Configuring Innovative Regolith Moving Techniques for Lunar Outposts

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Lunar Outpost Preparation

• Regolith moving for site preparation would occur early in lunar outpost operations, and effectiveness impacts architectural choices.

• Regolith moving opportunities include site and road leveling, obstacle clearing, habitat and cable trenching, berm construction, surface stabilization, and radiation shielding.

[Image Courtesy of Mueller and King, STAIF 08]
Questions about Robotic Lunar Construction

Questions concerning robotic lunar construction answered by this program:

• How much could be constructed with excavation robots of mass less than 300 kg?

• What are key parameters that affect construction feasibility and completion time?

• Are there innovative ways to accomplish site preparation and surface stabilization using native lunar materials?

• What lunar data is still required to ensure robotic construction success?
Example Task: Berm Construction

- Blast erosion from multiple landings / takeoffs must be contained or suppressed by:
  - Berm construction
  - Surface stabilization

- Berm construction is a useful task to study because it comprises the elemental actions of digging, transporting, dumping, compacting, and shuttling for recharge
Berm Construction with Small Excavation Robots

- How much could be constructed with excavation robots of mass less than 300 kg?

Robots with mass of 300 kg or less are capable of constructing a protective berm at a lunar polar outpost in less than 6 months, if equipped with dump beds (bins for accumulating regolith from multiple excavation bucket loads).
Key Berm Construction Parameters

- What are key parameters that affect berm construction feasibility and completion time?

**Driving speed** and **Payload ratio** (ratio of regolith mass carried to empty system mass) are the two parameters that most affect task completion time for vehicles with dump beds.

**Regolith cohesion** is the most significant parameter that is outside the designer’s control.

- Cohesion refers to the component of regolith strength that is caused by mechanical interlocking of particles and is independent of interparticle friction.
Innovative Regolith Moving Techniques

- Are there innovative ways to accomplish site preparation and surface stabilization utilizing native lunar materials?

  Include a dump bed to achieve sufficient payload ratio

  Use vibration and downforce to compact regolith for strength

  Perform rock paving to stabilize surface using native lunar materials
Outpost Scouting Mission

- What lunar data is still required to ensure robotic construction success?

  Excavation resistance force of regolith has not been characterized in the lunar environment

  - Excavation resistance is a function of the full tool/soil interface (measured with a test bucket) and is more comprehensive than soil properties such as cohesion (derived from cone penetrometers, etc.)

Distribution and abundance of rocks at the lunar poles is unknown

  - Rock paving can only work if there are enough rocks within a feasible collection area
REMOTE: Regolith Excavation, MObility & Tooling Environment

- Conclusions derived from analysis of task simulations, modeled in REMOTE

- REMOTE characterizes performance of machines within site-level tasks such as berm building, trenching, and road building
  - Creates a comprehensive context for a task from the elemental actions of digging, transporting, and shuttling for recharge
Task Simulation: REMOTE

- Task completion time is calculated from durations of elemental actions, which are underpinned by analytic models of traction, excavation resistance force, etc.

- REMOTE has 2 implementations: ‘Bucket-Only’ and ‘Bucket with Dump Bed’
Berm Construction Simulation: Bucket-Only

- Small excavation robots with buckets as their only regolith carrying containers can complete a berm in 1170 days (over 3 years)

- Some of the simulated parameters and values that lead to this result:
  - 2 excavation robots, each of mass 150 kg
  - 1,200,000 kg of regolith to transport
  - Transport shuttle velocity of 15 cm/s
  - 4% Payload ratio output by simulation
Berm Construction Simulation: Dump Bed

- Small excavation robots with dump beds for accumulating regolith can complete a berm in 152 days (5 months)

- Parameters and values that lead to this result are the same as for the Bucket-only case, except for Payload ratio:
  - 2 excavation robots, each of mass 150 kg
  - 1,200,000 kg of regolith to transport
  - Transport shuttle velocity of 15 cm/s

Robots with mass of 300 kg or less could construct a protective berm (50 m diameter semi-circle, 2.6 m height) at a lunar polar outpost in less than 6 months, if equipped with dump beds
Driving speed and Payload ratio are the two parameters that most affect task completion time for vehicles with dump beds.
Transport Shuttle Velocity

- Berm construction with small excavation robots is mostly driving
  - Approximately ¾ of total required time is transport shuttle time
- Without onboard astronaut drivers, lunar vehicle speeds will be limited by the capabilities of teleoperation and supervised autonomous technologies.

