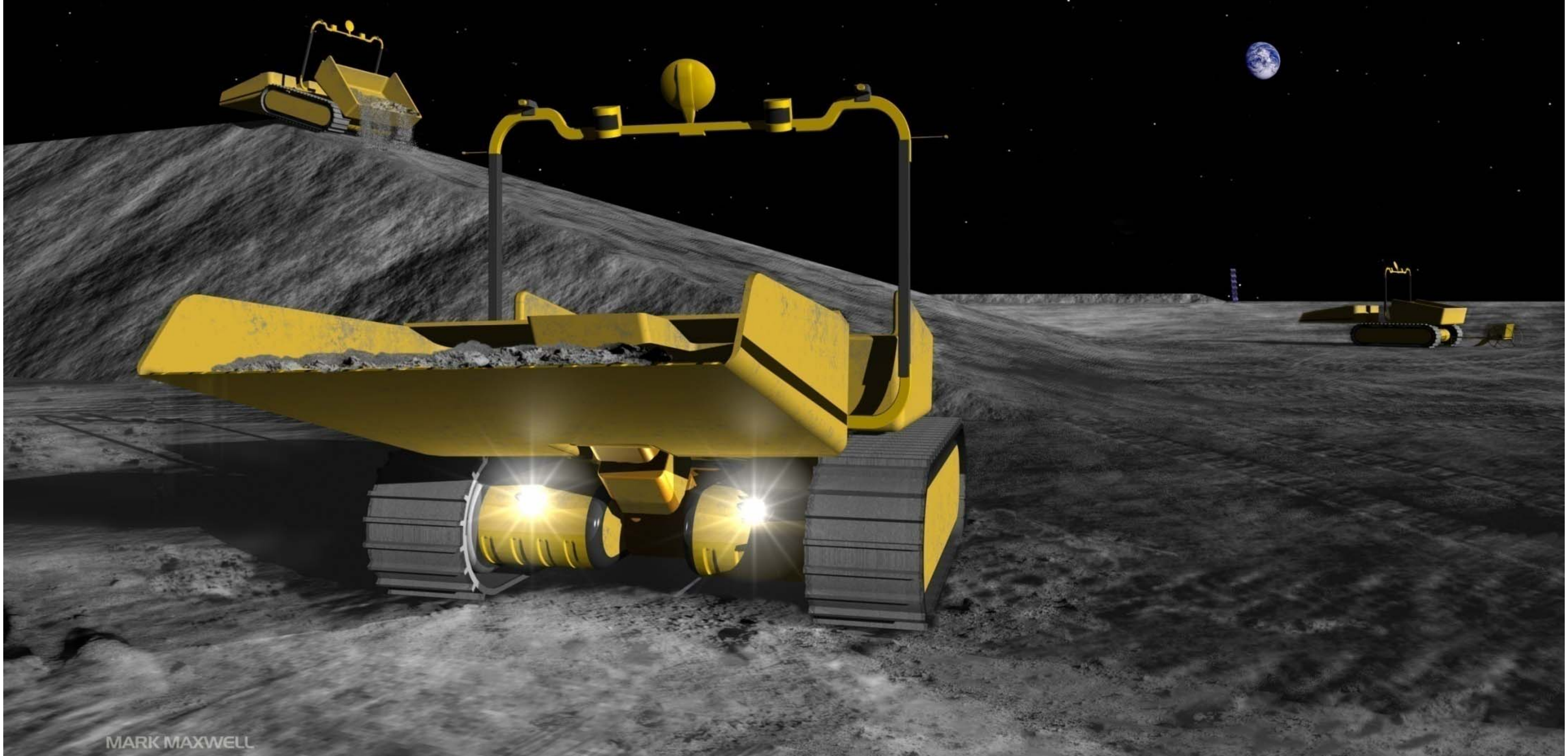
Configuring Innovative Regolith Moving Techniques for Lunar Outposts



U.S. Chamber of Commerce
Programmatic Workshop on
NASA Lunar Surface Systems Concepts

