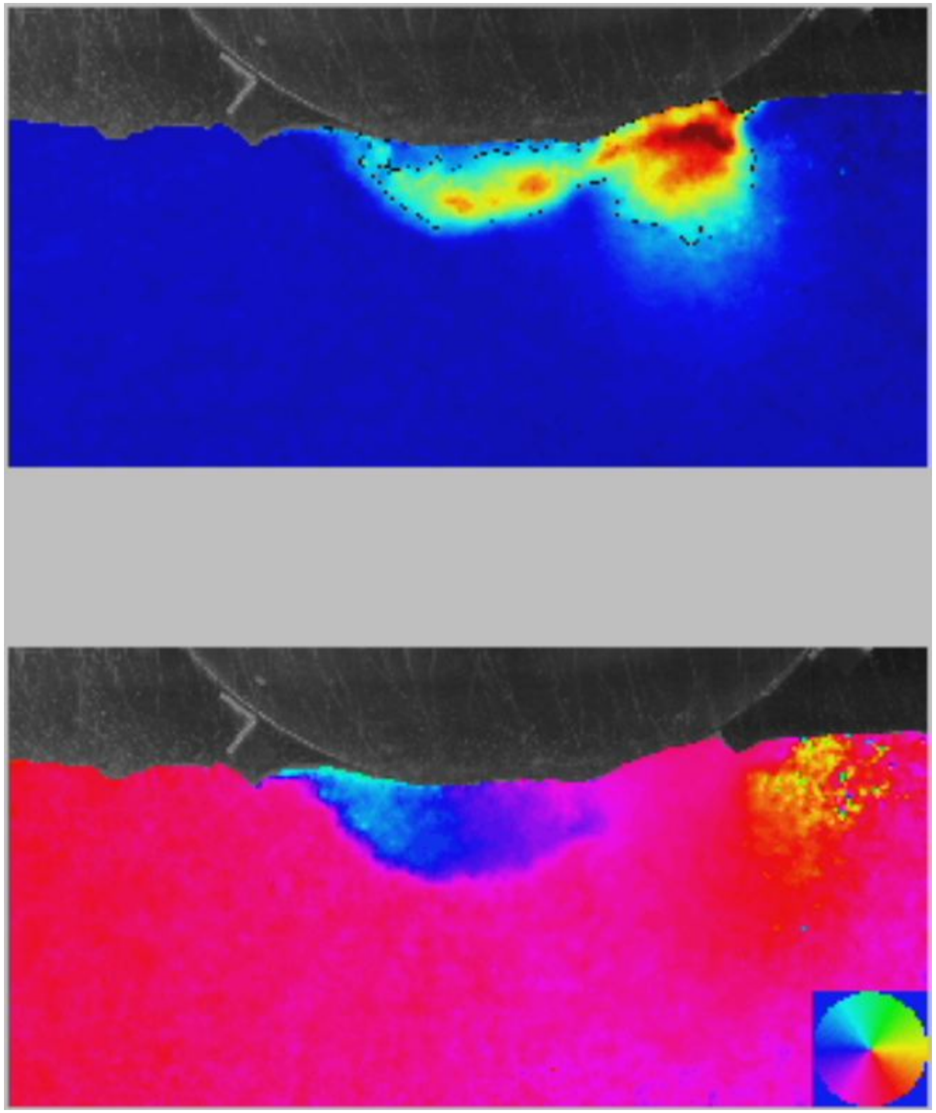


Polaris: A productive planetary excavator



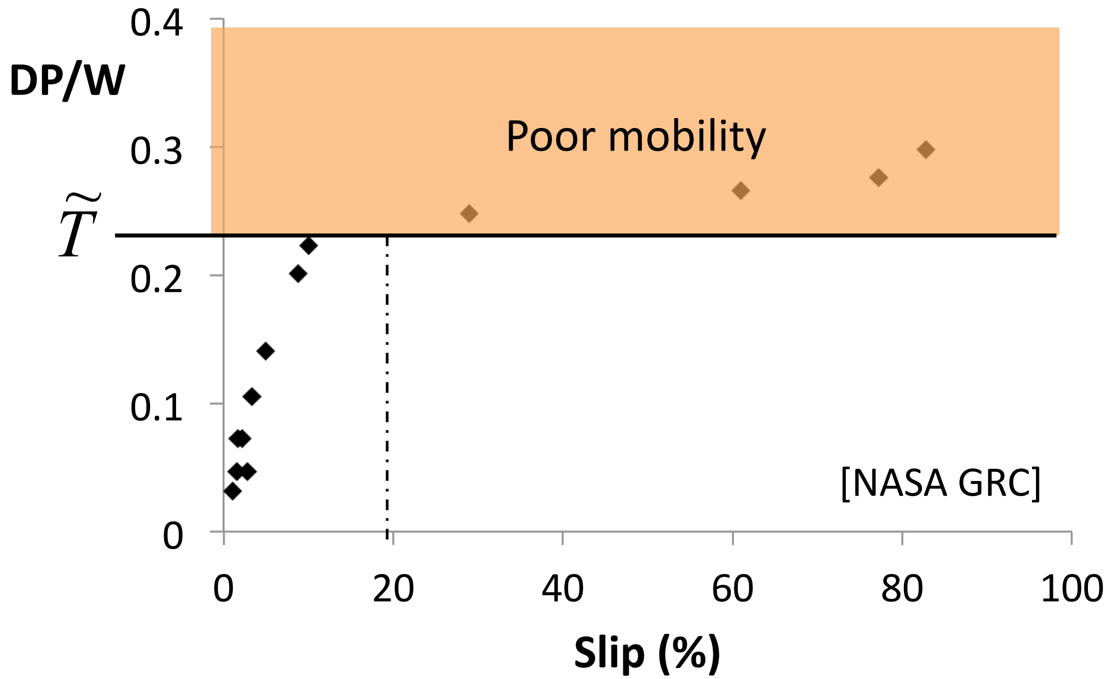
Thank you. Questions?





Excavation thrust from traction (drawbar pull)

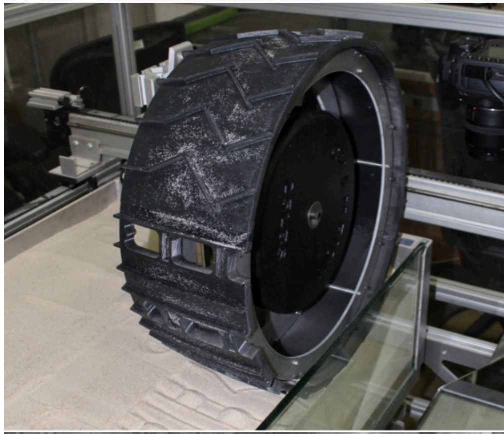
- Drawbar pull imposed by excavation must not impede mobility (poor mobility defined as exceeding 20% slip)

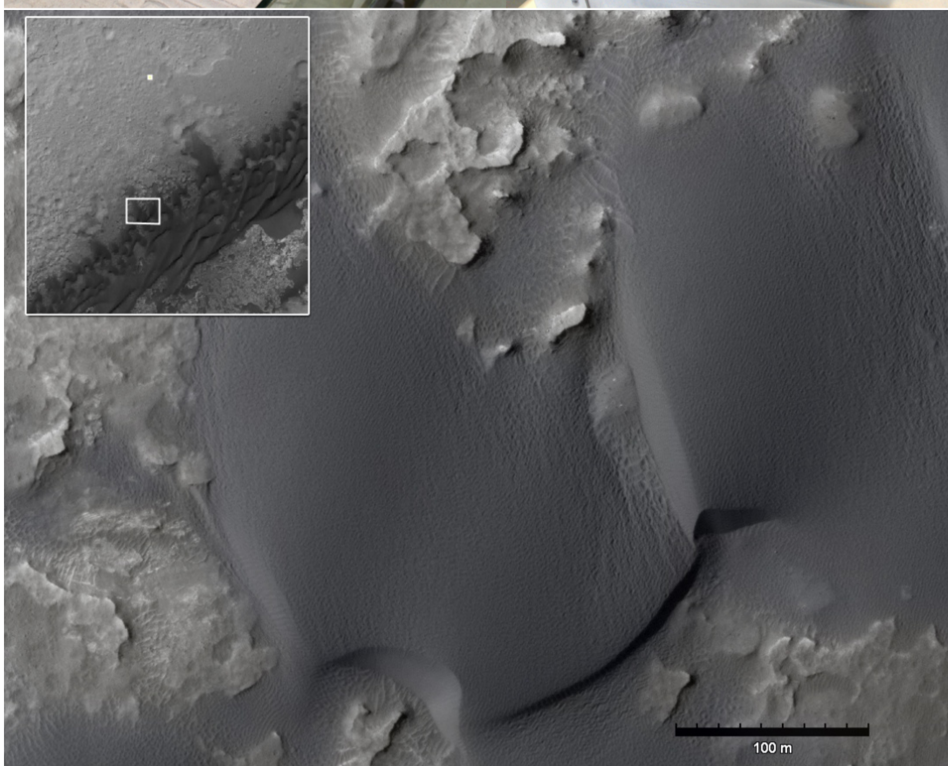


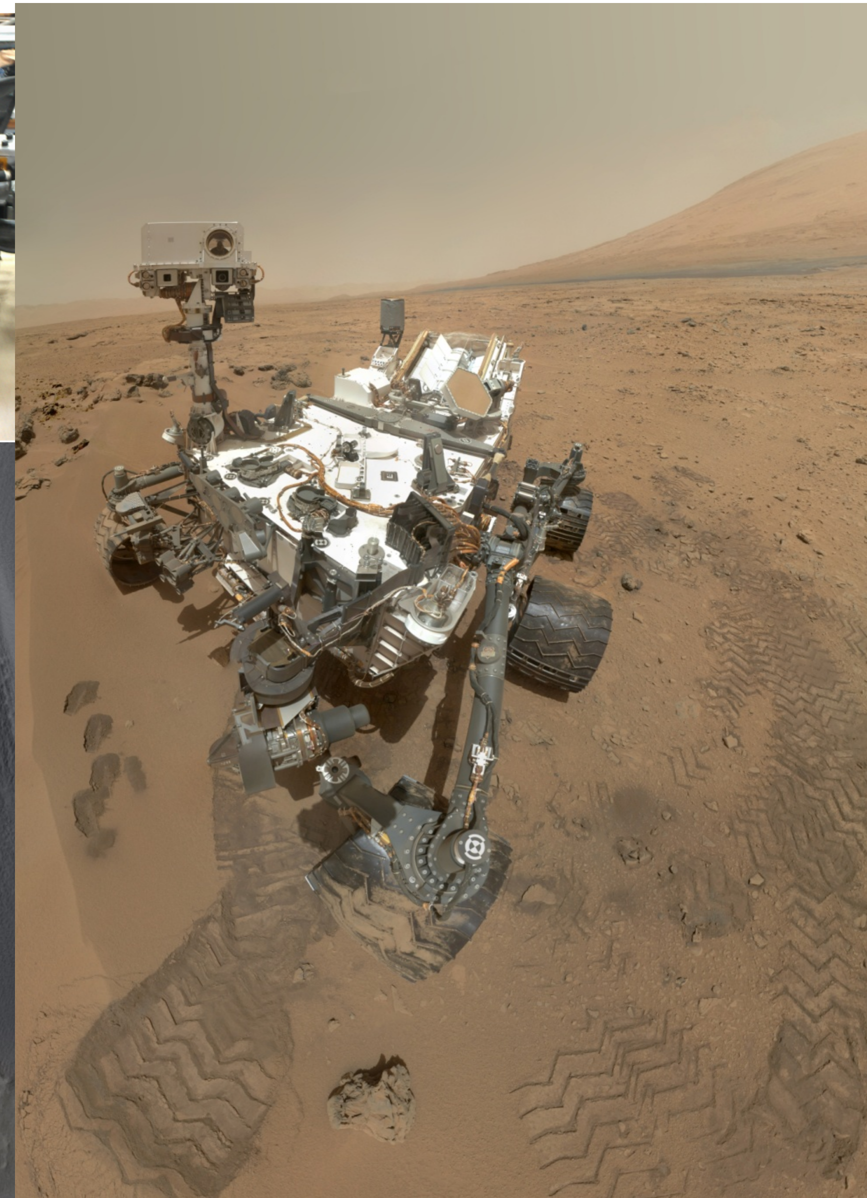
- $\widetilde{T} = {}^{P_{20}}\!/_{W}$ is a popular metric for characterizing mobility

[Freitag, 70; Wong, 12]

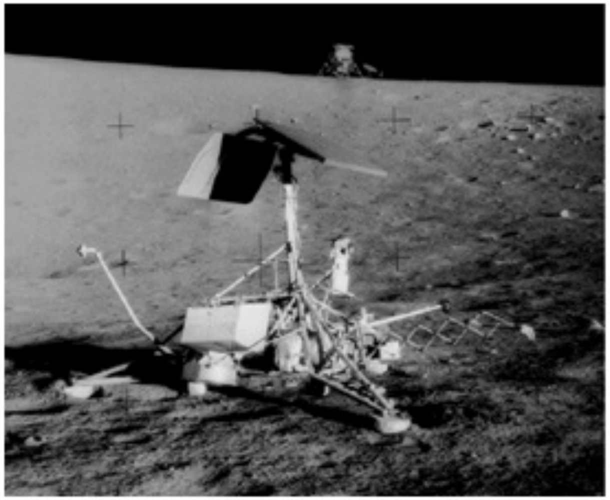
Granular soil research used to inform MSL mission



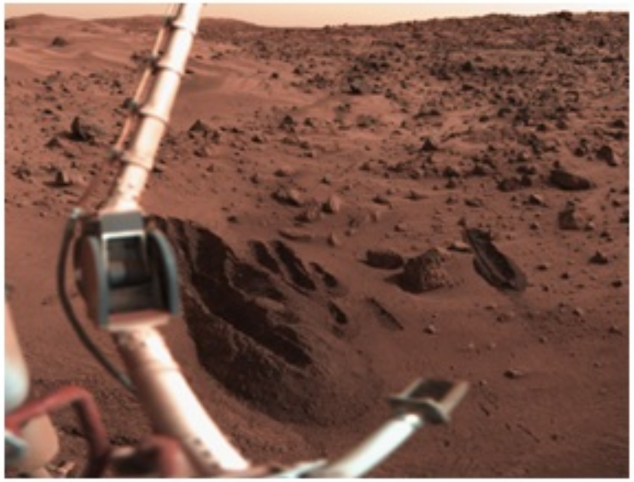




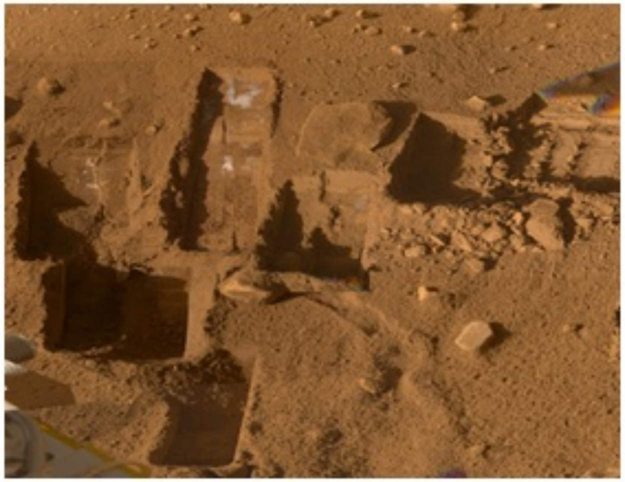
Planetary excavation



Surveyor



Viking



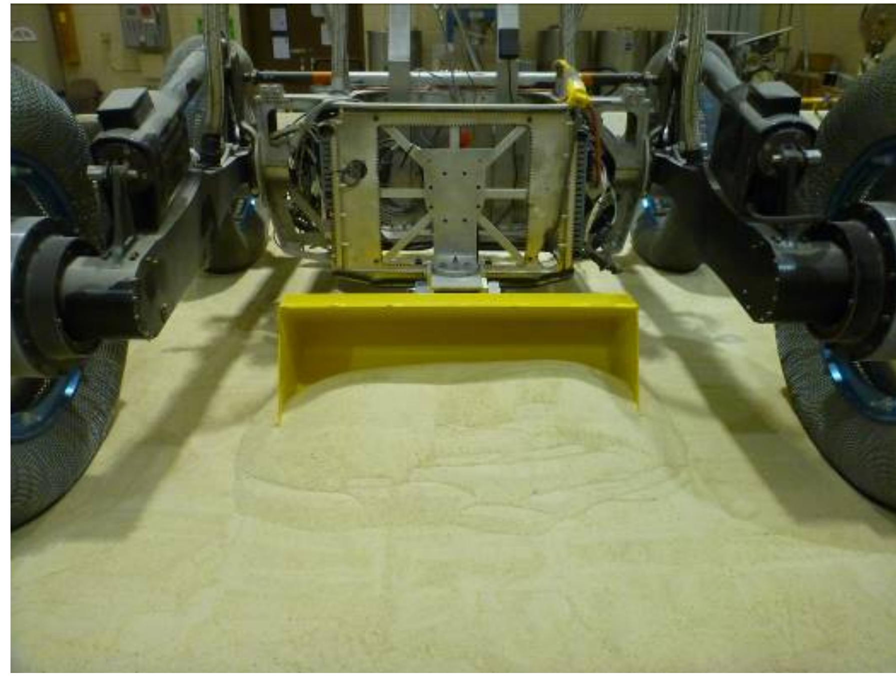
Phoenix

Offloaded discrete excavation collects little payload

Excavation in Earth gravity

45-50 kg collected

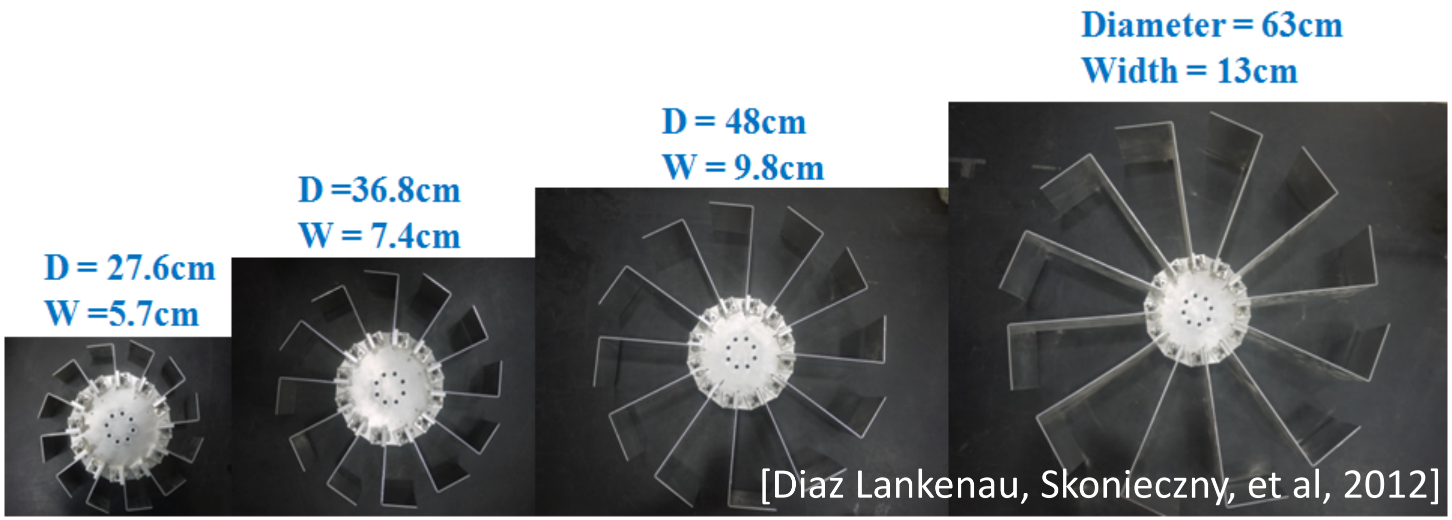
Excavation with gravity offload



15-20 kg collected

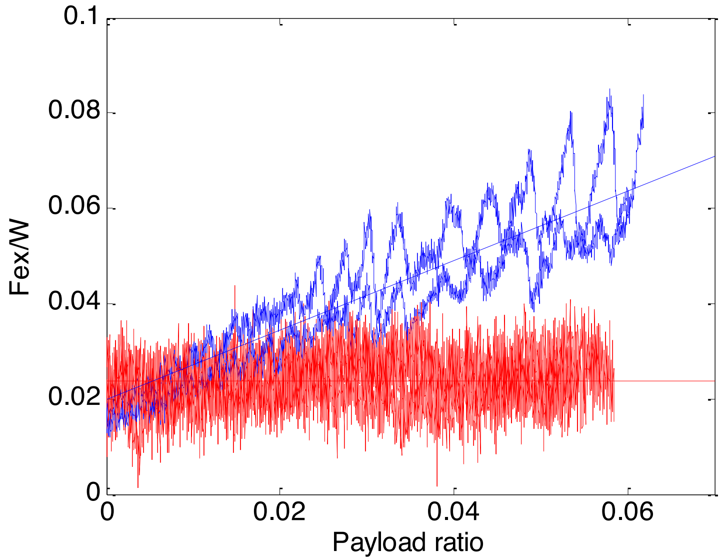
Bucket-wheel and flat-plate excavation scaling