An extraterrestrial vehicle cannot be expected to drive this fast…
Payload Ratio

- Payload ratio directly affects the number of transport shuttle trips required between dig and dump.

- As berm construction is mostly driving, completion time is sensitive to driving speed and number of driving trips.

- Without a dump bed, payload ratio depends on excavation parameters that may vary significantly and some of which are outside the designer’s control.
Sensitivity Analysis of Bucket-only Implementation

![Graph showing the impact of various parameters on the days to complete berm-building task.](image)
Innovative Regolith Moving: Dump Bed

• A dump bed...
  ➢ Reduces the number of transport shuttle trips required, making 6 month berm construction feasible
  ➢ Makes payload ratio a design parameter, instead of being dependent on the excavation reaction forces
  ➢ Reduces the effect of regolith cohesion on task completion time

• Dump beds do, however, require additional mass and complexity compared to a bucket-only design
Innovative Construction: Compaction

• Compacting (packing) regolith increases density and interparticle contact, improving strength and bearing capacity
  ➢ A compacted berm can be driven on by small excavation robots

• Compaction can reduce the quantity of regolith required

• Vibration and downforce are effective means to compact

• Loader/Compactor Concept: Combine a flat bottomed excavation bucket with a vibratory actuator
Innovative Surface Stabilization: Rock-Paving

- Rock-paving could suppress surface dust during takeoff / landing without sintering, chemical binding, or geotextiles.

- This technique is used for constructing stream-crossings, spillway linings, and road-edges on Earth, and may have utility on the Moon.

- Rocks resist erosion more than gravel; gravel resists erosion more than sand; and sand resists erosion more than silt.
Rock-Paving Rake

- A rock-paving rake raises buried rocks to the surface:

- Rock rakes were used for sample collection during Apollo missions.
Rock Rakes, Windrowers and Rock-Pickers

- Rock rakes, windrowers, and rock-pickers are used to collect, separate, or move rocks in agricultural applications.

- The rock rake concept, along with windrowers and rock-pickers, could be developed into machines for lunar surface stabilization.
Use of Native Lunar Rocks

- Feasibility of rock paving depends on:
  - Size of rock required to resist blast erosion: 10-15 cm diameter particles are thought to be sufficient
  - Abundance and distribution of rocks at lunar poles
  - Rake depth (depth from which rocks are collected)

- Sample cases based on rock distribution data from Surveyor missions:

<table>
<thead>
<tr>
<th>Case</th>
<th>Rock size</th>
<th>Rake Depth</th>
<th>Drive Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1 – 2 cm</td>
<td>Surface</td>
<td>1400 km</td>
</tr>
<tr>
<td>B</td>
<td>1 – 2 cm</td>
<td>15 cm</td>
<td>180 km</td>
</tr>
<tr>
<td>C</td>
<td>10 – 15 cm</td>
<td>Surface</td>
<td>11,000 km</td>
</tr>
</tbody>
</table>

An outpost scouting mission could determine the distribution and abundance of rocks.
Gabion Boxes

- If adequately sized rocks are not abundant at potential lunar outpost sites, smaller rocks could still provide stabilization if contained within gabion boxes (cages filled with rocks).

- Combining the concepts of rock paving with gabion-like geotextiles could decrease the mass of geotextile required to stabilize a surface.
  - Containing larger rocks (collected and paved) requires a sparser mesh than containing average regolith particles.
Excavation Resistance Force

- Excavation resistance is the force required to pass a tool (bucket) through regolith

- Excavation resistance encompasses cohesion (which is one of the most significant parameters in all excavation resistance force models, and is significant in task completion time)

> Excavation resistance can be measured with a test bucket analogous to one designed for an eventual excavation robot

An outpost scouting mission could characterize excavation resistance force for lunar regolith
Current Knowledge of Lunar Excavation Resistance

- Excavation resistance is correlated with cohesion, which is known for lunar regolith, but only for equatorial, intercrater areas (even then, great variability is observed with locale and depth)
  
  ➢ Example: At 30 cm depth, cohesion value could be anywhere between 0.74 kPa and 3.8 kPa

<table>
<thead>
<tr>
<th>Depth Range (cm)</th>
<th>Cohesion, c (kPa)</th>
<th>Friction Angle, ( \phi ) (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Range</td>
</tr>
<tr>
<td>0 - 15</td>
<td>0.52</td>
<td>0.44 - 0.62</td>
</tr>
<tr>
<td>0 - 30</td>
<td>0.90</td>
<td>0.74 - 1.1</td>
</tr>
<tr>
<td>30 - 60</td>
<td>3.0</td>
<td>2.4 - 3.8</td>
</tr>
<tr>
<td>0 - 60</td>
<td>1.6</td>
<td>1.3 - 1.9</td>
</tr>
</tbody>
</table>

[Lunar Sourcebook]
Summary

- Robots with mass of 300 kg or less could construct a berm in less than 6 months, if equipped with dump beds

  - REMOTE simulates task-level operations, such as berm construction, by combining analytical models of elemental actions such as excavation and mobility

- Driving speed and payload ratio are the two parameters that most affect task completion time for vehicles with dump beds

  - REMOTE identifies key parameters to construction task completion time by means of sensitivity analysis
Summary

• Innovative regolith moving techniques include:
  ➢ Using vehicles equipped with dump beds
  ➢ Compacting with a dual loader/compactor
  ➢ Stabilizing a landing pad by rock paving

• Effectiveness of construction and rock paving depend on further lunar data:
  ➢ Measuring excavation resistance force directly
  ➢ Determining distribution of lunar rocks
Opportunities for Follow-on Work: Moon Digger

- Analyze, prototype, and evaluate:
  - Technical implementations for bucket and dump bed designs
  - Teleoperation and automation of regolith moving with time delay
Opportunities for Follow-on Work: Rock Paver

- Construct, prototype, and experiment:
  - Technical solution to rock collection and dissemination for paving/surface stabilization (and clearing zones)
  - Resistance force evaluation to determine suitable raking depth
Questions?

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Images Courtesy of Mark Maxwell:
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www.aeromancy.us
Backups
Examples of dump beds

- Overshot loader:

- Scraper:

- Hauler teamed with excavator or loader:
REMOTE (Regolith Excavation, MObilité, & Tooling Environment)

- Modeling environment that enables task-level performance analysis
- Can be implemented for various mobility, tooling and work-function designs
REMOTE - Mobility subsystem

- Maximum tractive force for a wheel loader was estimated using Mohr-Coulomb relation for maximum soil shear strength:

\[ T_{\text{max}} = cA_G + mg \tan \phi \]

where \( c \) is cohesion, \( g \) is gravitational acceleration (1.62 m/s\(^2\)), \( \phi \) is angle of internal friction, \( A_G \) is the ground contact area, and \( m \) is the system mass
REMOTE - Mobility subsystem

• Drawbar pull is the net tractive force available for work after accounting for losses such as slip and rolling resistance

• Slip and rolling resistance are not modeled directly; losses are taken into account by an estimated aggregate scaling factor: “Fraction of traction available for excavation”

\[ DP = K_{HfT} T^{max} \]

where \( DP \) is drawbar pull, \( T^{max} \) is maximum tractive force, and \( K_{HfT} \) is fraction of traction available for excavation
REMOTE – End Effector subsystem