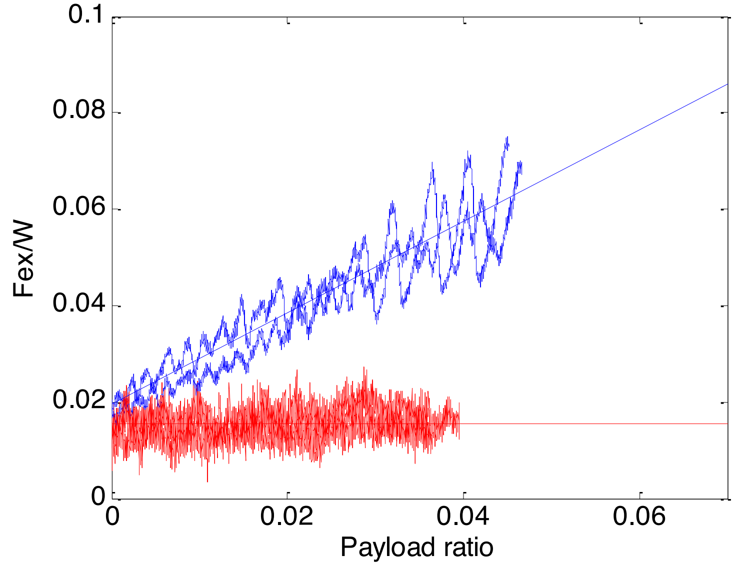
- Bucket-wheels and flat-plates (angled 10º down from horizontal) were compared at 4 scales



Flat plate widths: W=11.4cm W=14.8cm W=19.6cm W=26cm

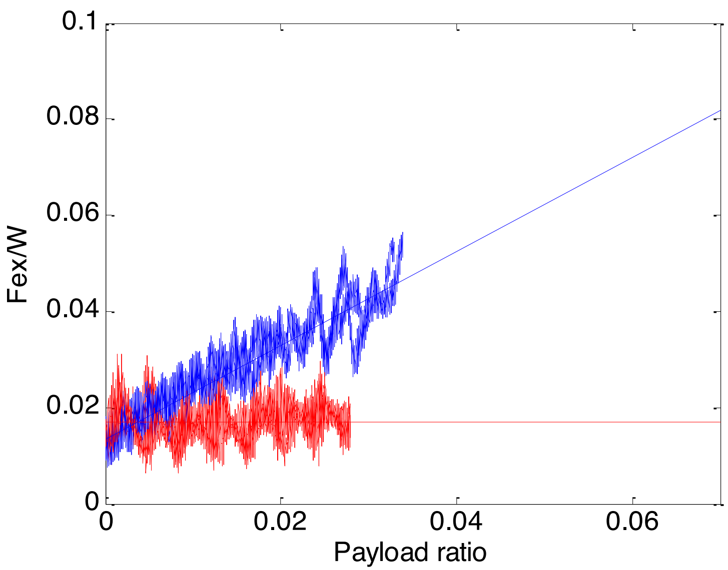
Excavation forces compare similarly as size scales

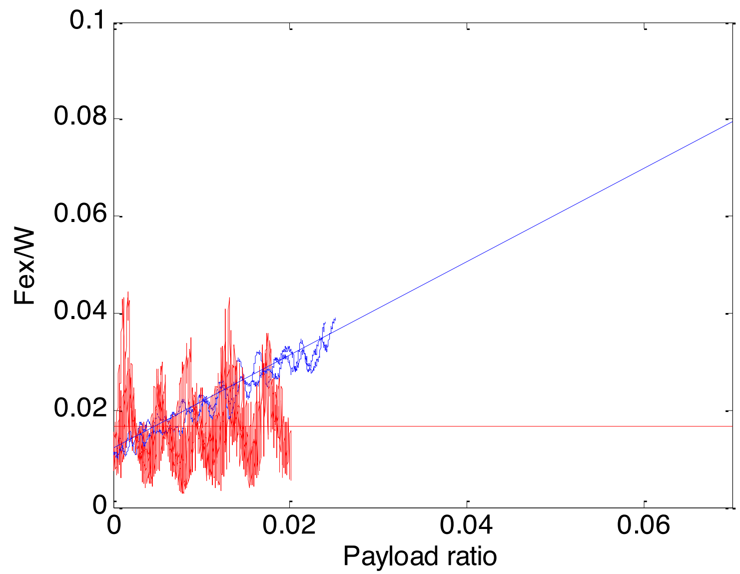




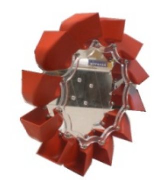
Discrete

Continuous





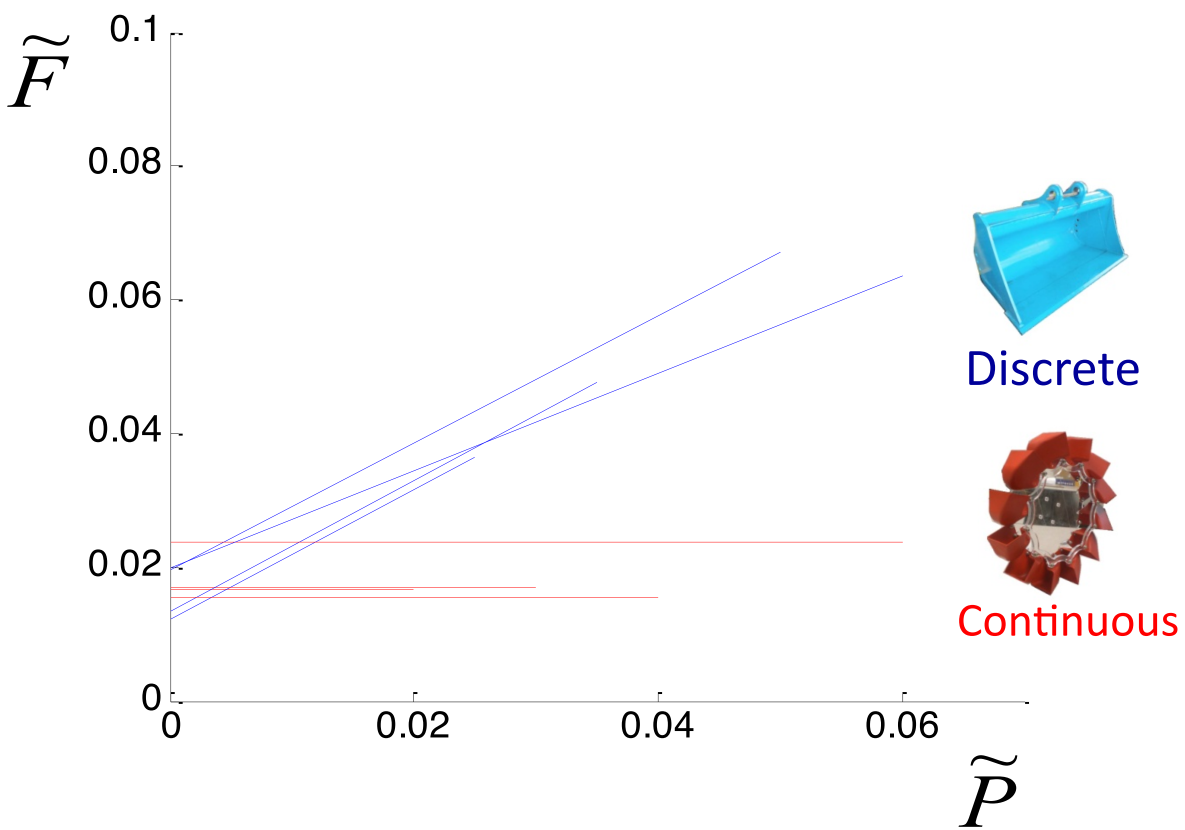
Discrete

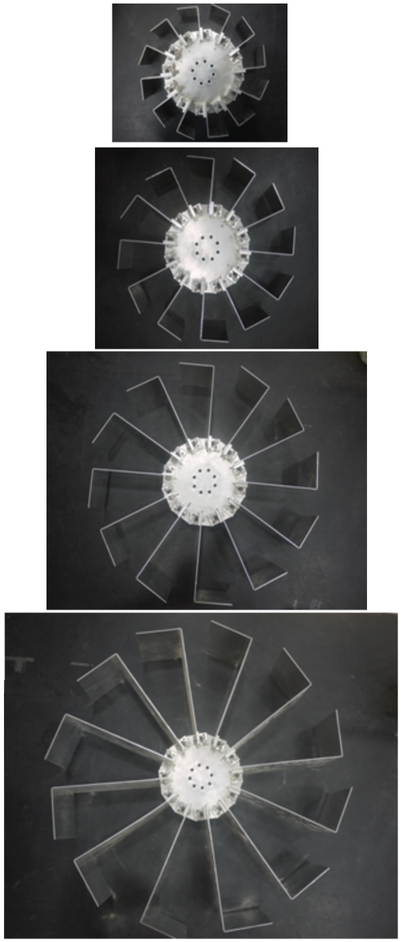


Continuous

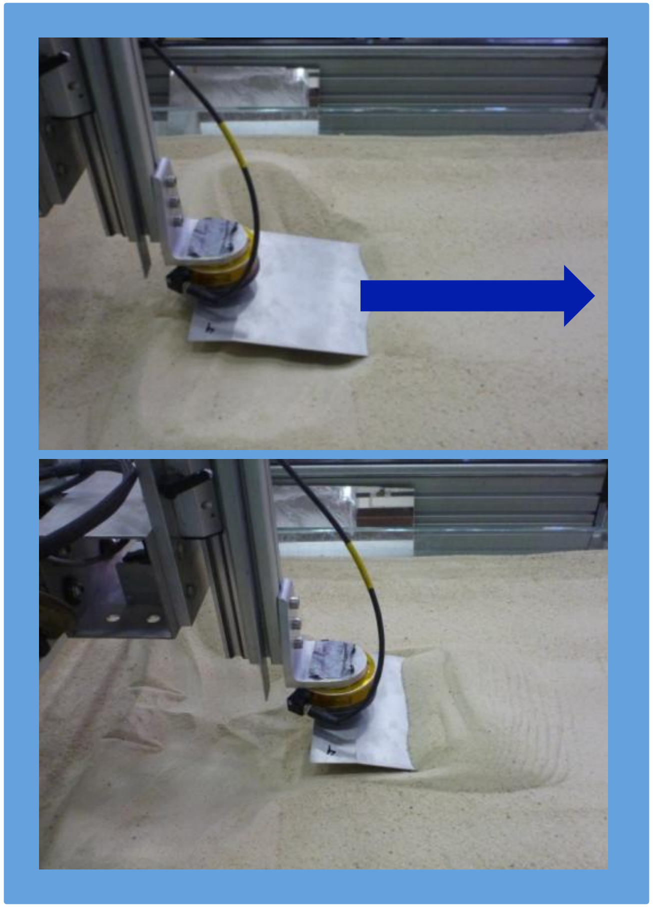
Excavation resistance responses consistent across scales

- Excavation resistance increases with increasing payload for discrete excavation, but is bounded for continuous excavation
- Normalized response to payload accumulation is not significantly sensitive to scale





Bucket-wheel and flat-plate excavation experiments

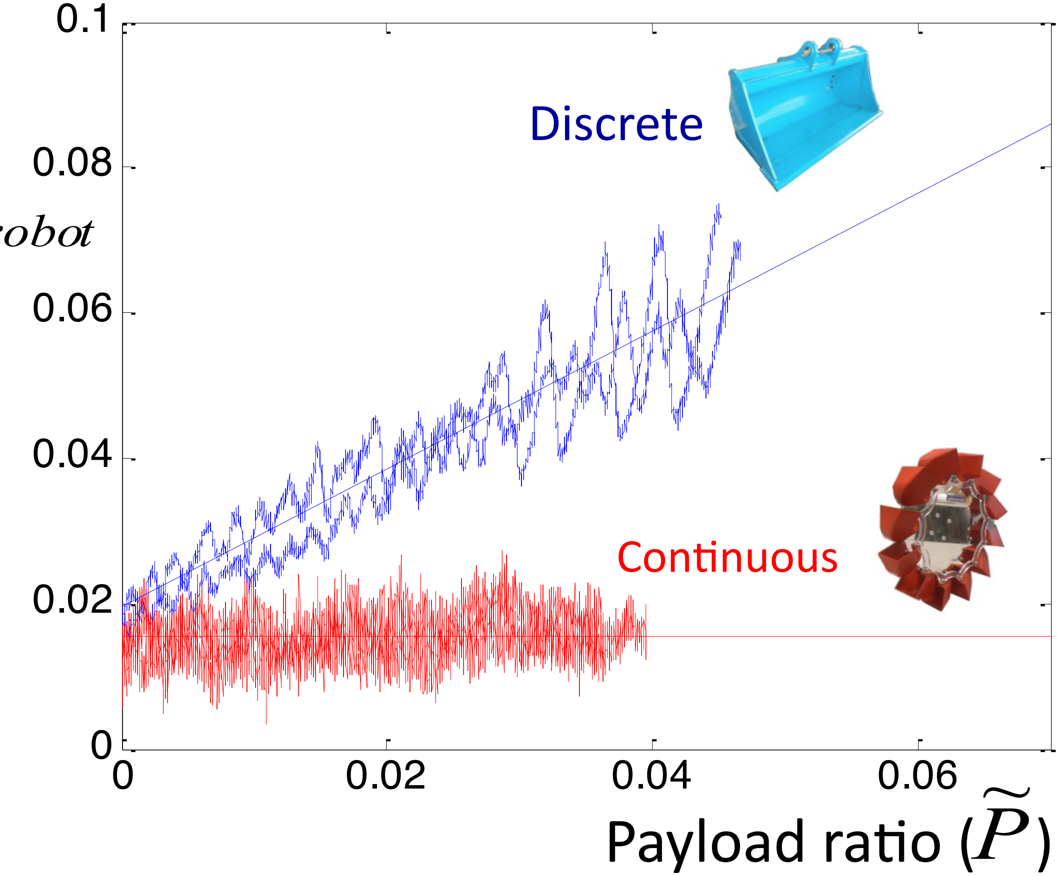


- Experiments compare continuous and discrete excavation resistance at equal production rate

Bounded vs. unbounded response to payload collection

- Excavation resistance coefficient, $\widetilde{F}$, increases with increasing payload for discrete excavation, but is bounded for continuous excavation

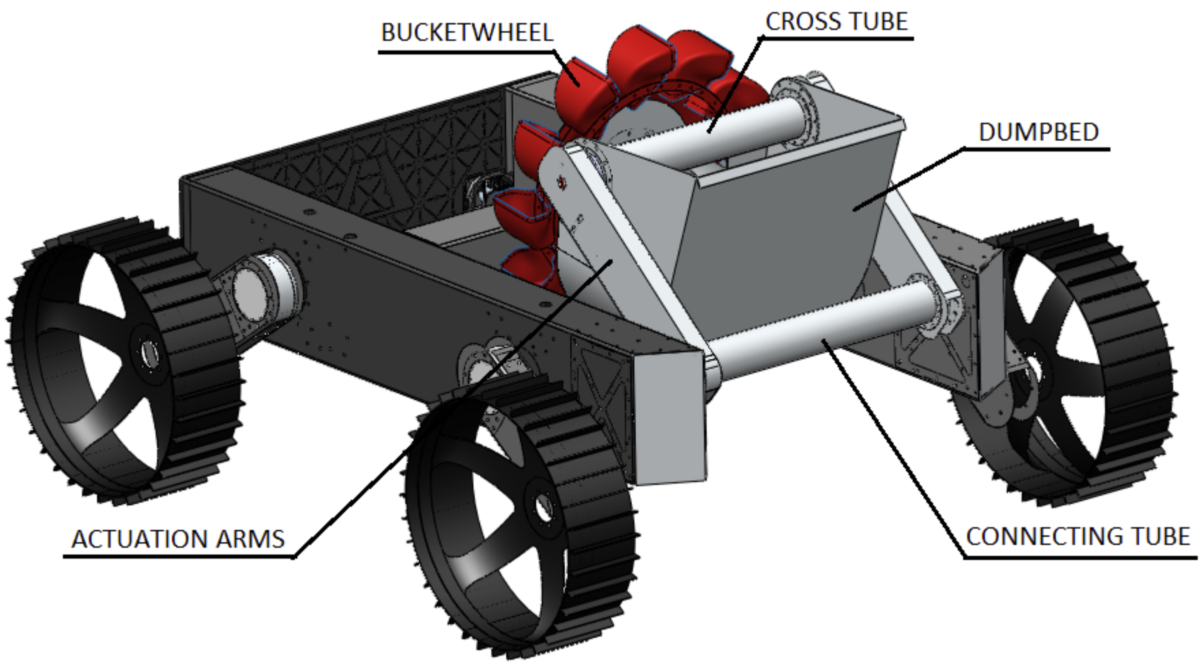
$$\widetilde{F} = F_{ex} / W_{robot}$$

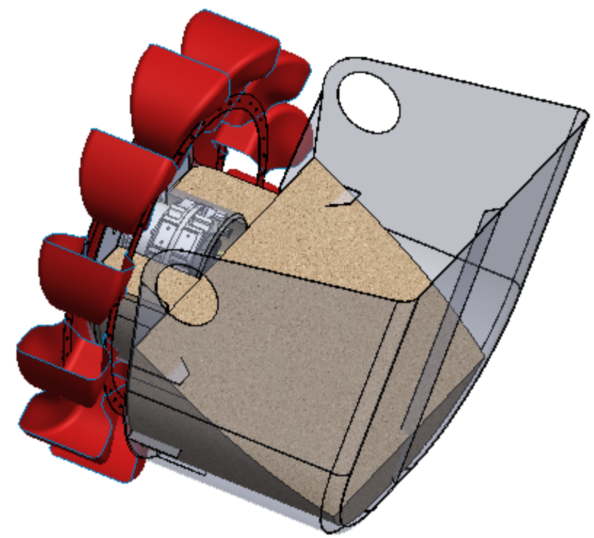


Similar trends for discrete excavation observed by Agui (2010), Gallo (2010)

Novel excavator design

- High payload ratio: $\widetilde{P} > 0.4$ (dump-bed rated for 800 N payload)
- High driving speed: 0.41 m/s (measured in field test)
- Continuous excavation (bucket-wheel)
- Direct regolith transfer to dump-bed using single moving part





The lightweight threshold

An excavator is operating in the lightweight regime when it is too light to produce enough traction to overcome resistance:

$$F_{ex} > P_{20}$$

$$\frac{F_{ex}}{W_{robot}} > \frac{P_{20}}{W_{robot}}$$

$$\frac{F_{ex}}{W_{robot}} > \frac{P_{20}}{W} \cdot \frac{W_{robot} + W_{payload}}{W_{robot}}$$

$$\widetilde{F} > \widetilde{T}\left(1 + \widetilde{P}\right)$$

Payload ratio:

$$\widetilde{P} = \frac{W_{payload}}{W_{robot}}$$

Excavation resistance coeff.:

$$\widetilde{F} = \frac{F_{ex}}{W_{robot}}$$

Excavation thrust coeff.:

$$\widetilde{T} = {P_{20}}/{W}$$

$$L = \frac{\widetilde{T}\left(1 + \widetilde{P}\right)}{\widetilde{F}_0 + \widetilde{F}'\widetilde{P}}$$

$$\lim_{\widetilde{P} \to \infty}\left(L_{disc}\right) = \frac{\widetilde{T}}{\widetilde{F}'_{disc}}$$

$$\min\left(L_{disc,\widetilde{P}=0.5}\right) < \frac{3\widetilde{T}}{\widetilde{F}'_{disc}}$$