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

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

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

- Horizontal excavation force is used to solve for loader blade geometry
  - Digging depth, $d$, digging angle, $\beta$, and blade length, $l$, all specified
  - Blade width, $w$, left as dependent variable
REMOTE - End Effector subsystem

• Bucket volume estimated by an equilateral triangular prism with edges of length $l$:

$$V_b = \frac{1}{2}wl^2 \sin(60^\circ)$$

• Volume of regolith collected with each bucket pass is some fraction of $V_b$ (multiply by bucket filling efficiency)
REMOTE - Power modeling

- Number of required charges during task completion calculated based on energy spent executing task, and battery energy storage

- 10% of vehicle mass budget set aside for batteries

- Lithium Ion batteries with 150 W-hr/kg energy density

- 2 hr charging time
  - If the power available for recharge at the charging station is capped, larger vehicles will require more time than smaller ones to reach full charge, thus adversely affecting the computed advantage of a 300 kg machine

- Hotel power of 80 W assumed for electronics and other systems, and added to driving and excavating power
REMOTE - Power modeling

Power consumed while driving is estimated by:

\[ P_{\text{driving}} = K_{pd} \cdot m g \cdot v \]

Power consumed while excavating is estimated by:

\[ P_{\text{excavating}} = K_{pex} \cdot H F \cdot v_{ex} \]
Operational duty cycle

• Illumination efficiency of 70% is assumed for lunar pole

• Of the illuminated time, only a fraction is assumed to be spent operating (operational efficiency)
  • An efficiency multiplier is applied to account for operation planning, reduced situational awareness, etc.
## Legend - Variable Parameters Examined