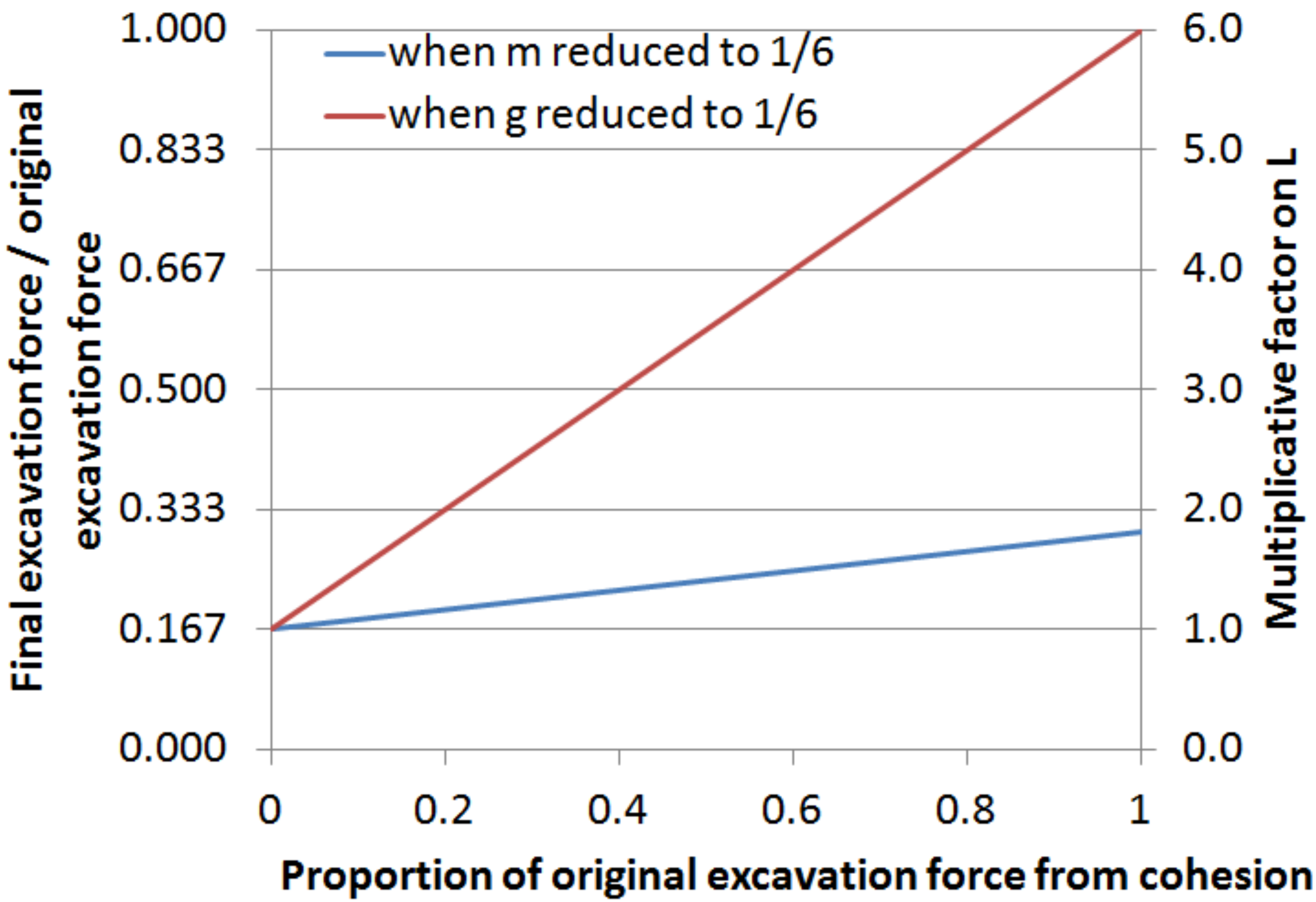
Predicted lightweight numbers

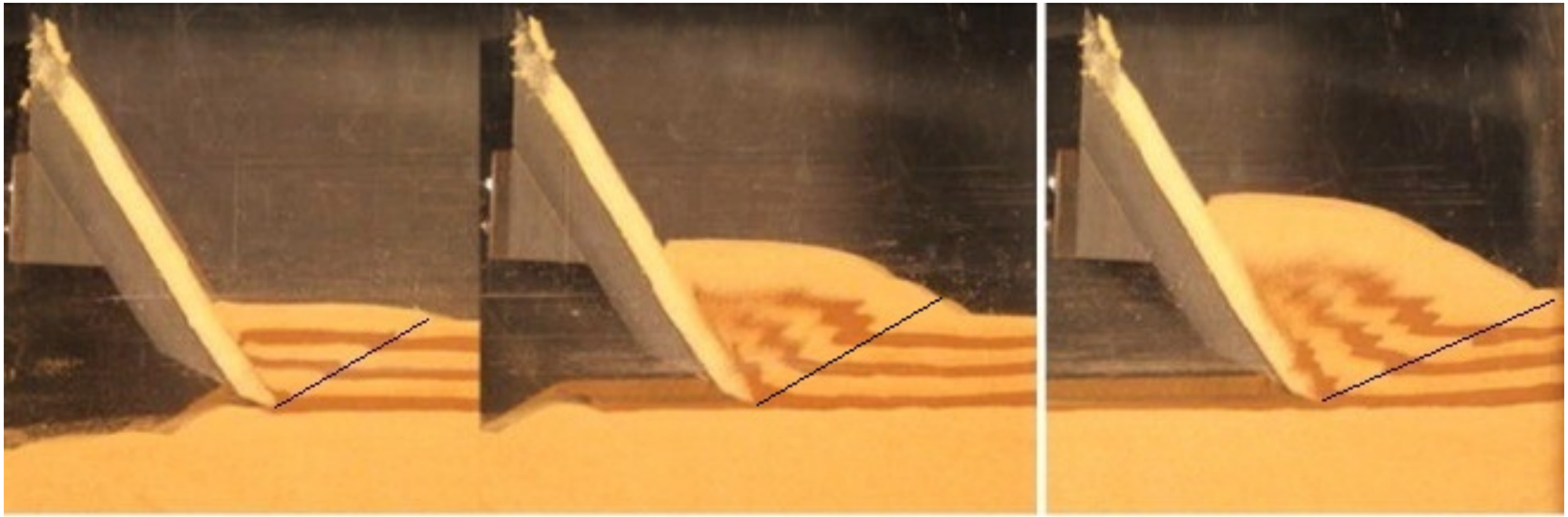
- Excavating with gravity offload overestimates the detrimental effects on excavation resistance, but underestimates the detrimental effects of gravity on traction
  - Assumes $L(g) \propto g$

- Excavating in Earth gravity underestimates detrimental effects on both excavation resistance *and* traction

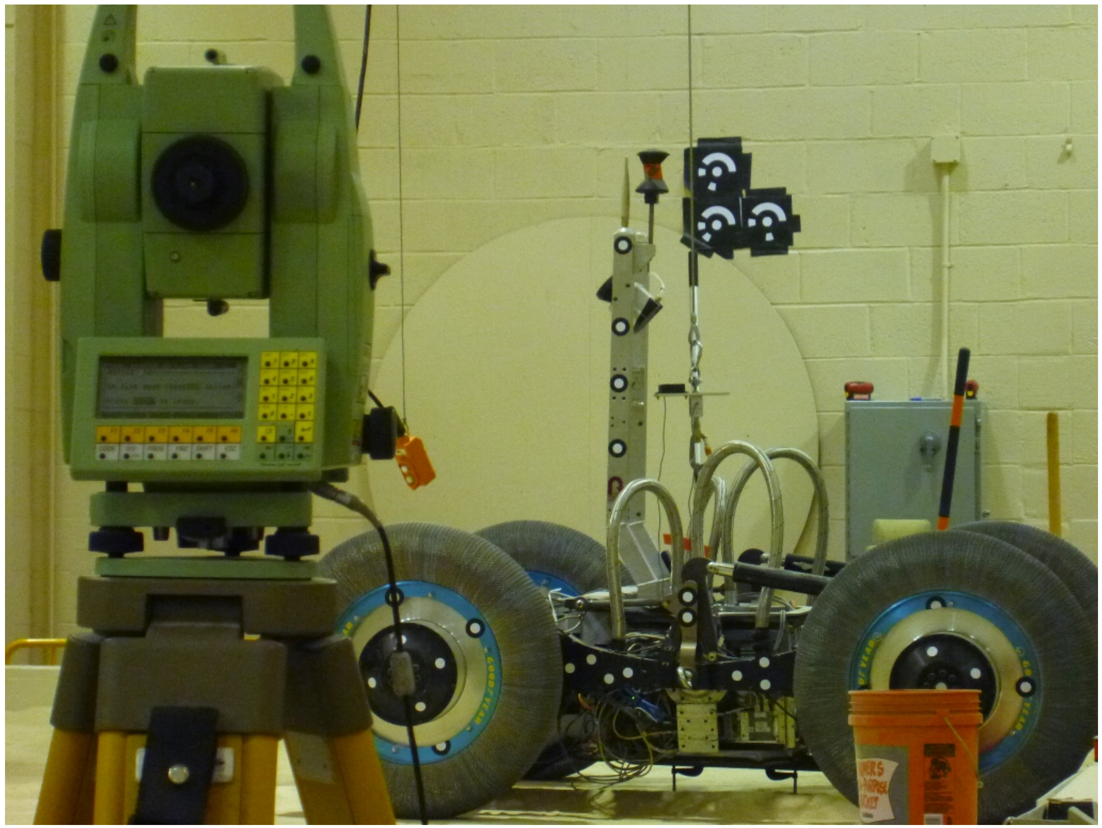
Excavation resistance does not scale directly with gravity in cohesive soil

$$F_{ex} = C_1 \rho g w d^2 + C_2 c w d + \ldots$$



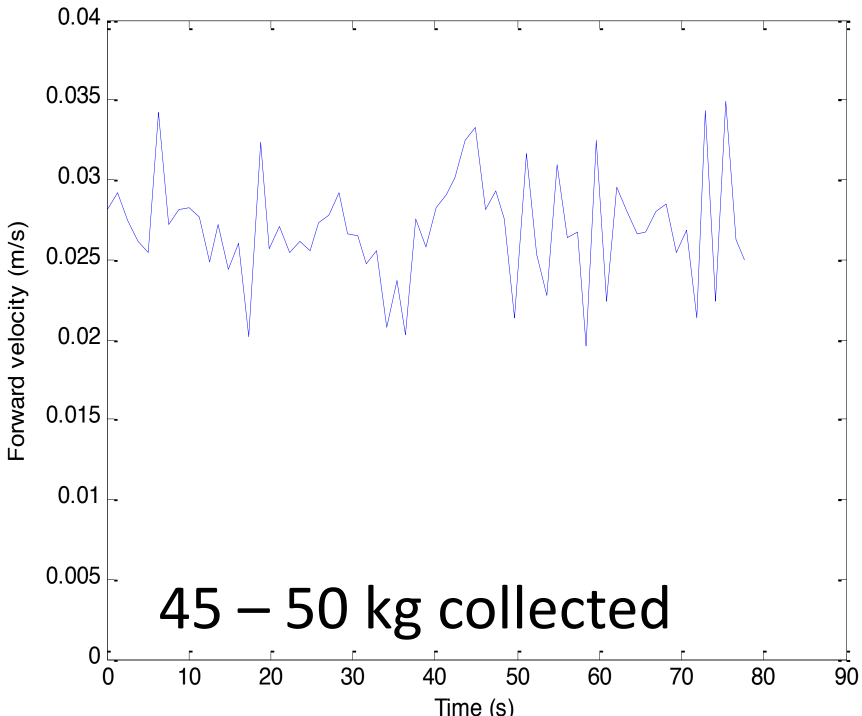


Position tracking



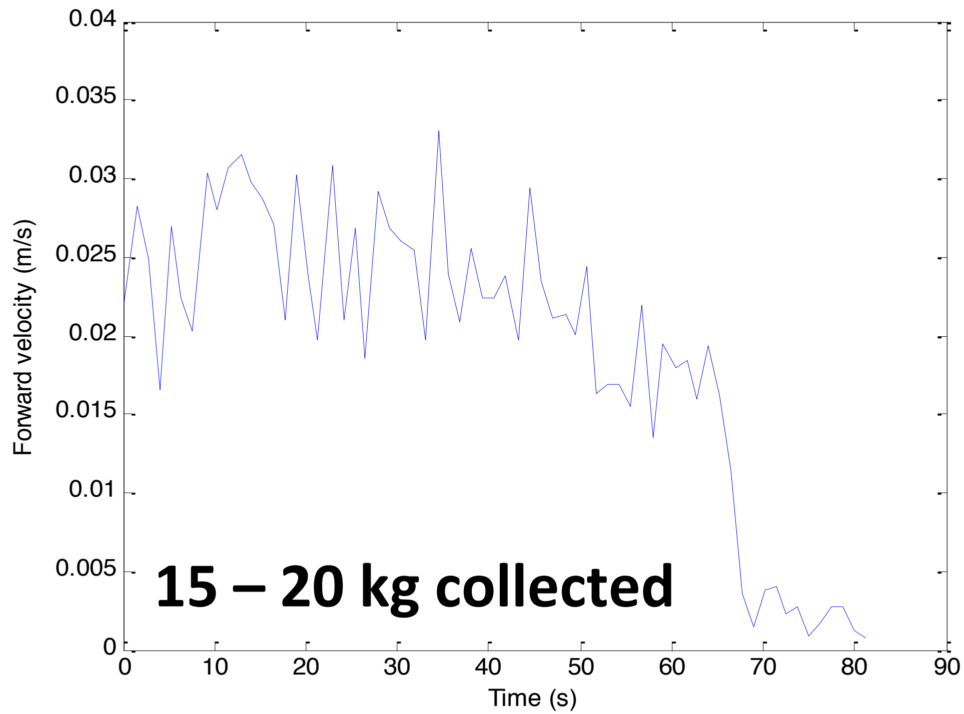
Lightweight excavation

- Bucket-wheel excavation offloaded to 1/6 g

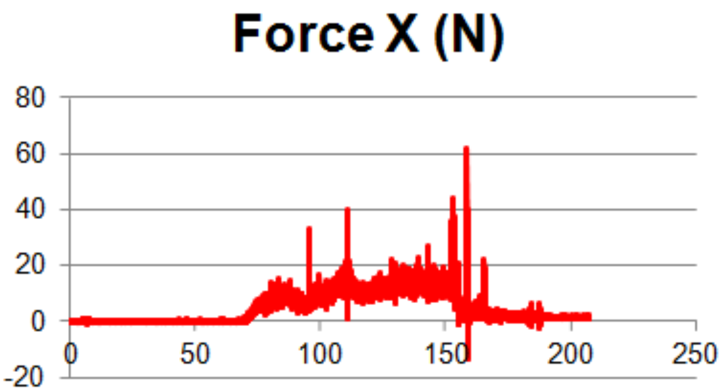


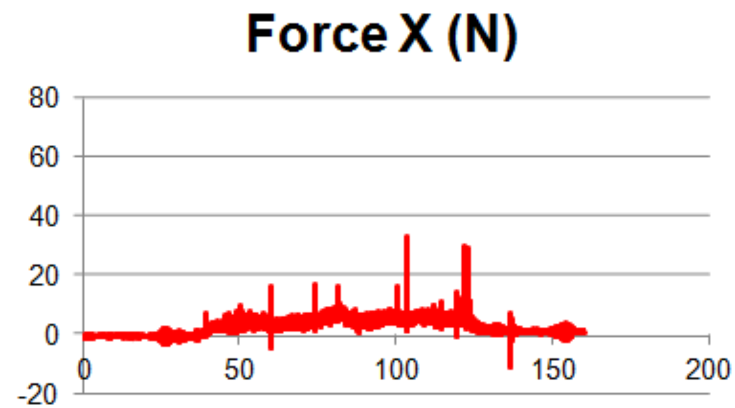
- Mobility and production also typical of 1 g bucket-wheel and front-loader excavation

Front-loader excavation offloaded to 1/6 g

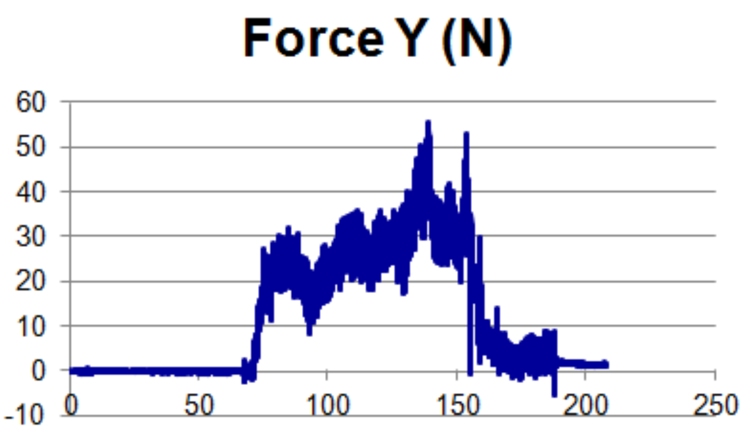


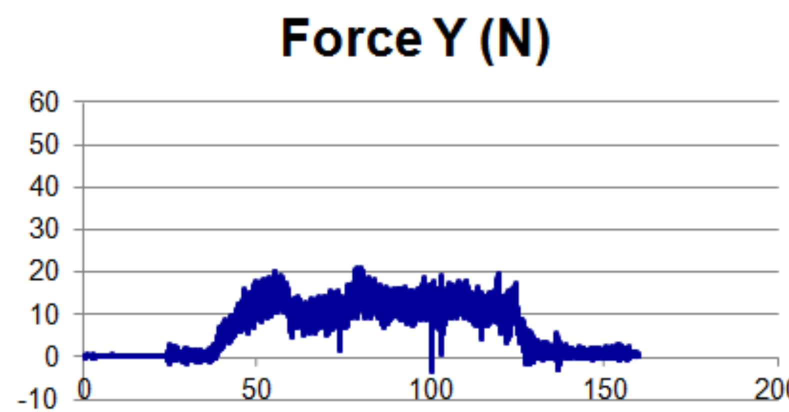
Bucket-wheel excavation forces



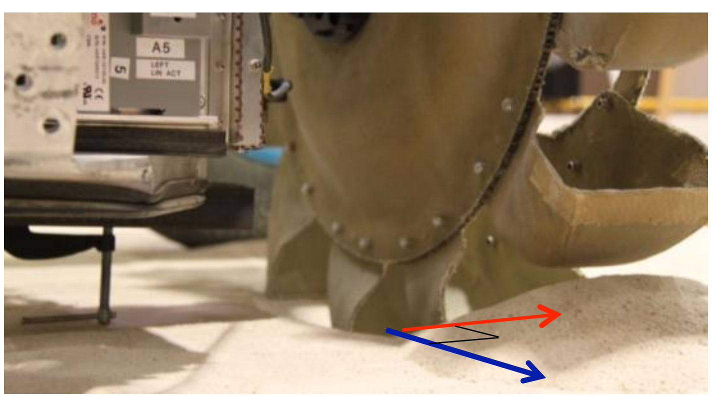


Longitudinal Force:
6 – 14 N





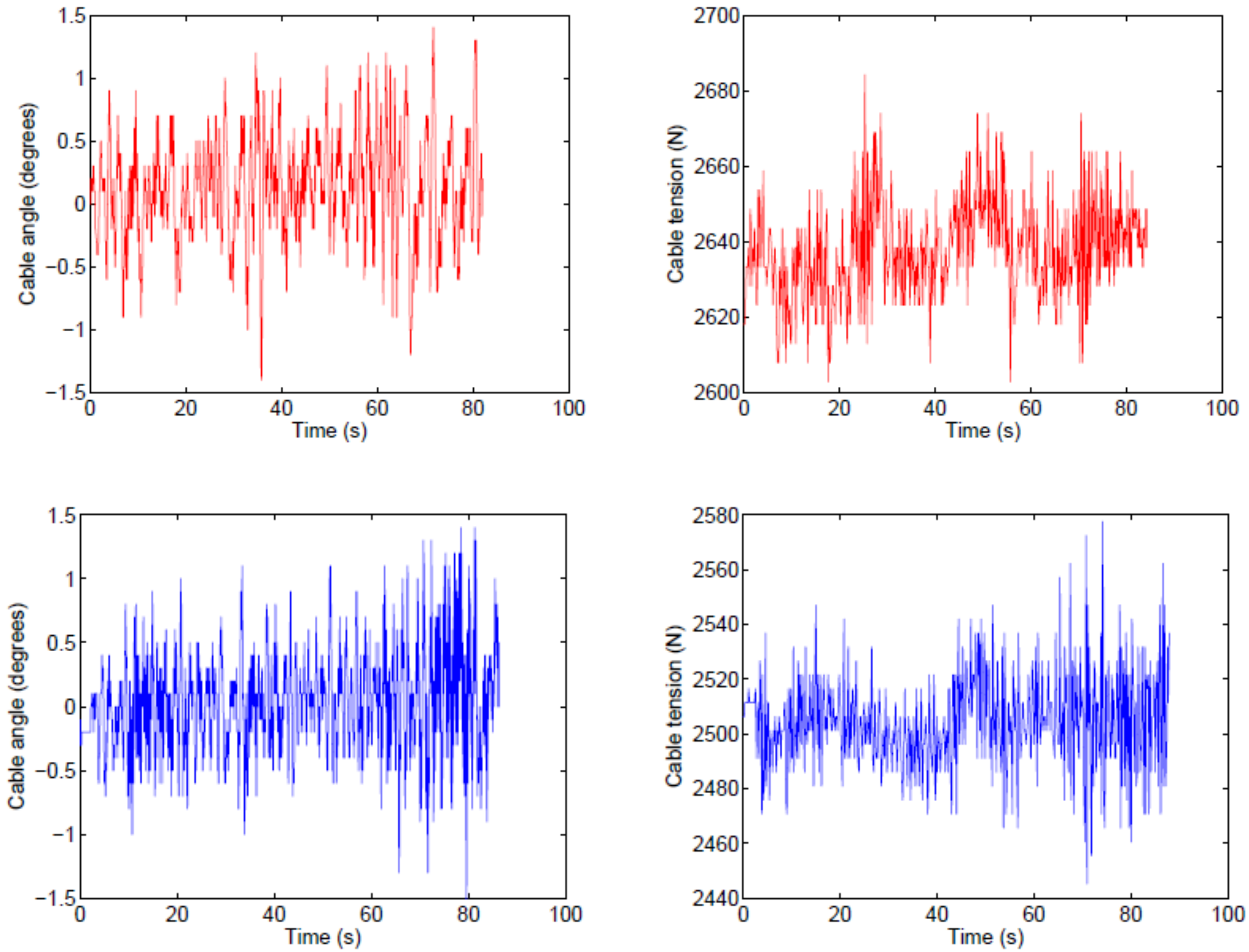
Lateral Force:
12 – 33 N



Forces imposed by bucket-wheel excavation are too low to degrade mobility, even in 1/6 g

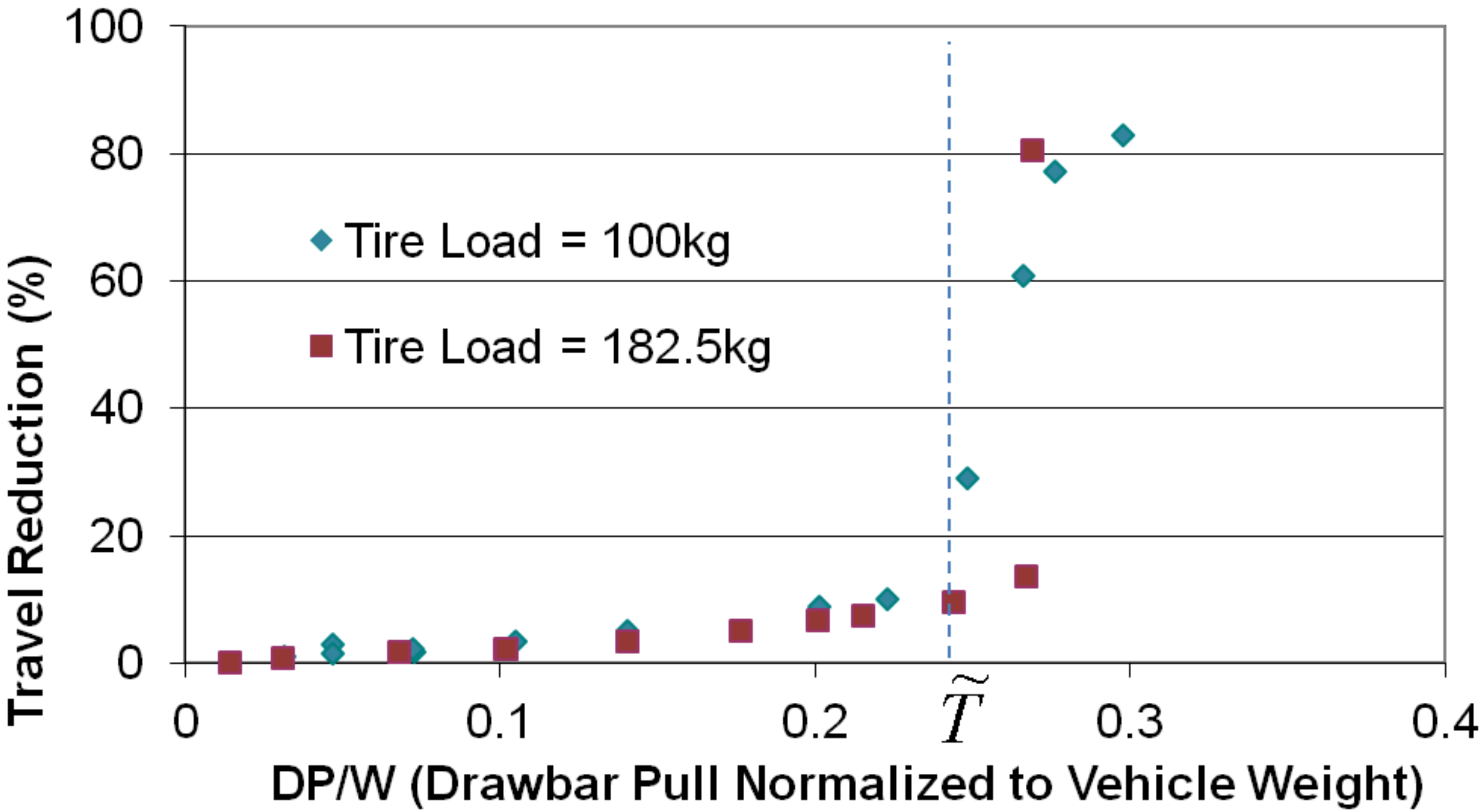
[GRC-1 compacted to 1,700 kg/m^3]