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Expected value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lunar Environmental Parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lunar gravity</td>
<td>g</td>
<td>1.62 m/s²</td>
<td>LSB</td>
</tr>
<tr>
<td>Minimum lunar regolith angle of internal friction</td>
<td>(\varphi_{\text{min}})</td>
<td>35°</td>
<td>Wilkinson07</td>
</tr>
<tr>
<td>Minimum lunar regolith cohesion</td>
<td>(c_{\text{min}})</td>
<td>170 N/m²</td>
<td>Wilkinson07</td>
</tr>
<tr>
<td>Maximum lunar regolith cohesion</td>
<td>(c_{\text{max}})</td>
<td>1100 N/m²</td>
<td>LSB, p. 510</td>
</tr>
<tr>
<td>Maximum lunar regolith bulk density</td>
<td>(\gamma_{b,\text{max}})</td>
<td>1920 kg/m³</td>
<td>LSB, p. 494</td>
</tr>
<tr>
<td>Bulk density of lunar regolith compacted to 75% relative density</td>
<td>(\rho_{\text{berm}})</td>
<td>1765 kg/m³</td>
<td>Calculated value, based on LSB</td>
</tr>
<tr>
<td>Minimum bulk density of excavated lunar regolith</td>
<td>(\rho_{\text{ex}})</td>
<td>1450 kg/m³</td>
<td>LSB, p. 484</td>
</tr>
</tbody>
</table>
## Concept of Operations Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berm diameter</td>
<td>D</td>
<td>50 m</td>
<td>Mueller08b</td>
</tr>
<tr>
<td>Plume ejecta angle</td>
<td>(\alpha)</td>
<td>3°</td>
<td>Mueller08b, Lane08</td>
</tr>
<tr>
<td>Berm height</td>
<td>H</td>
<td>2.6 m</td>
<td>Calculated value</td>
</tr>
<tr>
<td>Berm top width</td>
<td>(W_t)</td>
<td>0.6 m</td>
<td></td>
</tr>
<tr>
<td>Berm slope angle</td>
<td>(\theta)</td>
<td>50°</td>
<td></td>
</tr>
<tr>
<td>Berm arc angle at center</td>
<td>(\psi)</td>
<td>180°</td>
<td>Mueller08b</td>
</tr>
<tr>
<td>Total volume to excavate</td>
<td>(V_{ex})</td>
<td>710 m³</td>
<td>Calculated value</td>
</tr>
<tr>
<td>Maximum required excavation depth</td>
<td>(d_{ex})</td>
<td>36 cm</td>
<td>Calculated value</td>
</tr>
<tr>
<td>Average transport shuttle distance</td>
<td>(x_t)</td>
<td>25 m</td>
<td>Calculated value</td>
</tr>
<tr>
<td>Shuttle recharge distance</td>
<td>(x_r)</td>
<td>500 m</td>
<td></td>
</tr>
<tr>
<td>Transport shuttle velocity</td>
<td>(v_t)</td>
<td>15 cm/s</td>
<td></td>
</tr>
<tr>
<td>Recharge shuttle velocity</td>
<td>(v_r)</td>
<td>15 cm/s</td>
<td></td>
</tr>
<tr>
<td><strong>System Parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------------------------------------------------</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Number of robots</td>
<td>$N$</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Individual vehicle mass</td>
<td>$m$</td>
<td>150 kg</td>
<td></td>
</tr>
<tr>
<td>Ground contact area</td>
<td>$A_G$</td>
<td>0.3 m²</td>
<td></td>
</tr>
<tr>
<td>Excavation depth</td>
<td>$d$</td>
<td>5 cm</td>
<td></td>
</tr>
<tr>
<td>Excavation rake angle</td>
<td>$\beta$</td>
<td>20°</td>
<td></td>
</tr>
<tr>
<td>Bucket length</td>
<td>$L$</td>
<td>14 cm Calculated value</td>
<td></td>
</tr>
<tr>
<td>Bucket width</td>
<td>$w$</td>
<td>88 cm Calculated value</td>
<td></td>
</tr>
<tr>
<td>Bucket volume</td>
<td>$V_b$</td>
<td>0.0072 m³ Calculated value</td>
<td></td>
</tr>
<tr>
<td>Trickle power</td>
<td>$P_{Trickl}$</td>
<td>0 W</td>
<td></td>
</tr>
<tr>
<td>Hotel power</td>
<td>$P_{Hotel}$</td>
<td>80 W</td>
<td></td>
</tr>
<tr>
<td>Fraction of mass budget for batteries</td>
<td>$m_{%batt}$</td>
<td>10 %</td>
<td></td>
</tr>
<tr>
<td>Battery energy density</td>
<td>$SE$</td>
<td>150 W·hr/kg LSMPR</td>
<td></td>
</tr>
<tr>
<td>Battery charging time</td>
<td>$t_{batt}$</td>
<td>2 hr</td>
<td></td>
</tr>
</tbody>
</table>
# Legend - Variable Parameters Examined

## Efficiency Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction of traction available for excavation</td>
<td>$K_{HFT}$</td>
<td>60 %</td>
</tr>
<tr>
<td>Bucket filling efficiency</td>
<td>$\eta_V$</td>
<td>50 %</td>
</tr>
<tr>
<td>Driving power coefficient</td>
<td>$K_{Pd}$</td>
<td>2</td>
</tr>
<tr>
<td>Excavation power coefficient</td>
<td>$K_{Pex}$</td>
<td>2</td>
</tr>
<tr>
<td>Light availability percentage</td>
<td>$\eta_{light}$</td>
<td>70 %</td>
</tr>
<tr>
<td>Operational efficiency</td>
<td>$\eta_{Op}$</td>
<td>60 %</td>
</tr>
</tbody>
</table>
REMOTE uses the Viking excavation model

- Viking is simple and conservative
- Viking model is more conservative than 2D Balovnev model
- The models could serve as upper and lower bounds for excavation force
- There are a number of excavation models, of which the Viking and Balovnev models are common for use in designing for planetary surfaces
## Comparison of excavation models