Gravity offload quality



Changing load does not significantly affect DP/W

- Spring tire data

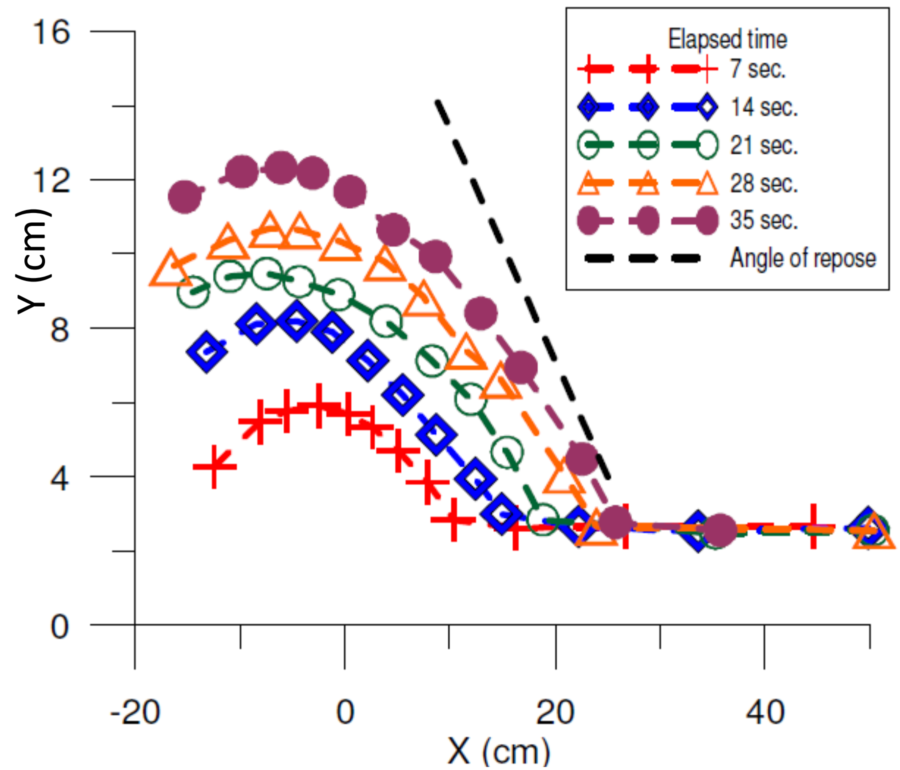


- See also Freitag (1970)

Measuring bucket-wheel excavation resistance

Effects of soil accumulation on productivity

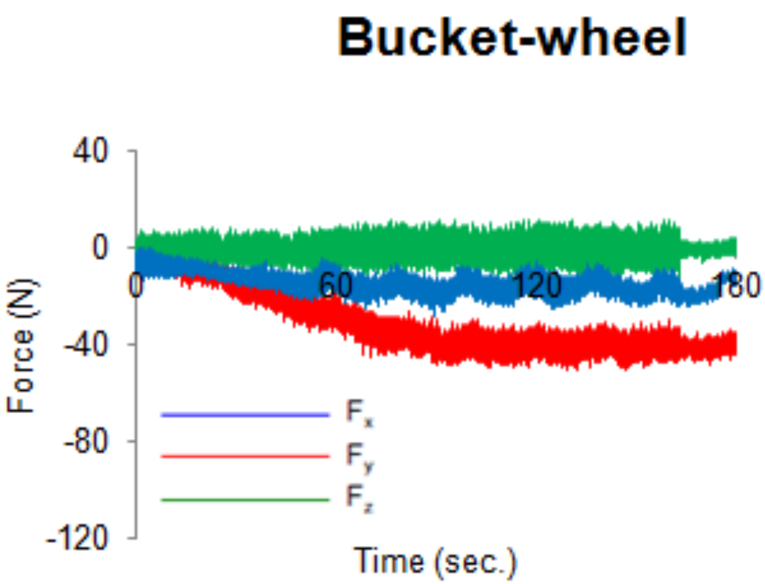
- Analytical excavation models (Luth & Wismer, Balovnev) will be augmented with first-order approximations of soil accumulation effects
- Depth, d(x), and surcharge mass, q(x), will be utilized for approximation

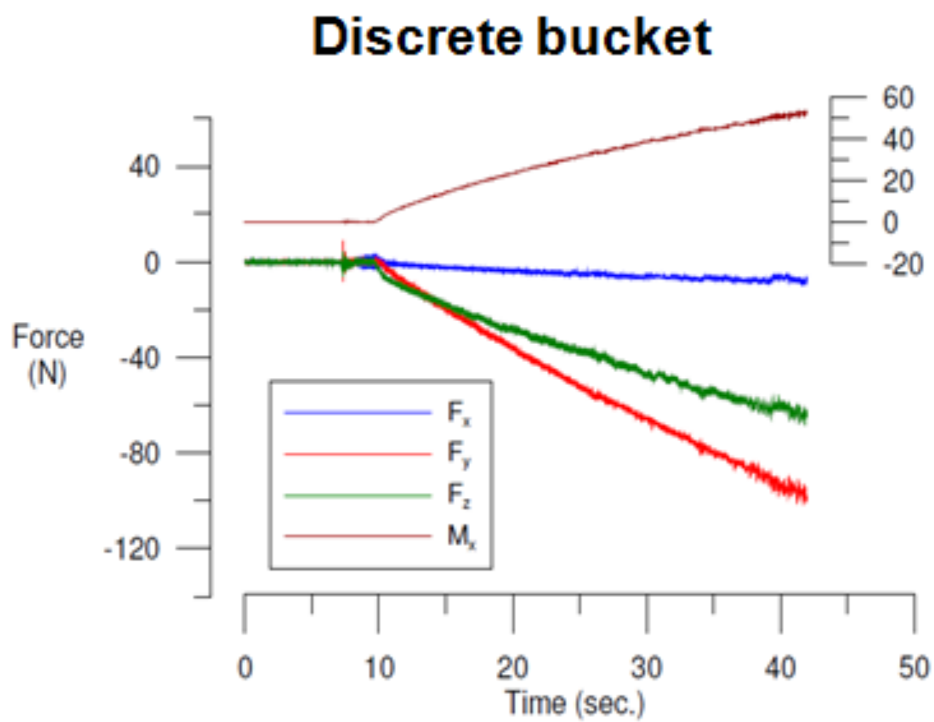


Agui and Wilkinson (2010)
Earth & Space

Bucket-wheel excavation resistance results

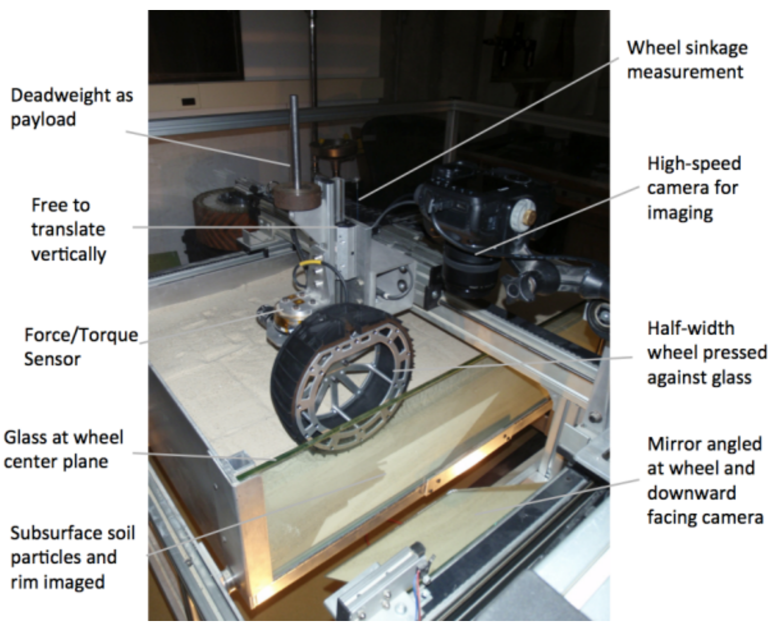
- Excavation resistance does not rise as cutting progresses with a continuous excavator such as a bucket-wheel

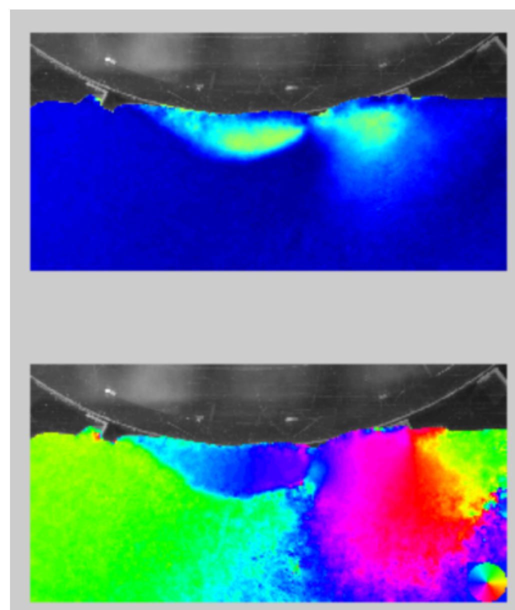




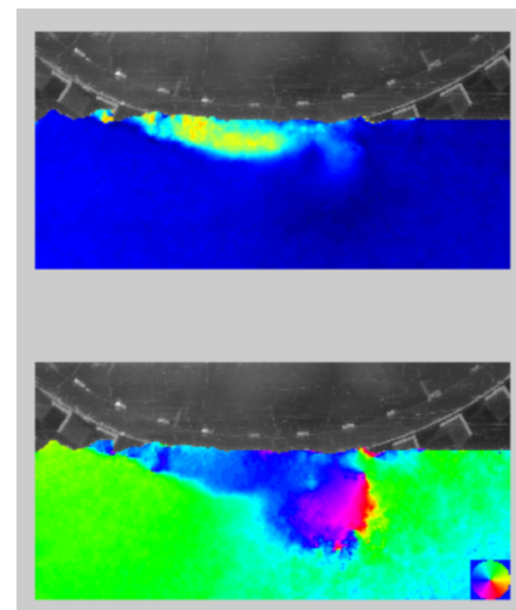
Testing grouser spacing

- Soil flow below and ahead of a wheel illustrates the effectiveness of its grouser spacing
- Large forward flows correspond to significant motion resistance and thus reduced traction

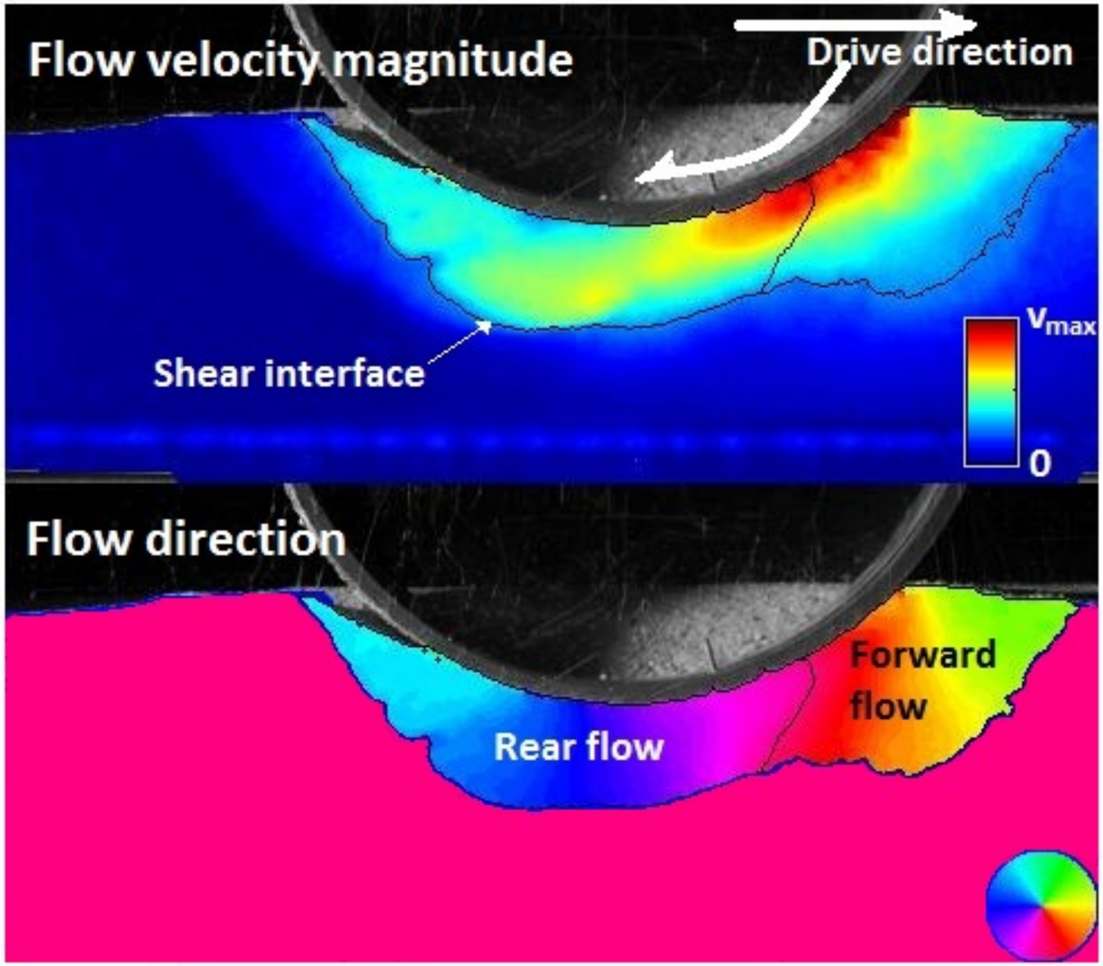




Insufficient grousers

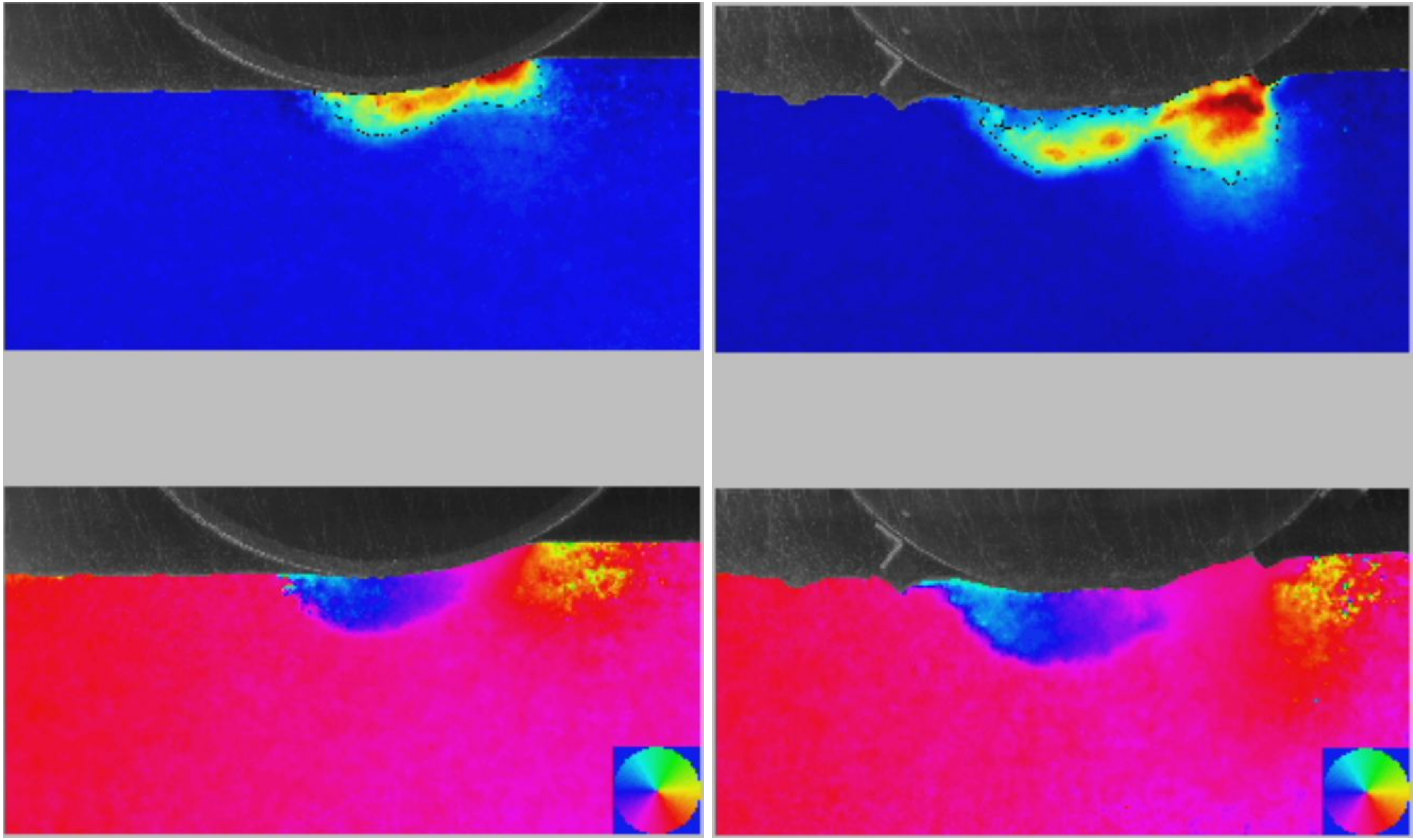


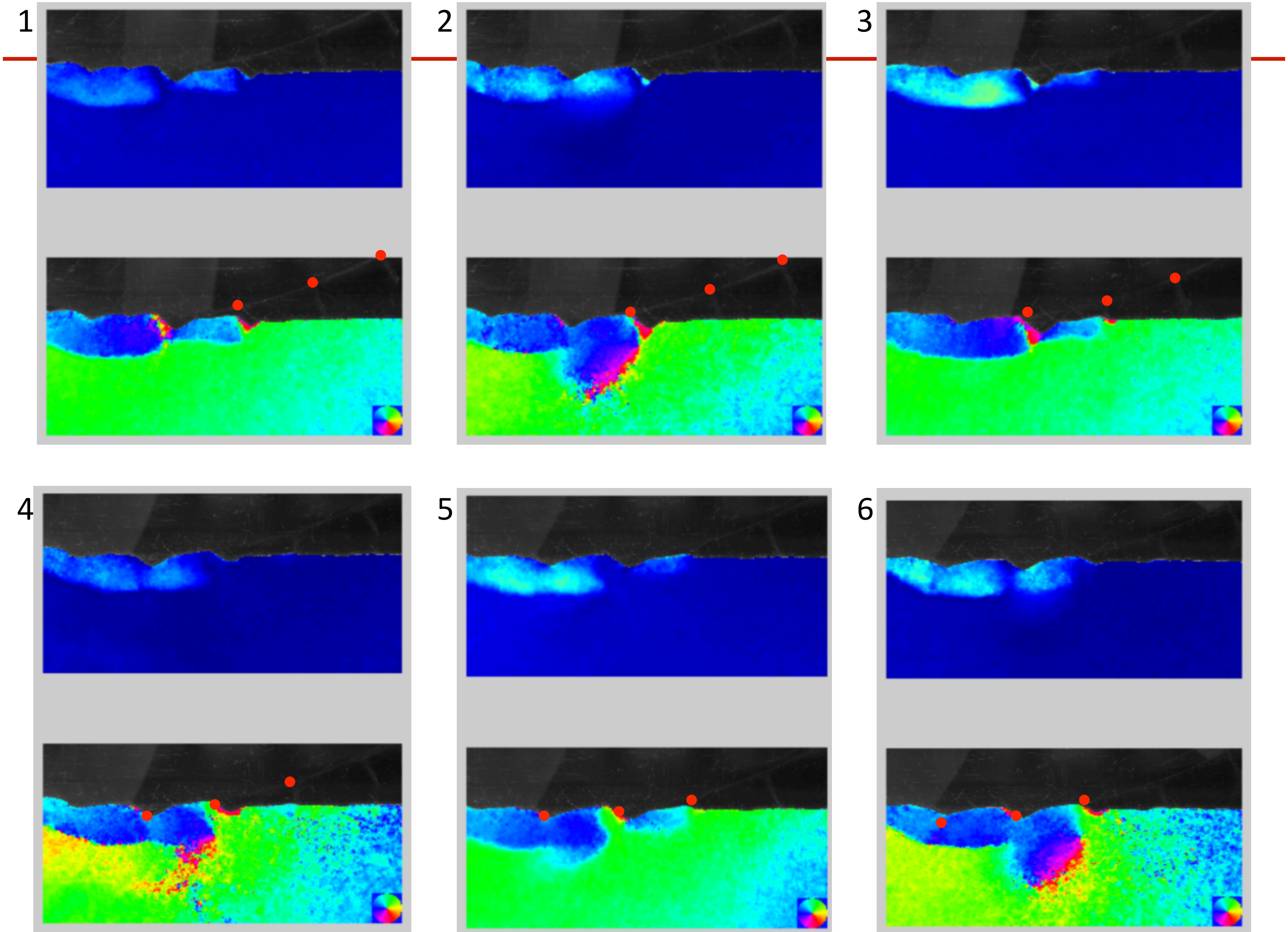
Sufficient grousers

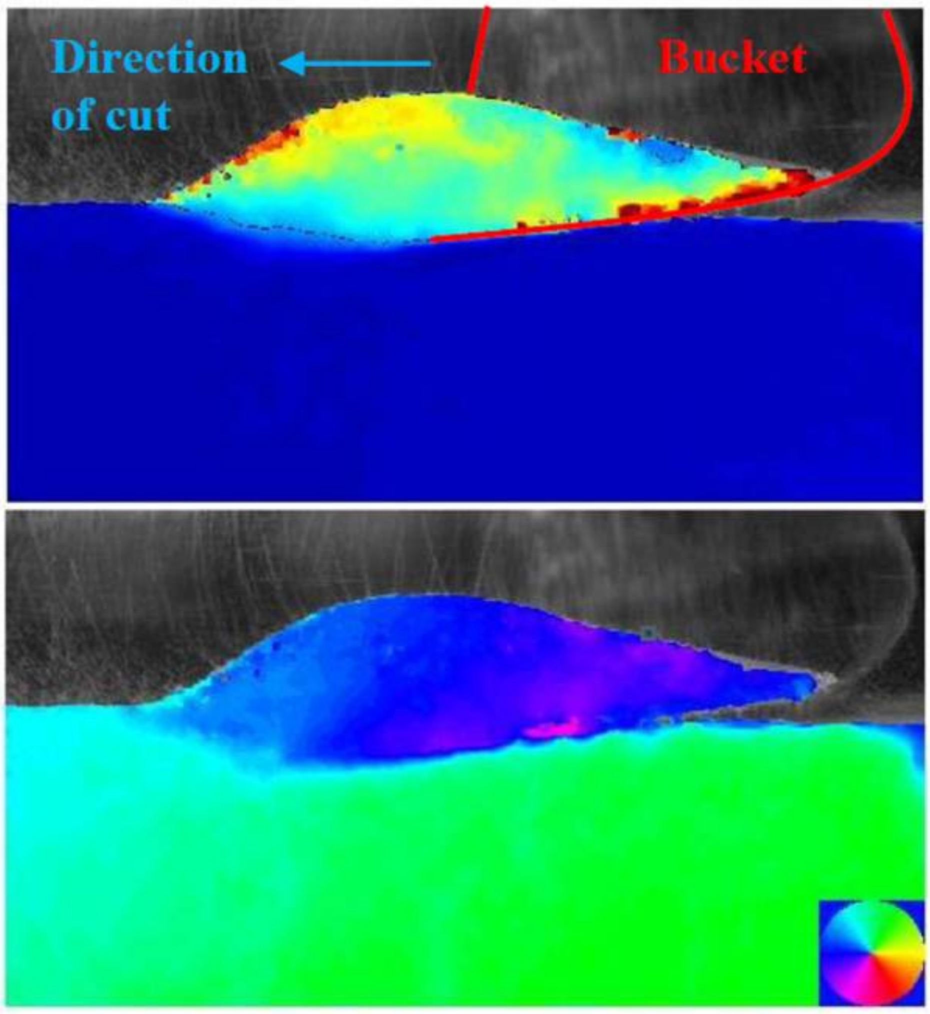

Flow velocity magnitude
Drive direction
Shear interface
v_max
0
Flow direction
Forward flow
Rear flow

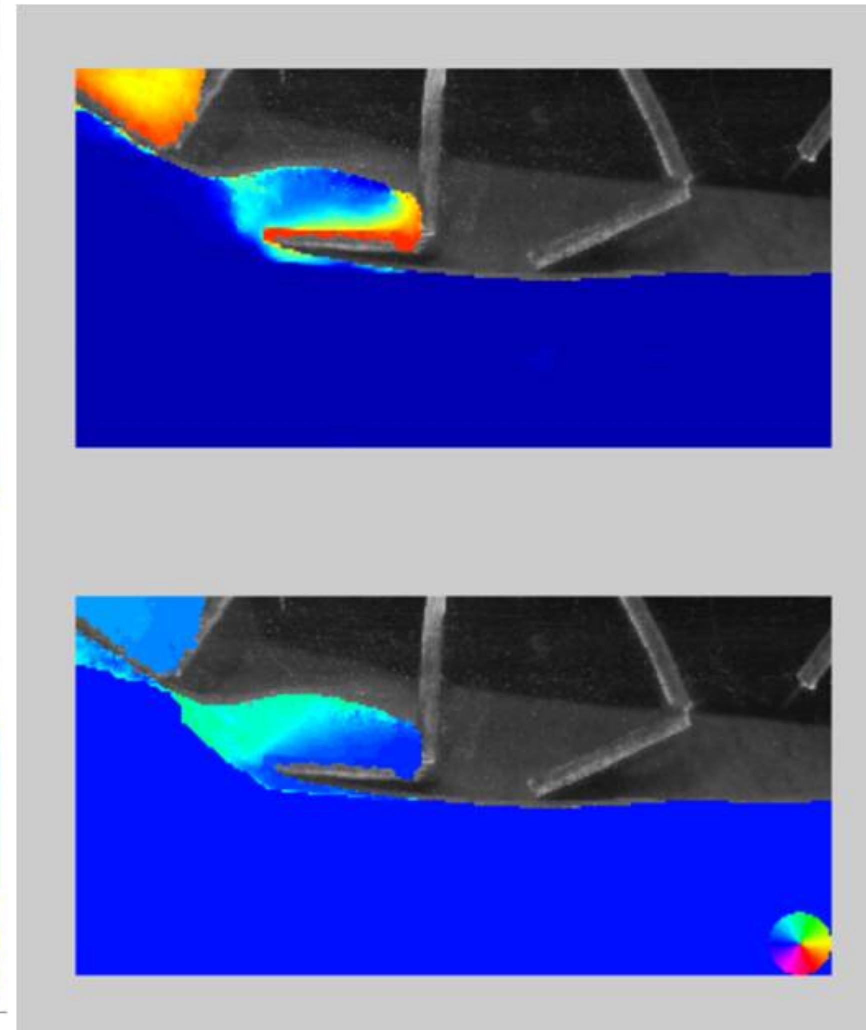
Sinkage in rigid wheels is related to resistive forward flow

- This resistive forward flow is similar to excavation resistance




1
2
3
4
5
6


Direction
of cut
Bucket



Bucket-wheels and bucket-ladders

- **Bucket-wheel and bucket-ladder configurations have both been shown to be viable options for lightweight excavation**

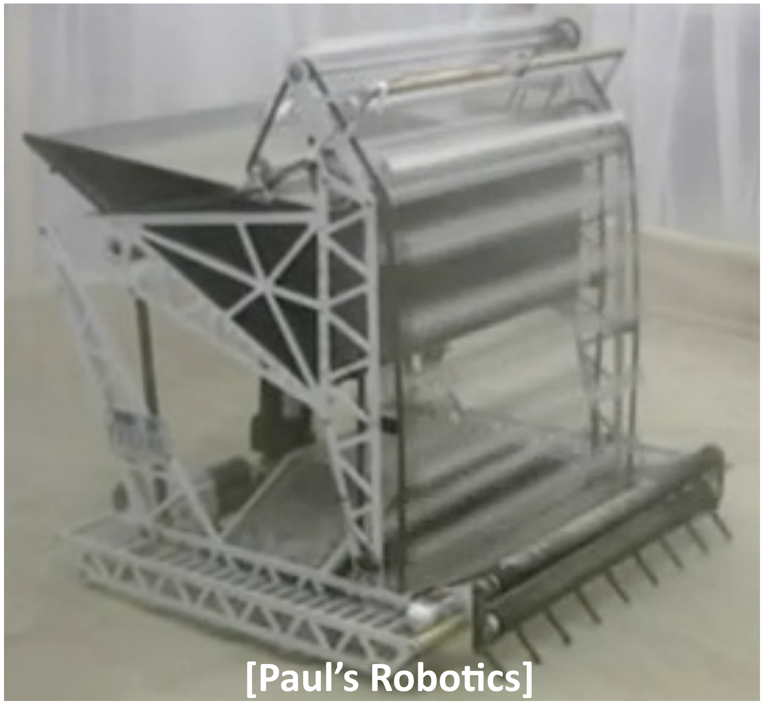
- **Bucket-ladders have won favor due to inherent combination of regolith excavation and transfer**

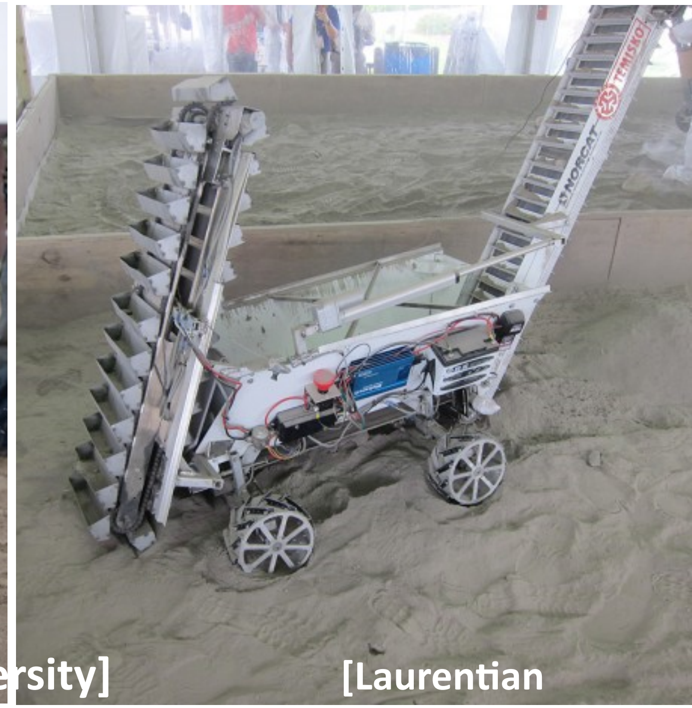
[Colorado School of Mines]

Johnson and van Susante (2006) *SRR* **Johnson and King (2010) *J Terramechanics***

Bucket-ladders have proven very productive

A bucket-ladder won the Regolith Excavation Challenge and each of the Lunabotics competitions

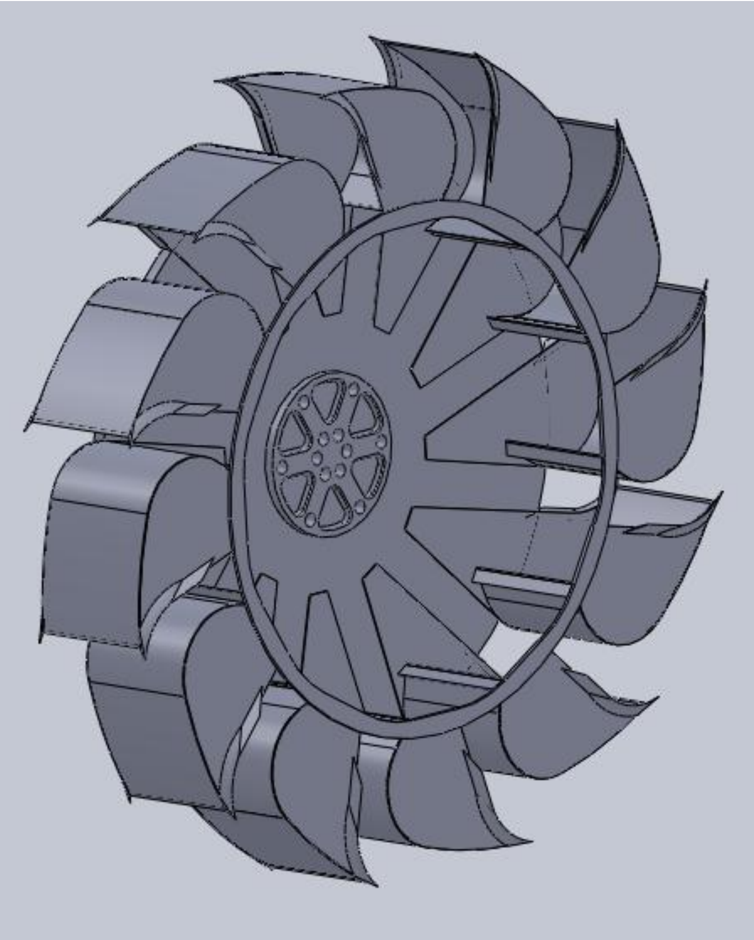


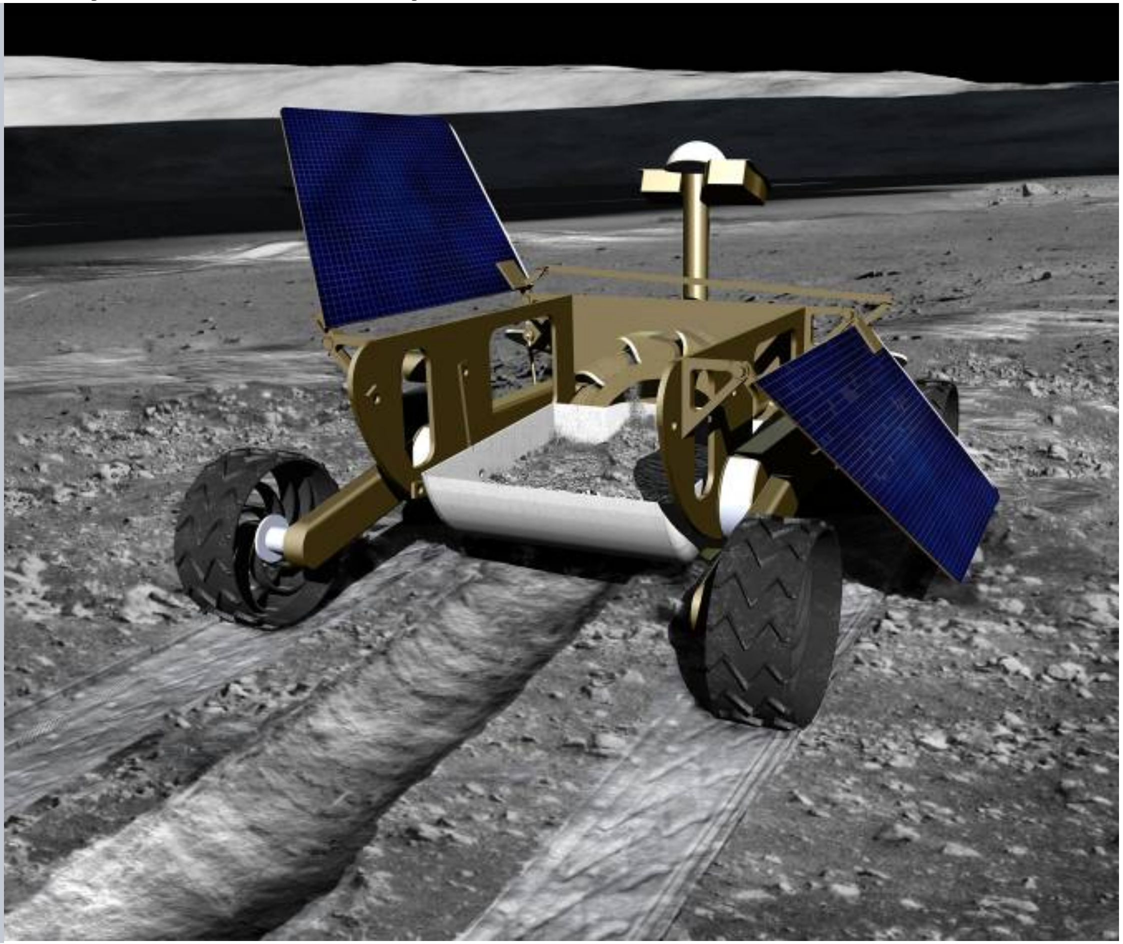


Bucket-ladder designs to date all feature chains exposed directly to regolith and dust

Transverse bucket-wheel configuration

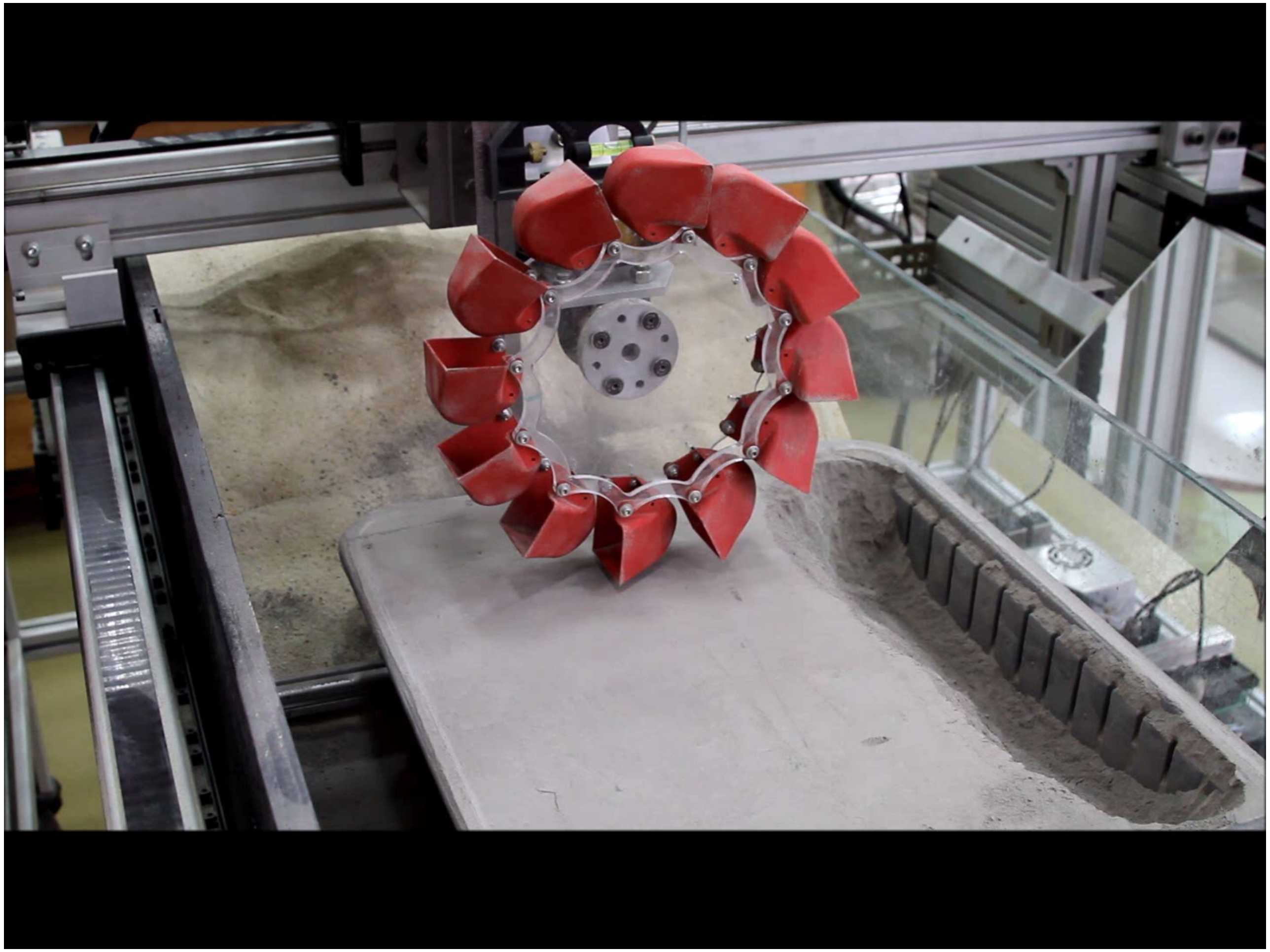
- A bucket-wheel is a single moving part and, mounted transverse, can transfer regolith directly into a dump-bed





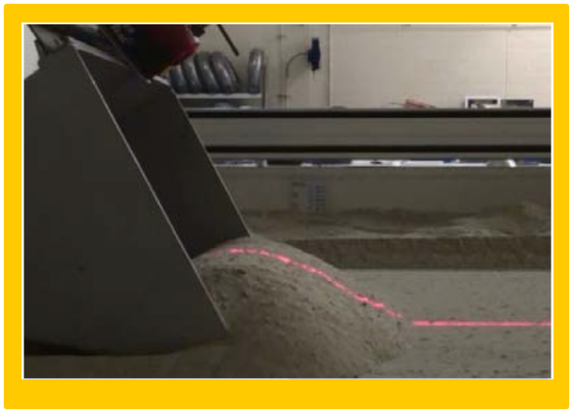
Novel bucket-wheel configuration for regolith transfer

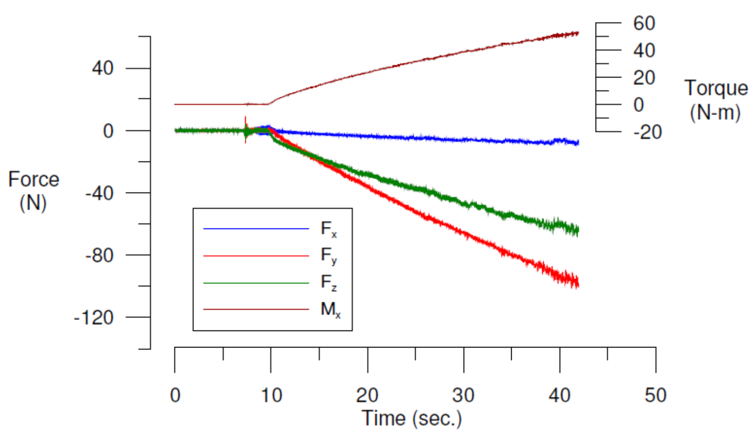
- **Bucket-wheel and bucket-ladders both yield low excavation resistance, but bucket-ladders have won favor due to inherent combination of excavation and transfer [Johnson 2006, 2010]**