<table>
<thead>
<tr>
<th>Model</th>
<th>Osman</th>
<th>Gill &amp; Vanden</th>
<th>Swick &amp; Perump-ral</th>
<th>McKyes</th>
<th>Viking</th>
<th>Balovn-ev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2 or 3</td>
</tr>
<tr>
<td>Geo.</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>4 (3)</td>
<td>8</td>
</tr>
<tr>
<td>Terrain</td>
<td>4</td>
<td>5</td>
<td>7</td>
<td>7</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Grav.</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Speed</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Etc.</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>17</td>
<td>11</td>
<td>12</td>
<td>12</td>
<td>8 (7)</td>
<td>15</td>
</tr>
<tr>
<td>Problem</td>
<td>Need iteration</td>
<td>Math. singularity</td>
<td>-</td>
<td>Math. singularity</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Digging depth for given force (~240N)</td>
<td>-</td>
<td>&lt;0.05 (m)</td>
<td>0.15 (m)</td>
<td>0.15 (m)</td>
<td>0.062 (m)</td>
<td>0.14 (m)</td>
</tr>
</tbody>
</table>
Baseline parameters for model comparisons

Parameters

<table>
<thead>
<tr>
<th>CONSTANTS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil specific mass</td>
<td>gamma</td>
</tr>
<tr>
<td>Moon gravity</td>
<td>g_M</td>
</tr>
<tr>
<td>Cohesion</td>
<td>c</td>
</tr>
<tr>
<td>Total width</td>
<td>w</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VARIABLES</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool length</td>
<td>l</td>
</tr>
<tr>
<td>Tool depth</td>
<td>d</td>
</tr>
<tr>
<td>Rake angle</td>
<td>beta</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Tool speed</td>
<td>v</td>
</tr>
</tbody>
</table>
Excavation models

![Graph showing the relationship between horizontal force (kN) and cohesion (N/m²) with two lines: one labeled L - M / V and another labeled Balovnev.](image-url)
Excavation models

![Graph showing the relationship between soil density and horizontal force](image)

- **L - M / V**
- **Balovnev**
Excavation models

- Excavation force is independent of tool velocity in the Balovnev model
Excavation models

![Graph showing horizontal force (kN) vs. accel. gravity (m/s²)]

- L - M / V
- Balovnev
Excavation models
Excavation models

![Diagram showing horizontal force vs. tool angle for different models.]
Wheel loader production ratios by weight and task

- A machine’s production ratio is the weight it can dig and dump in an hour relative to its own weight.
Berm building task incorporating different machines

- 300 kg machines converted a higher percentage of total task energy into berm-building work

- 100 kg machines spent a larger proportion of their task-completion time charging batteries

- Some of the key assumptions that lead to these factors:
  - The hotel power (baseline during idling) stays constant with changing mass (for the class of 100 kg to 300 kg machines), and is a large proportion of their total task power
  - The proportion of the mass budget allocated to batteries stays constant with changing mass
  - Significant time is required to charge batteries
  - Size does not significantly influence the operating velocity
Terrestrial equipment

- Production rates for terrestrial excavators increase with size of machine
Terrestrial equipment

- Scaling production by vehicle weight shows that advantages of larger vehicles may not carry over on a pound-for-pound basis.

![Graph showing scaling of excavator production by vehicle weight](image)
Terrestrial equipment

- Scaling forces by vehicle mass shows that highest drawbar pull is in the low- to mid-mass range
Terrestrial equipment

Payload ratios of terrestrial loaders

Scaling of terrestrial loader lift capacity with size
Regolith compaction

Compacted regolith can be piled in steeper berms:
Regolith compaction

Uncompacted regolith (1380 kg/m$^3$):

- 1.5 m high berm will pile at 59°, requires 2,490 kg/m
- 3 m high berm will pile at 46°, requires 13,240 kg/m

Compacted regolith (1650 kg/m$^3$):

- 1.5 m high berm will pile at 90°, requires 740 kg/m
- 3 m high berm will pile at 65°, requires 8,410 kg/m

Such results may merit investigating means of compaction:

- Vibratory compactors, rollers, block compactors (sandcastle buckets)