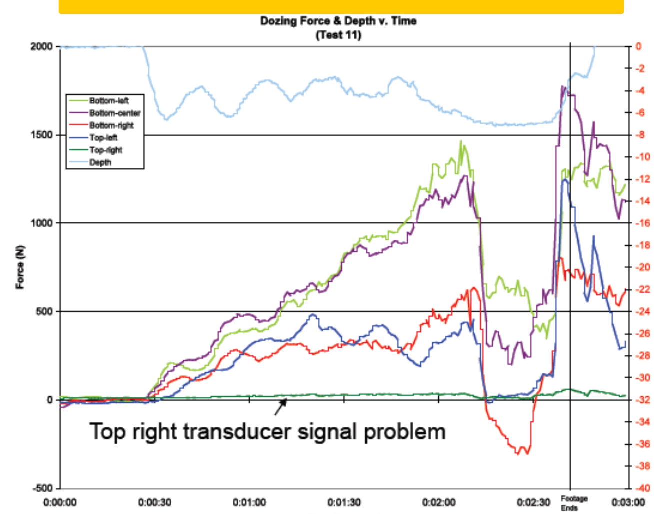
Discrete excavators experience rising resistance

- Discrete excavators such as loader buckets and dozer blades undergo rising excavation resistance as soil accumulates



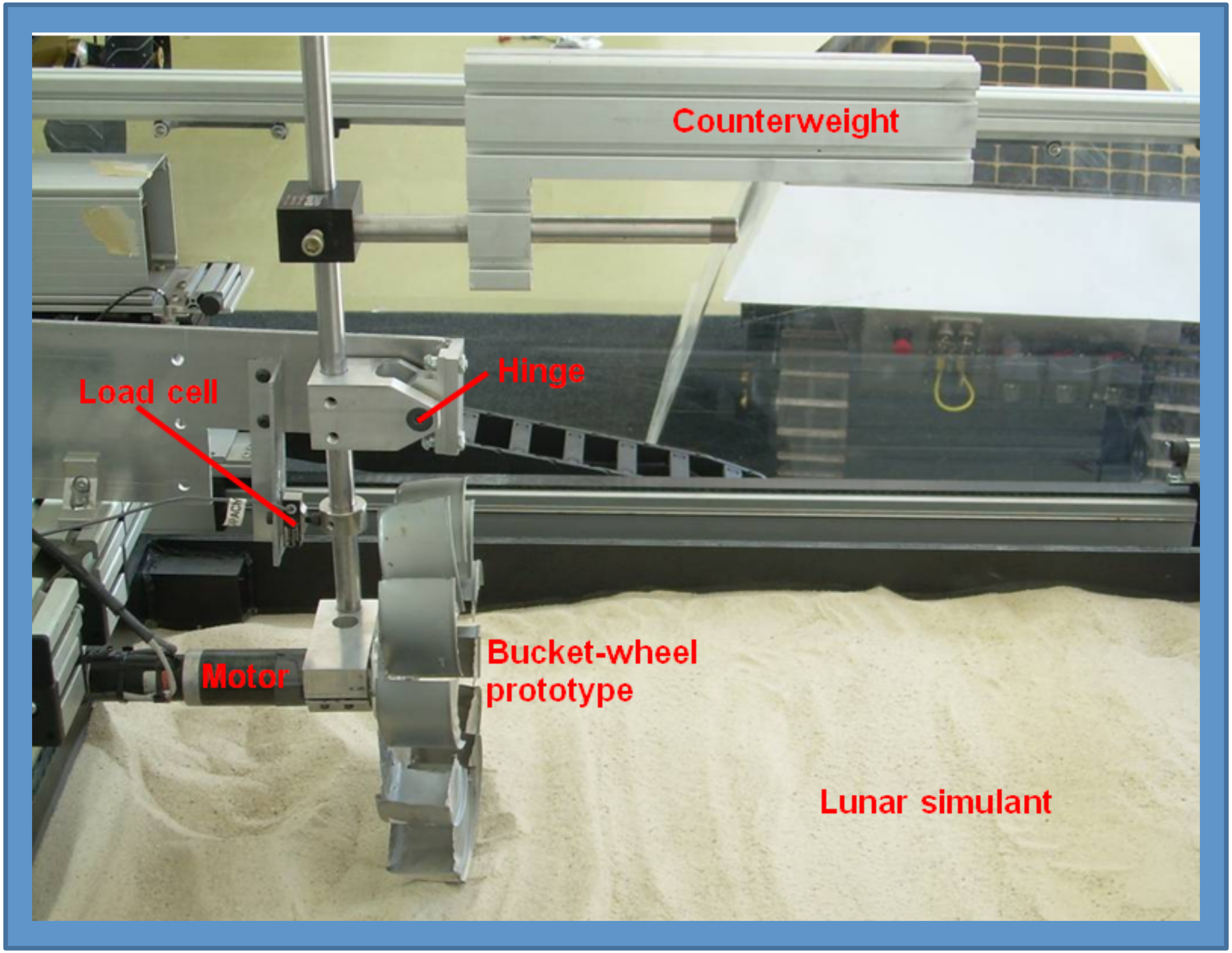


Agui and Wilkinson (2010)
Earth & Space



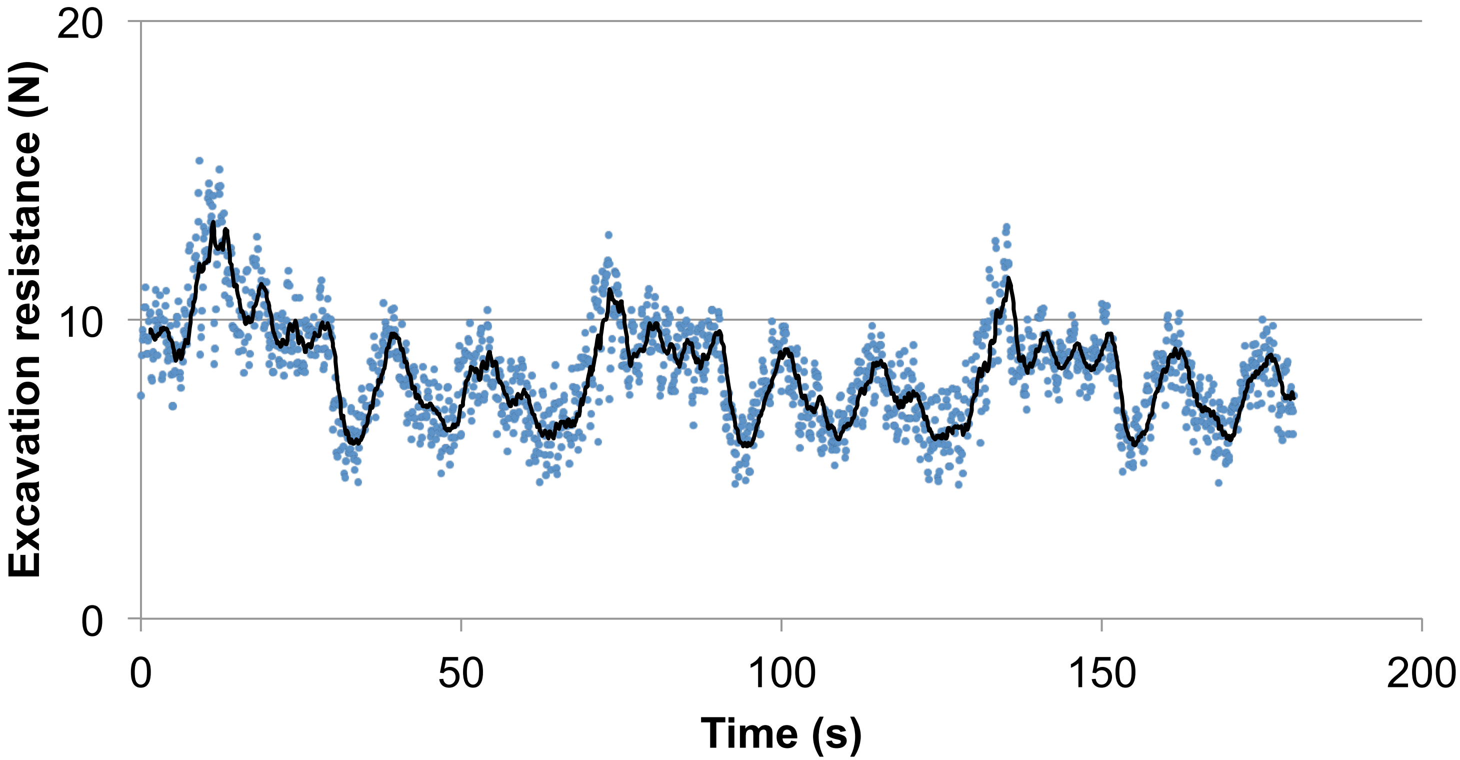
King, van Susante, and Mueller (2010) *PTMSS/SRR*

Measuring bucket-wheel excavation resistance



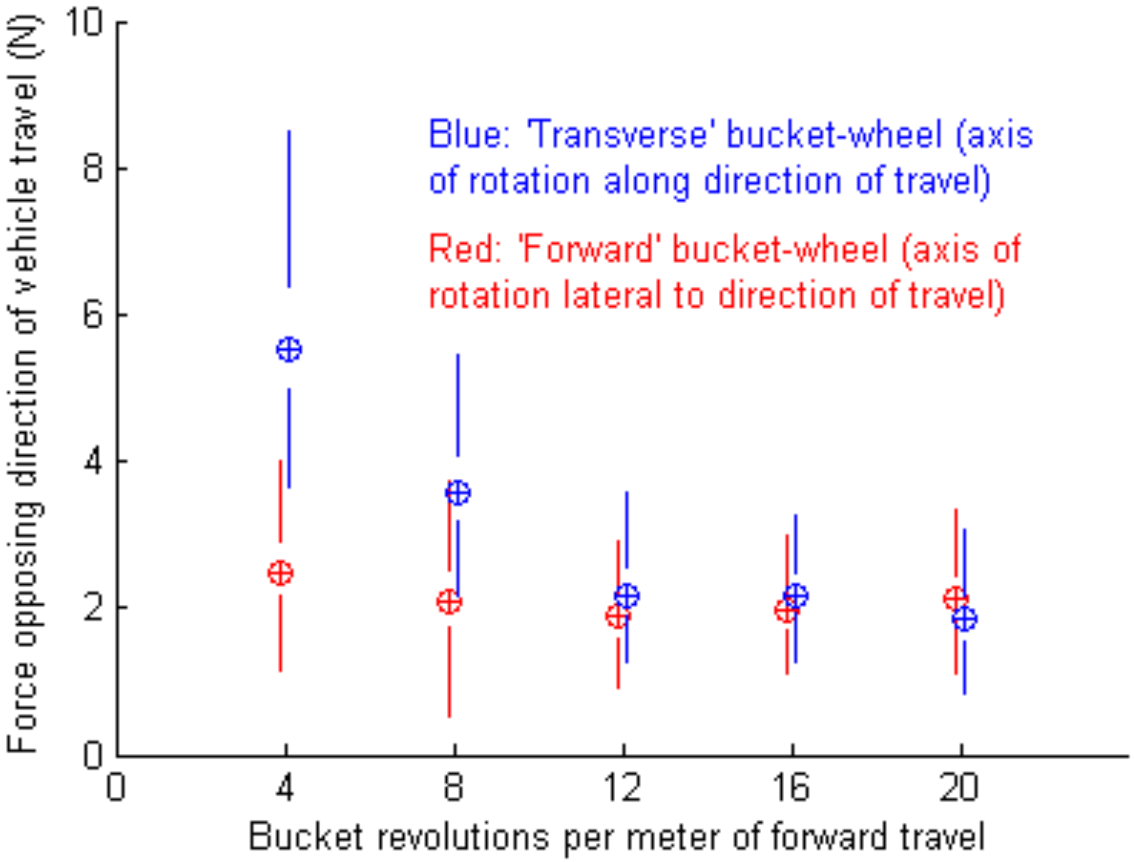
Bucket-wheel excavation resistance results

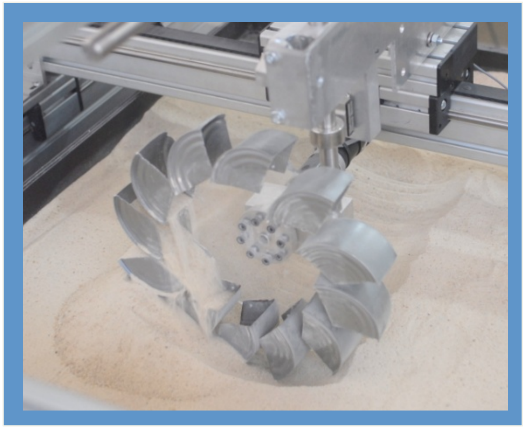
- Excavation resistance does not rise as cutting progresses with a continuous excavator such as a bucket-wheel



Transverse vs. forward excavation resistance

- Transverse bucket-wheels do not experience significantly higher excavation resistance as long as rotation speed is sufficient

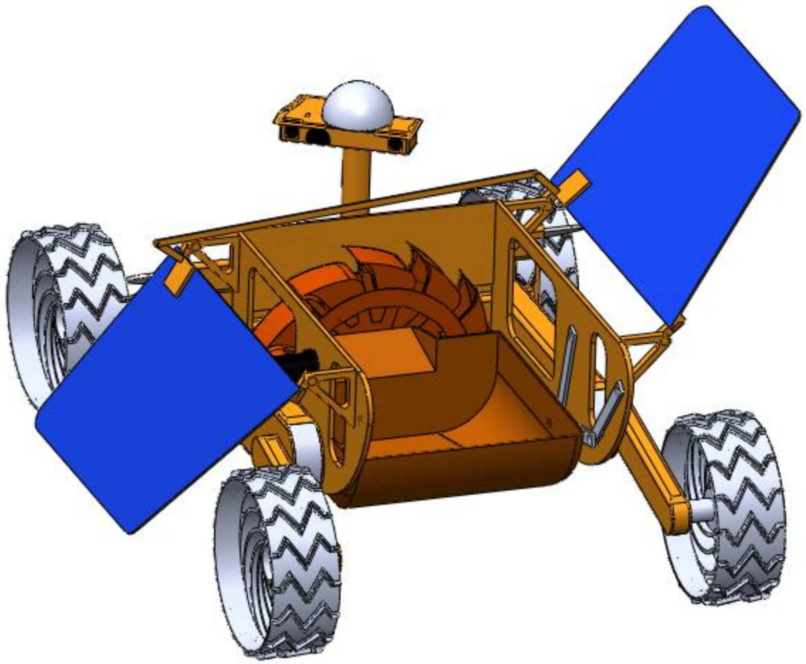




Scarab configuration is centered around the tool

Bucket-wheel excavator experiments

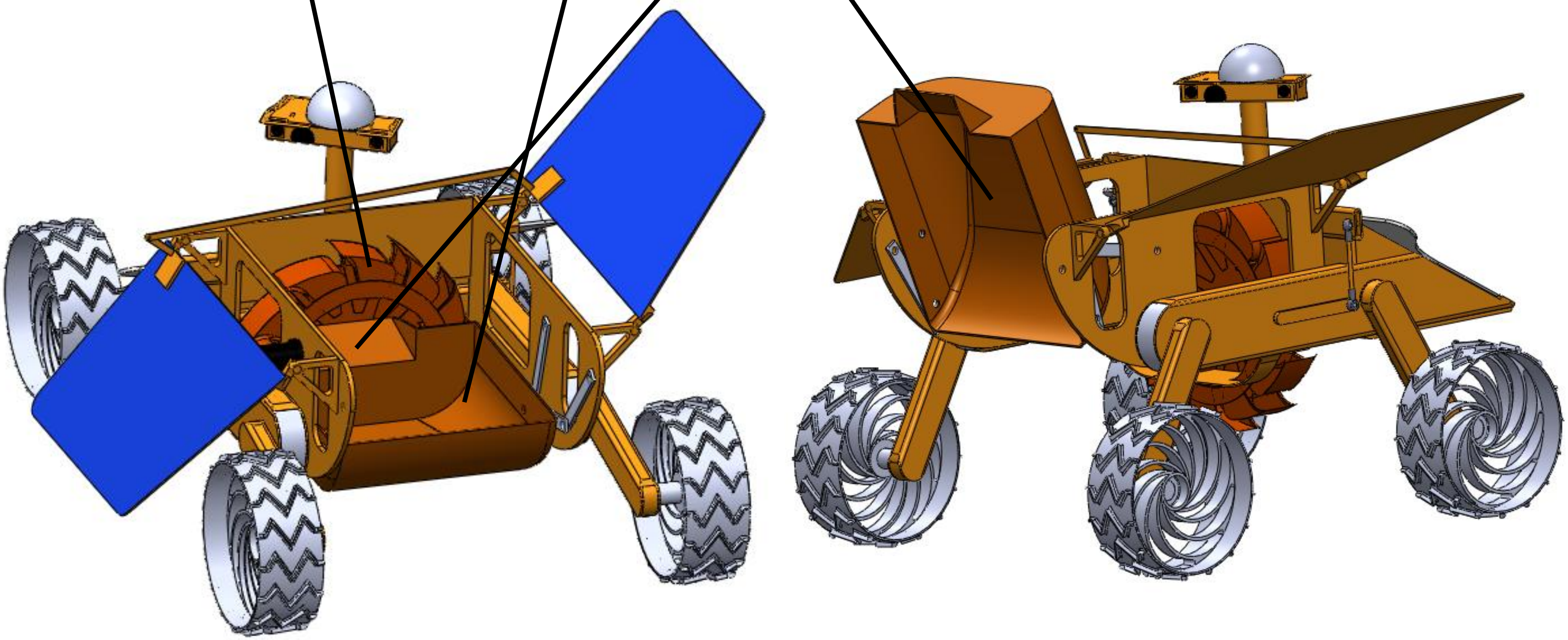
- Excavation field tests will be conducted with a lightweight mobile robot excavator
- Gravity offload will enable investigating productivity at various weights



- Field testing will expose operational effects not captured in idealized analysis and experiments

Lightweight robotic excavator prototype

- High payload ratio dump-bed
- Bucket-Wheel
  - Mounted transverse for direct transfer to dump-bed
- Instrumentation for experimental data collection
  - Force/torque, configuration, localization, power monitoring



Past lightweight robotic excavator prototypes

Robot	Mass	Payload Ratio	Driving Speed	Image
Bucket wheel excavator	< 100 kg	n/a	0	 [Colorado School of Mines]
Bucket drum excavator	< 100 kg	Mod.	< 5 cm/s	 [NASA / Lockheed Martin]
Bucket ladder excavators	< 100 kg	High	Various	 [Paul's Robotics]
NASA Cratos scraper	< 100 kg	High	5 cm/s	 [NASA]

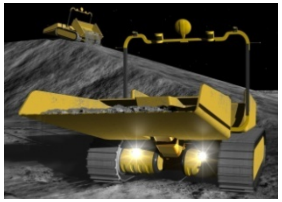
Other past space-relevant excavators

Robot	Mass	Payload Ratio	Driving Speed	Image
Juno load-haul-dump	> 300 kg	Low	> 1 m/s	
NASA Chariot w/ LANCE blade	> 1000 kg	Low	> 1 m/s	
NASA Centaur II w/ bucket	> 500 kg	Low	> 1 m/s	

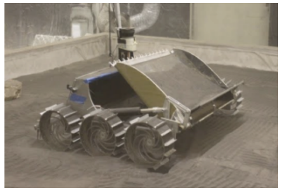
Sensitivity analysis

- The design space of small robotic excavators is so vast that identifying the few significant parameters is a valuable contribution
- Each parameter is systematically varied and the effect these changes have on task-level productivity is gauged
- Sensitivity analysis is performed in both:

- Simulation

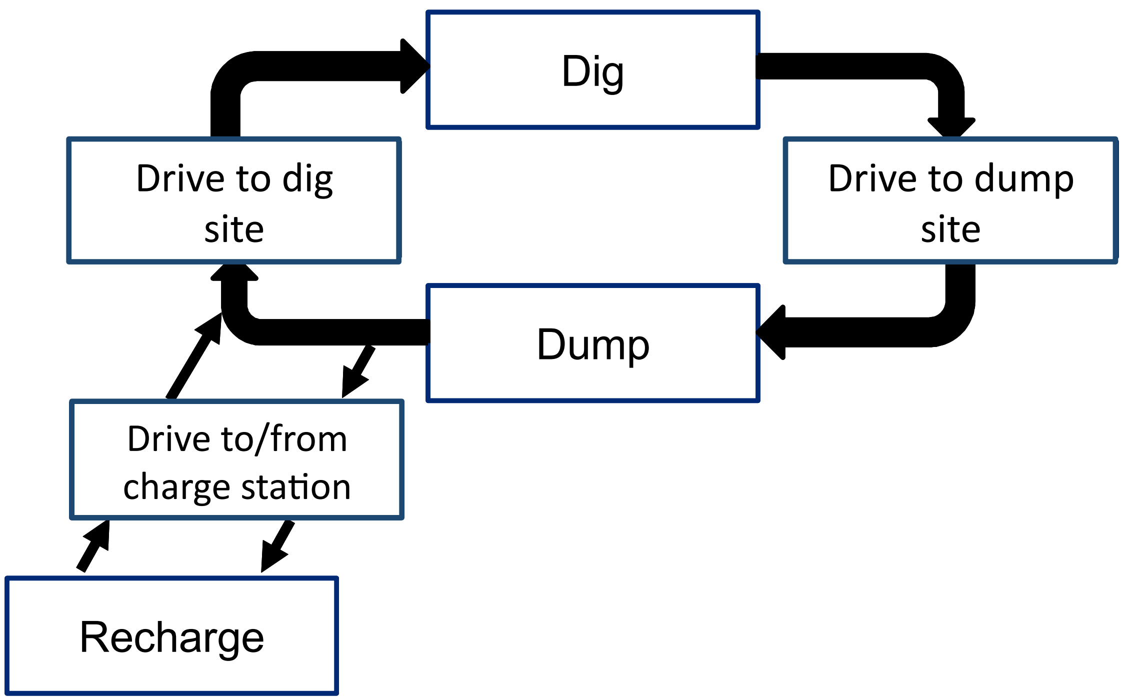


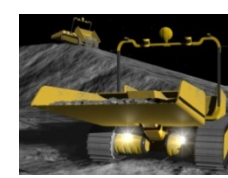
- Experimentation



REMOTE: Regolith Excavation, MObility & Tooling Environment

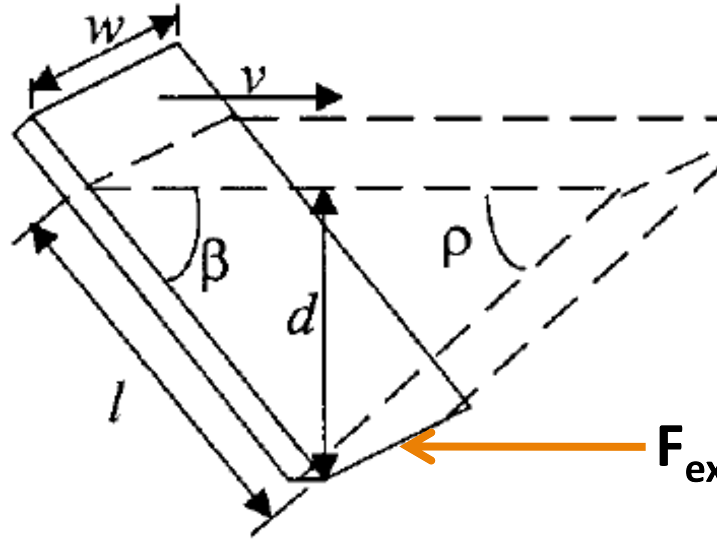
- REMOTE characterizes performance of machines within site-level tasks such as dig-dump and trenching, and identifies issues that govern these tasks



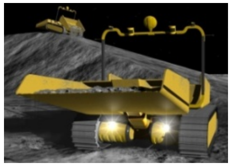


REMOTE: Excavation models

- Excavation force, F_{ex} , is predicted from bucket geometry, as well as operational and soil parameters (8+ parameters)

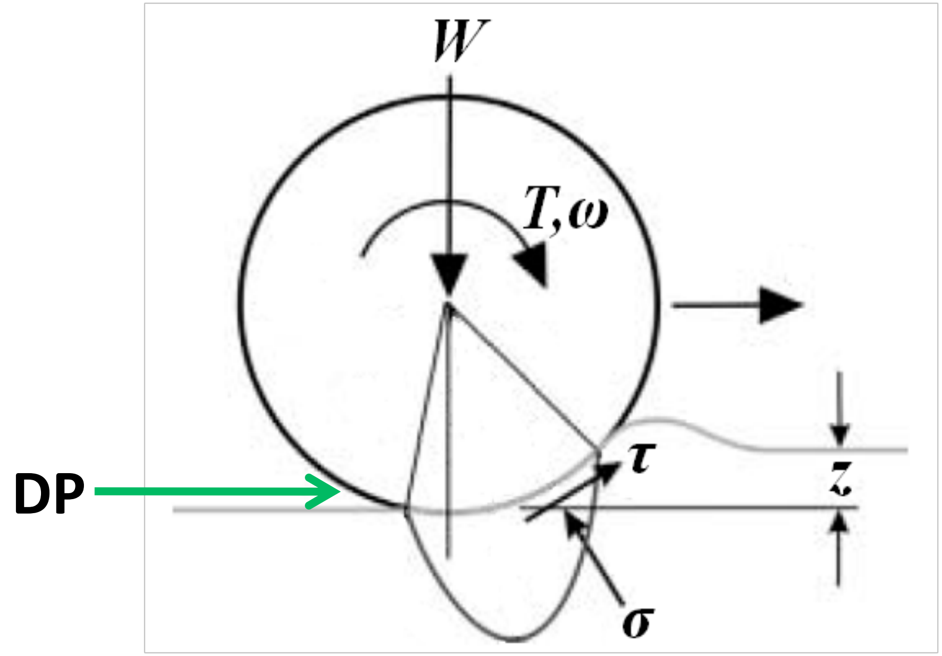


- Wilkinson & DeGennaro (2007) concluded that it is unknown which excavation models are most applicable for the Moon
- REMOTE includes Luth-Wismer and Balovnev excavation models, commonly used within the field of lunar excavation

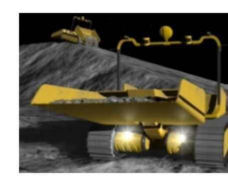


REMOTE: Traction model

- Drawbar pull (DP) is the amount of tractive force available for work
- Drawbar pull depends on wheel geometry, loading, and soil parameters (10 parameters)

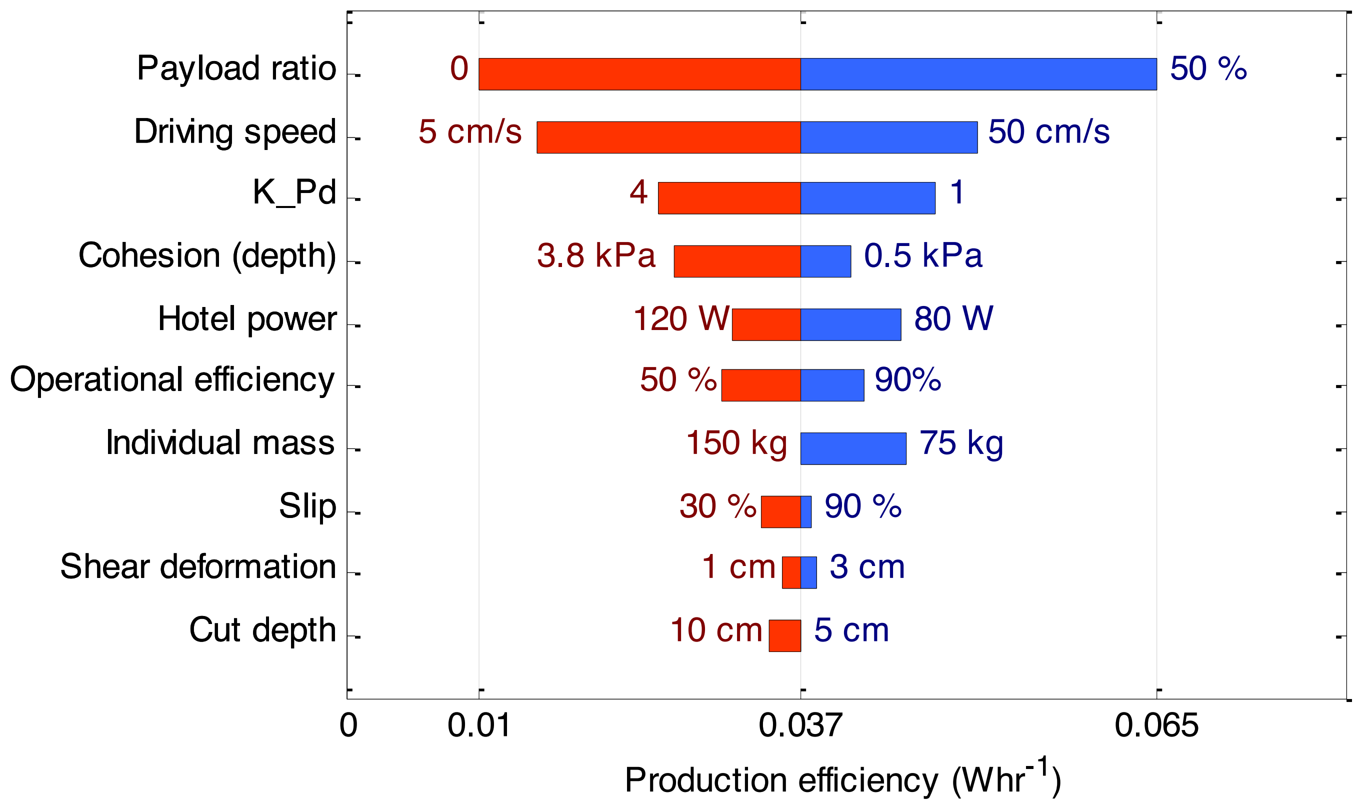


- REMOTE includes the Bekker-Wong traction model, which is the classical model in the field of terramechanics

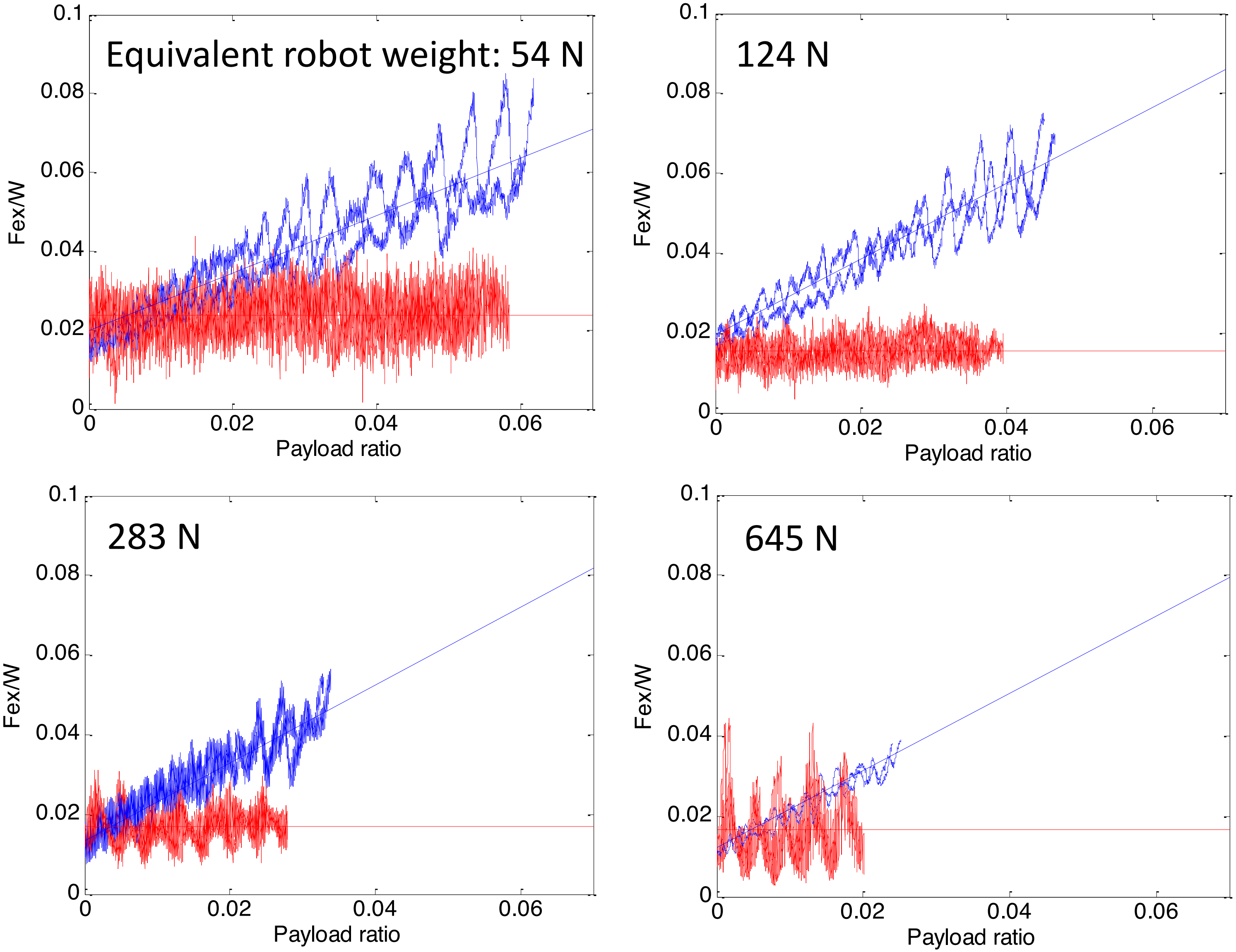


Sensitivity analysis of energy-efficiency

- Payload ratio and driving speed still predicted to govern efficiency, but other parameters such as drivetrain efficiency also emerge as important



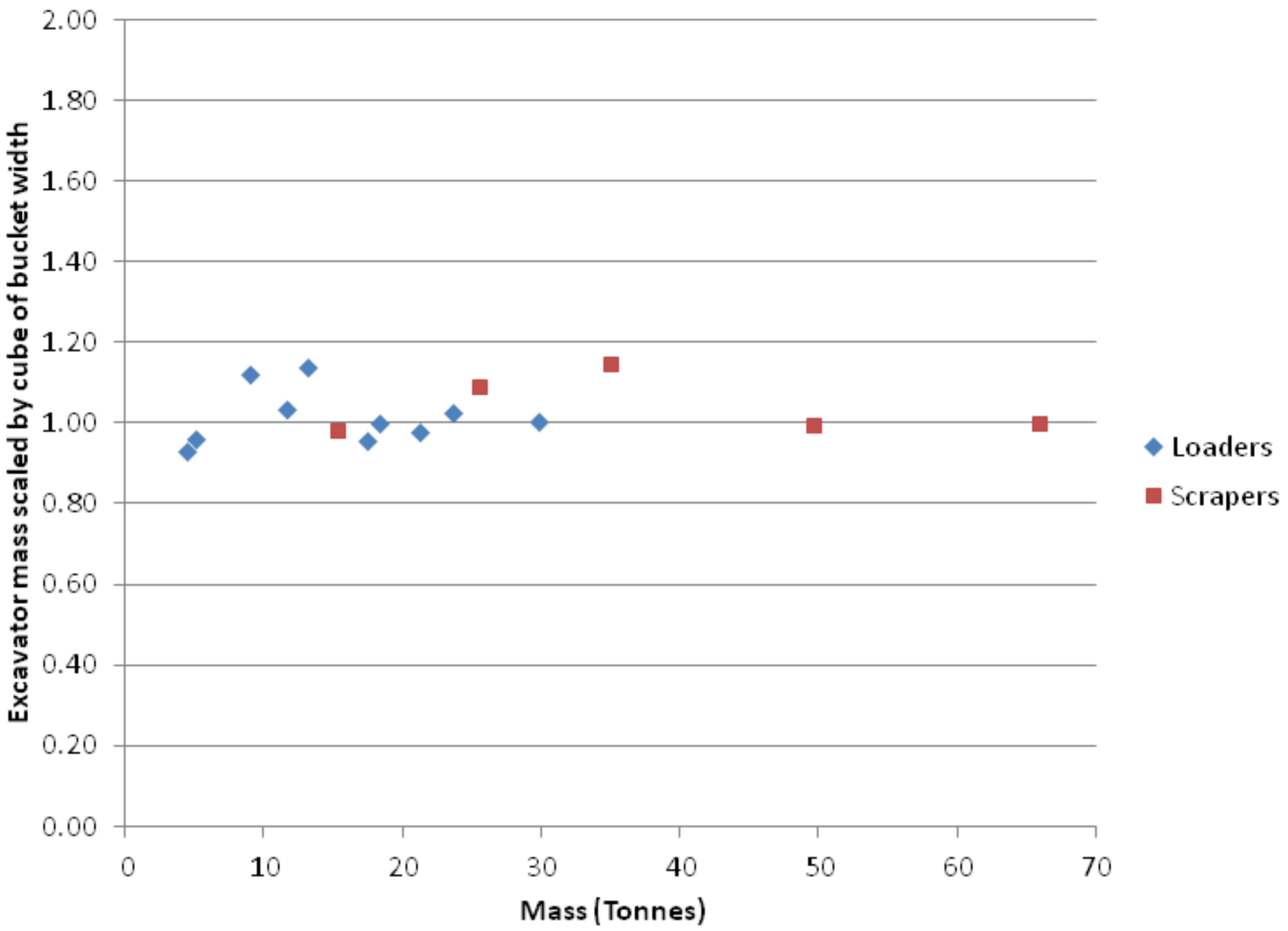
Excavation forces compare similarly as size scales



- Flat-plate
- Bucket-wheel

Flat-plate

Bucket-wheel


Excavator mass scaled by cube of bucket width
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0
10
20
30
40
50
60
70
Mass (Tonnes)
Loaders
Scrapers

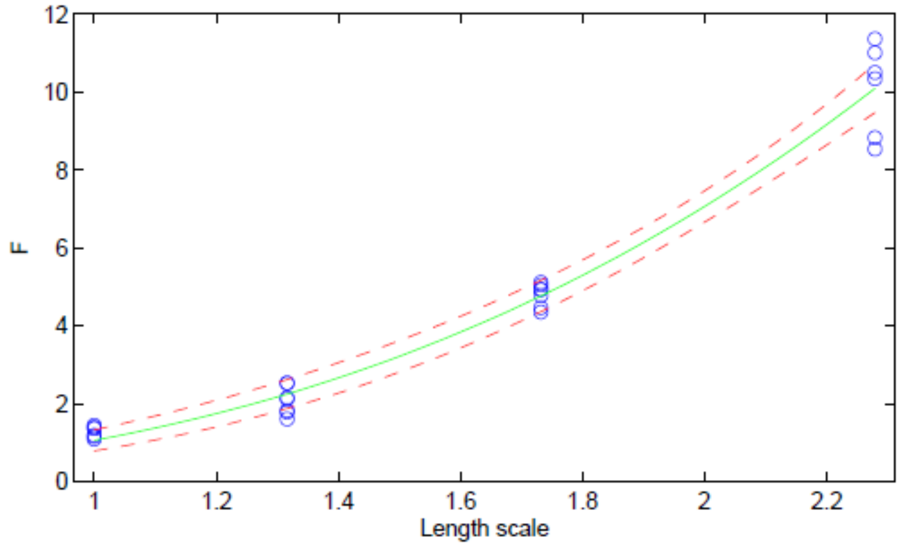


Figure 4.14: Scaling of mean bucket-wheel excavation resistance force. Best fit power law exponent = 2.73 (compared to a predicted value of approximately 3)

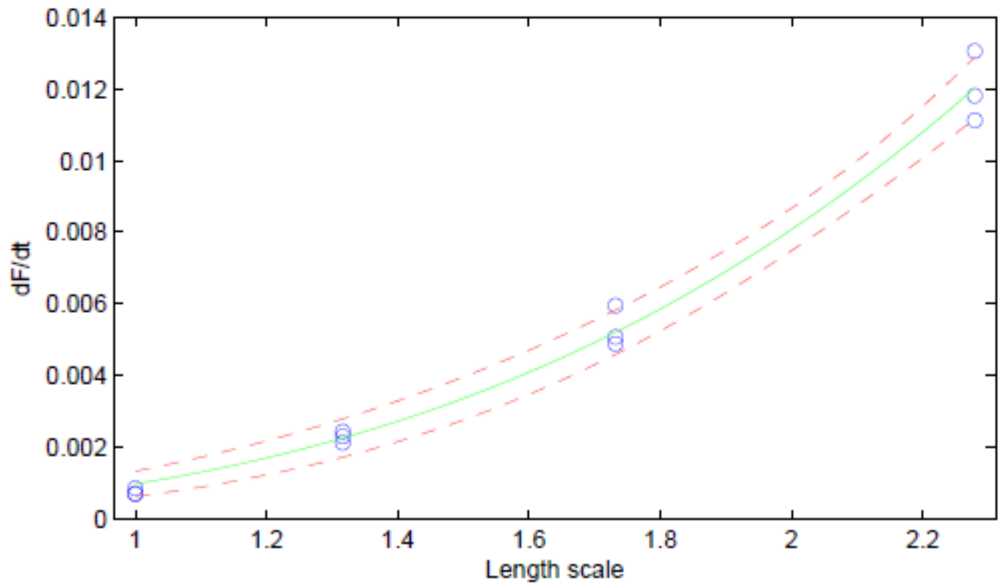
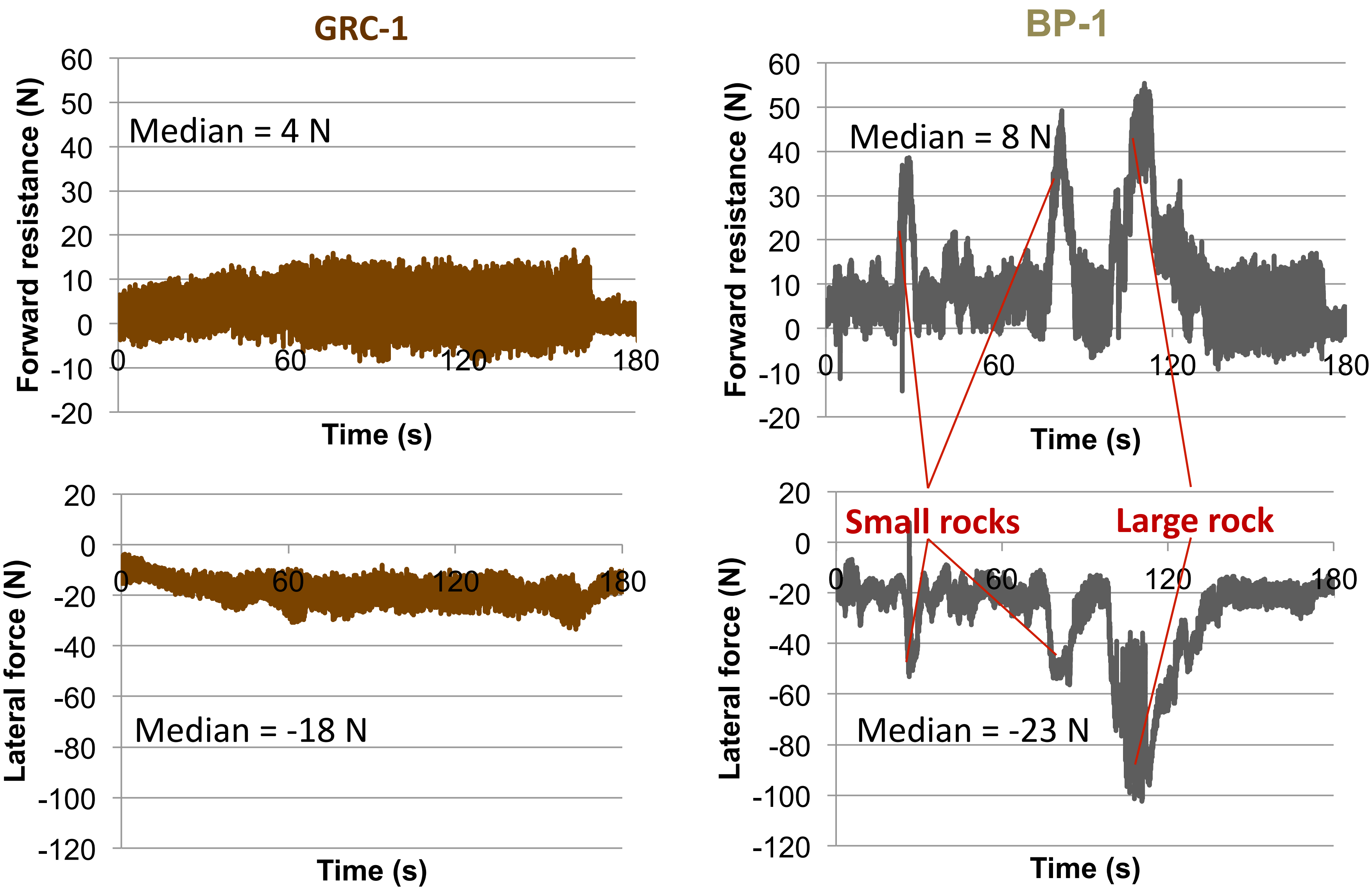


Figure 4.16: Scaling of the slope of flat-plate excavation resistance force. Best fit power law exponent = 3.05

Excavation forces in different simulants



6 cm deep cuts

- Depth, d(x), and surcharge, q(x), will be utilized for approximation

Balovnev model, for example:

$$
\begin{aligned}
F_H \;=\;& wd(1+\cot\beta\tan\delta)A_1\left[\frac{dg\gamma}{2}+c\cot\phi+gq+B*(d-l\sin\beta)\left(g\gamma\frac{1-\sin\phi}{1+\sin\phi}\right)\right] \\
&+we_b(1+tan\delta\cot\alpha_\beta)A_2\left[\frac{e_b g\gamma}{2}+c\cot\phi+gq+dg\gamma\,(frac1-\sin\phi 1+\sin\phi)\right] \\
&+2sdA_3\left[\frac{dg\gamma}{2}+c\cot\phi+gq+B*(d-l_s\sin\beta)\left(g\gamma\frac{1-\sin\phi}{1+\sin\phi}\right)\right] \\
&+4\tan\delta A_4 l_s d\left[\frac{dg\gamma}{2}+c\cot\phi+gq+B*(d-l_s\sin\beta)\left(g\gamma\frac{1-\sin\phi}{1+\sin\phi}\right)\right]
\end{aligned}
$$

REMOTE – End Effector subsystem

- Drawbar pull is equated to the excavation force, H_f, which is calculated based on the Viking excavation model:

$$H_{\text{friction}} = \gamma g w l^{1.5} \beta^{1.73} \sqrt{d} \left(\frac{d}{l \sin \beta} \right)^{0.77} \times \left\{ 1.05 \left(\frac{d}{w} \right)^{1.1} + 1.26 \frac{v^2}{gl} + 3.91 \right\}$$

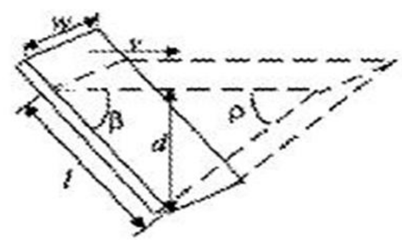
$$H_{\text{cohesion}} = \gamma g w l^{1.5} \beta^{1.15} \sqrt{d} \left(\frac{d}{l \sin \beta} \right)^{1.21} \times \left\{ \left(\frac{11.5c}{\gamma g d} \right)^{1.21} \left(\frac{2v}{3w} \right)^{0.121} \left(0.055 \left(\frac{d}{w} \right)^{0.78} + 0.065 \right) + 0.64 \frac{v^2}{gl} \right\},$$

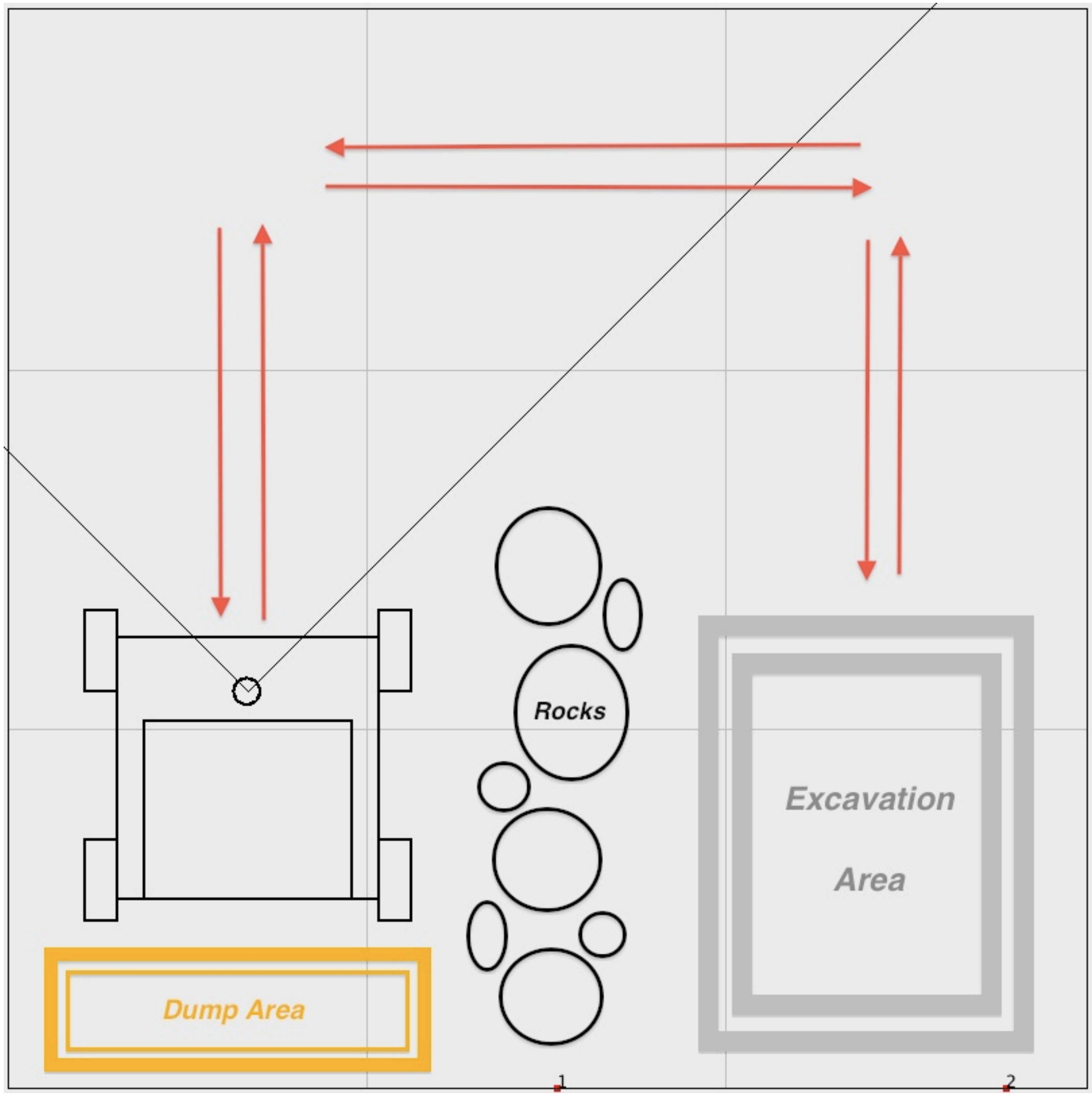
[Wilkinson 07]

…olve for loader blade

and blade length, l, all specified

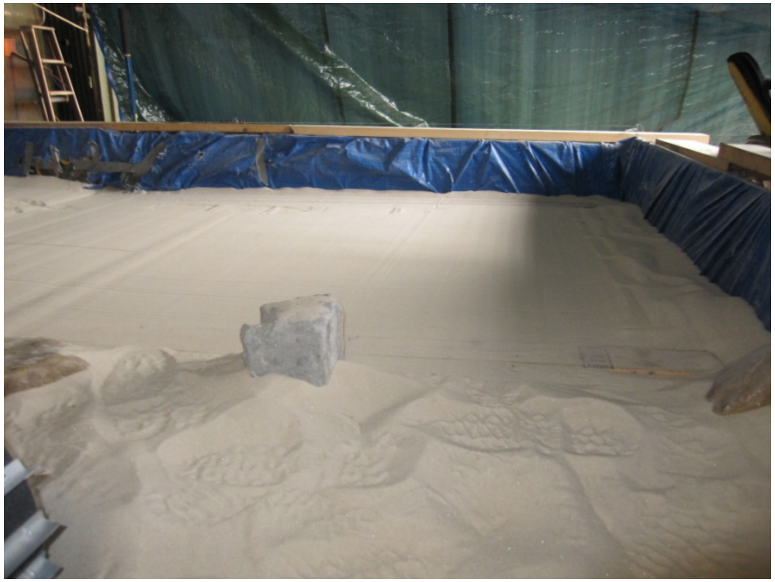
  - Blade width, w, left as dependent vari…




Rocks
Excavation
Area
Dump Area
1
2

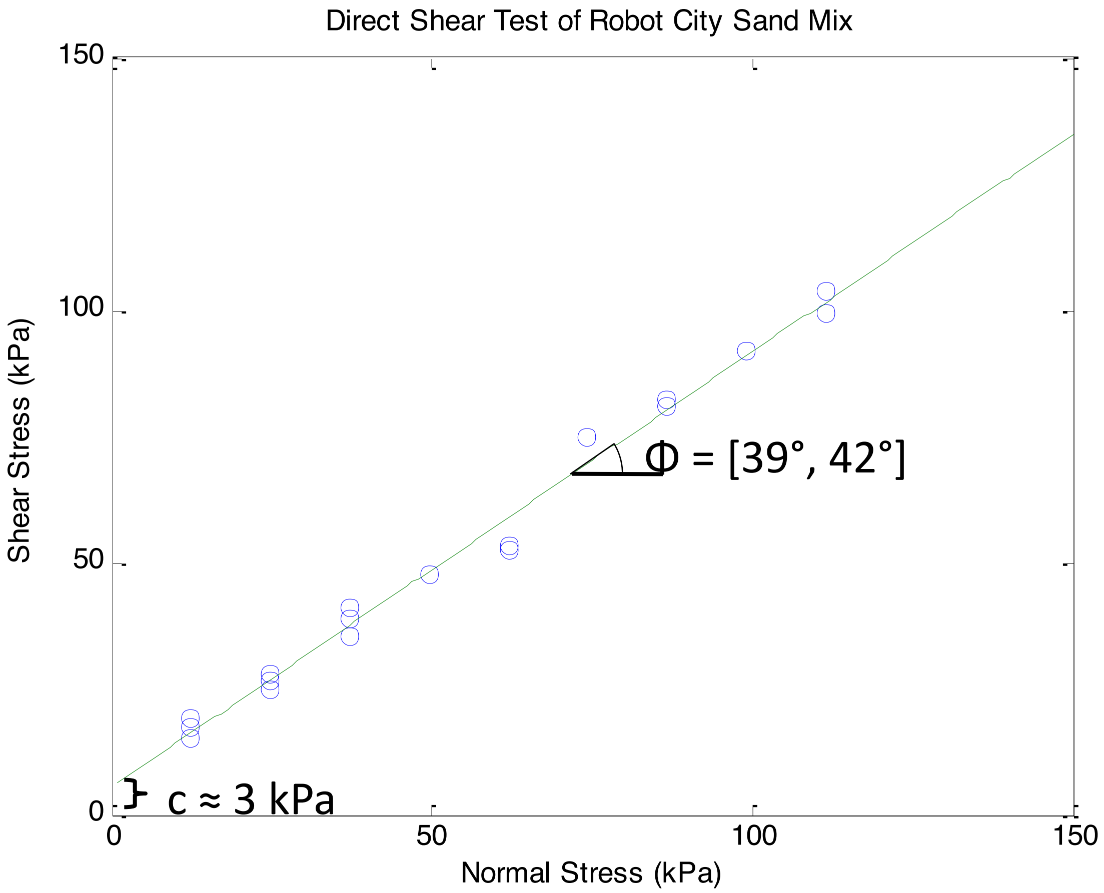
Controlling soil conditions I: Churn / loosen

Controlling soil conditions II: Compact & smooth

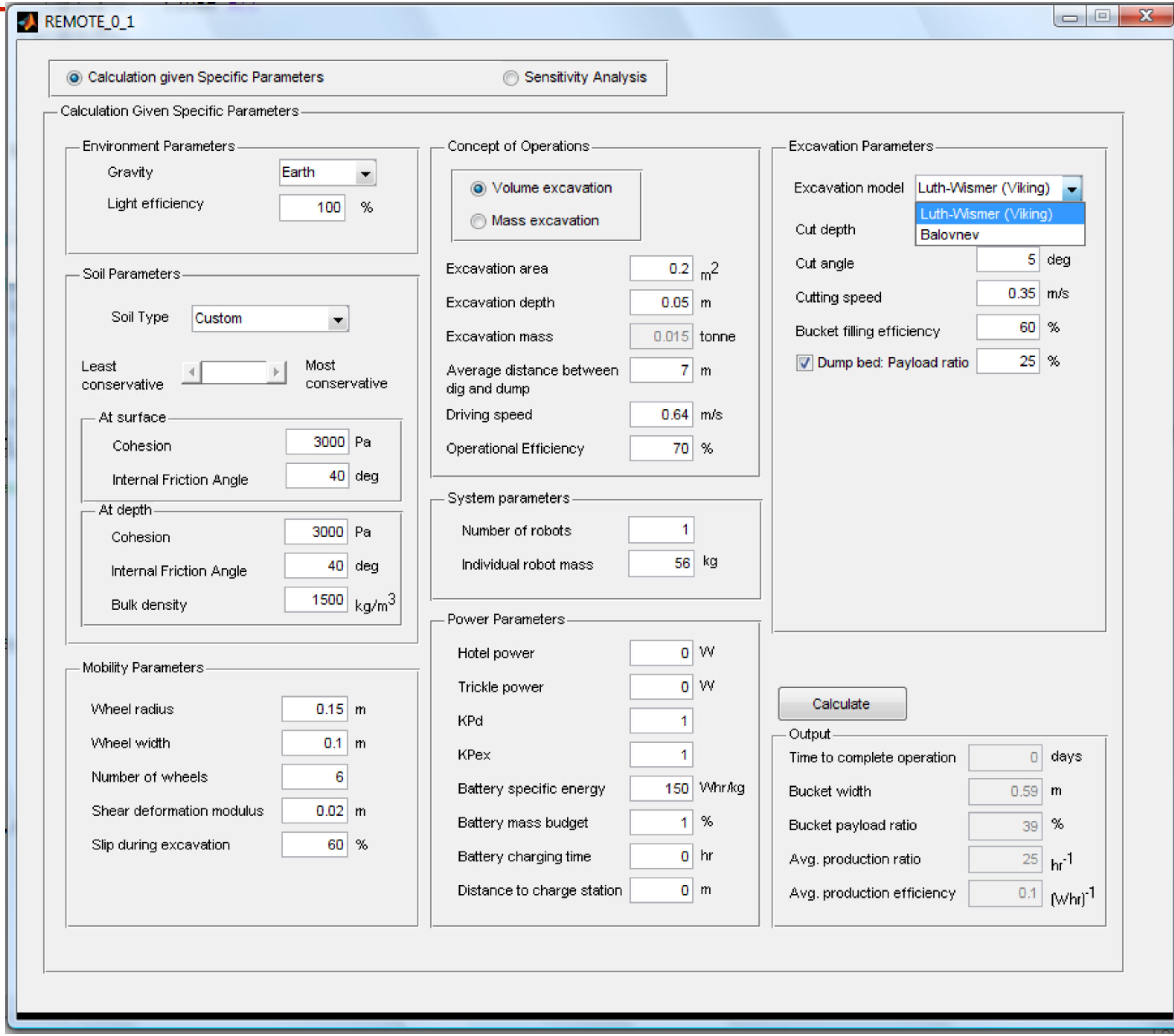


Validation experiments

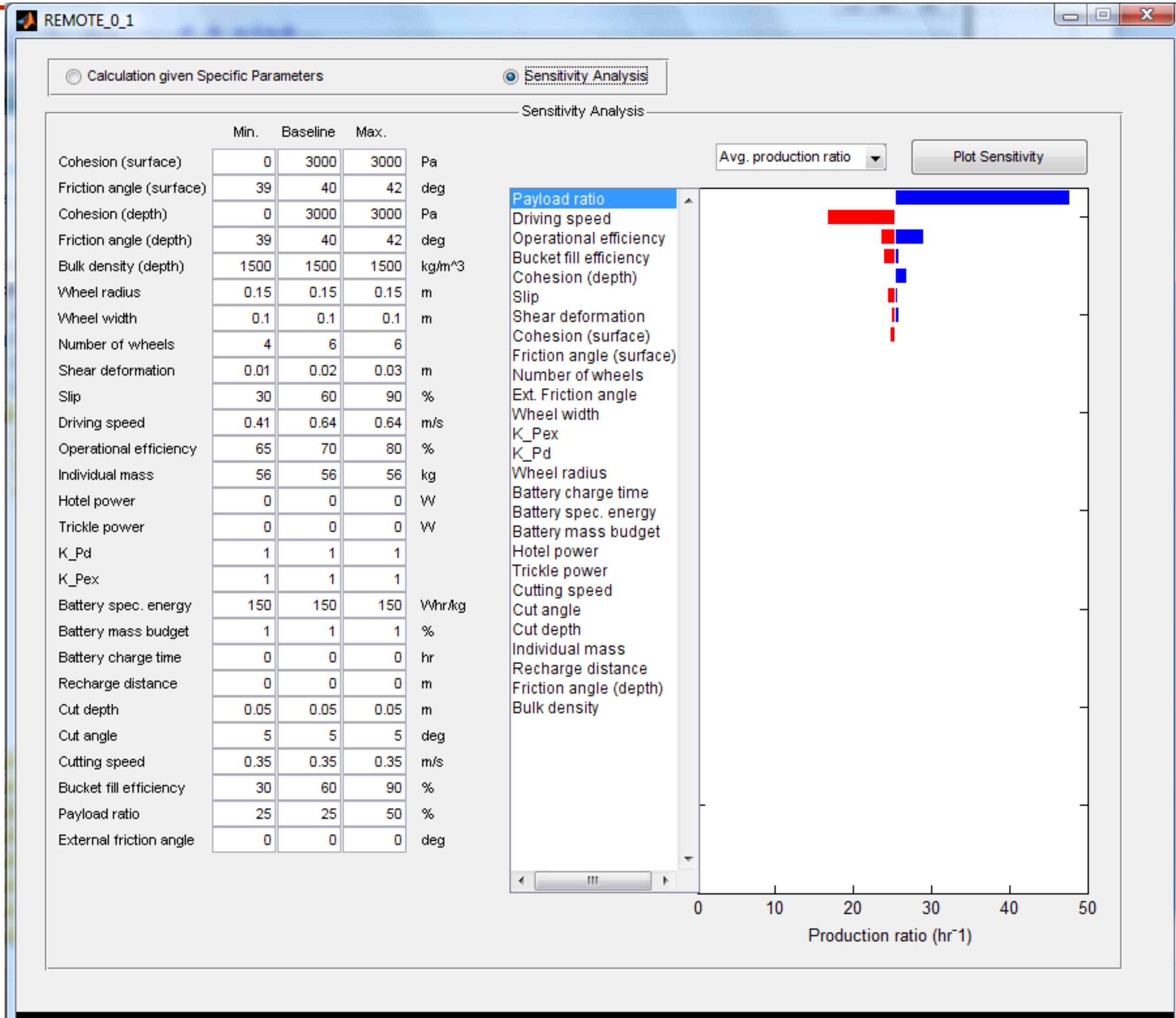
- As-measured sand properties (as well as other measured experimental conditions) are applied to simulations and results are compared to experiments



REMOTE graphical interface (specific calculations)



REMOTE graphical interface (sensitivity analysis)



Model	Gravity	Cohesion	Surcharge	Adhesion	Inertia
Reece	✓	✓	✓	✓	
Osman	✓	✓	✓	✓	
Gill	✓	✓			✓
Luth & Wismer	✓	$\sim^1$			$\sim^1$
Godwin	✓	✓	✓	✓	
Balovnev[2]	✓	✓	✓		
McKyes / Swick	✓	✓	✓	✓	✓
Qinsen	✓	✓	✓[3]	✓	
Willman	✓	✓			
Zeng	✓	✓	✓		$\sim^4$

Table 2.1: Models vary in which force terms they include, but gravity and cohesion are always considered. [1]In Luth & Wismer, cohesion and inertia terms are multiplied by gravity terms, rather than added to them. [2]Balovnev includes additional terms to account for sidewalls and a blunt cutting edge. [3]Qinsen models a curved bulldozer blade, and explicitly models surcharge due to soil accumulation. [4]Zeng treats acceleration directly, rather than inertia.