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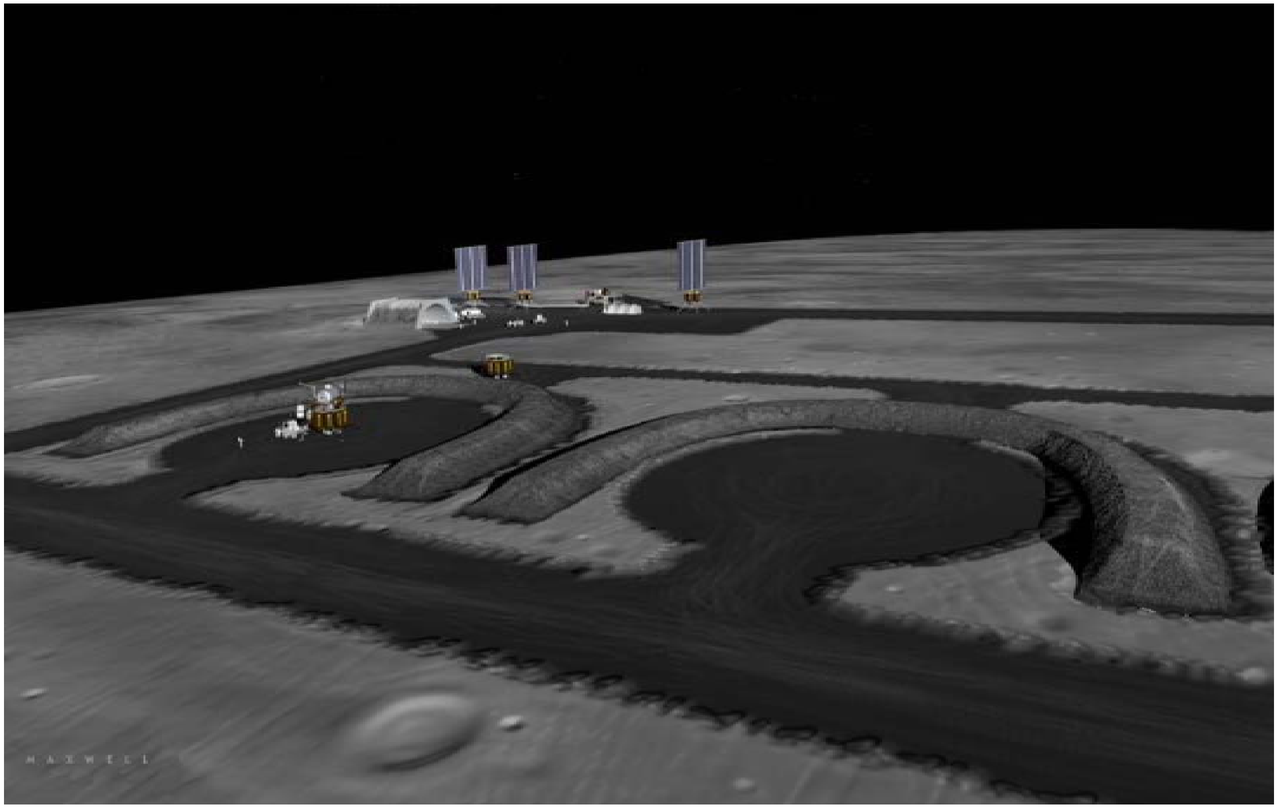
ASTROBOTIC
Technology, Inc.

Lunar Outpost Preparation

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



[Image Courtesy of Mueller and King, STAIF 08]

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

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?**

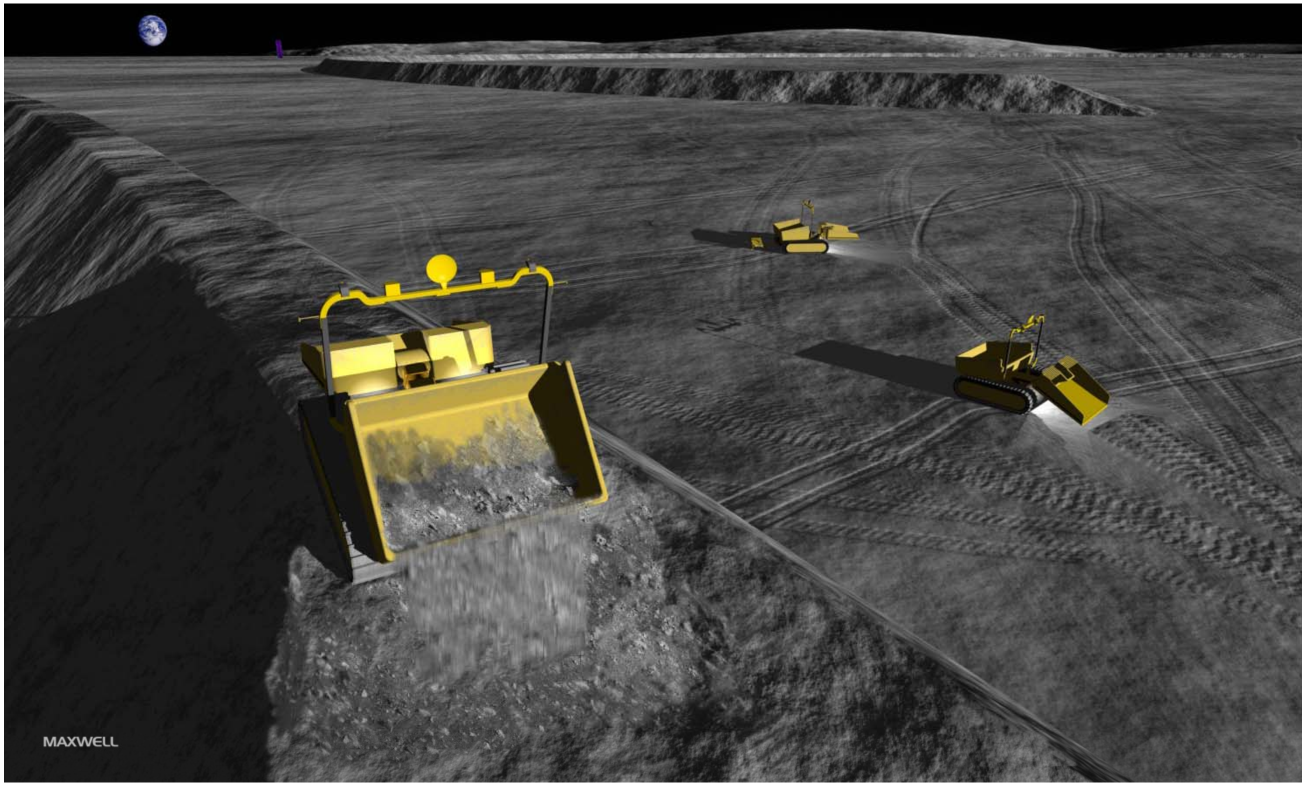
Example Task: Berm Construction

- 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?**

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

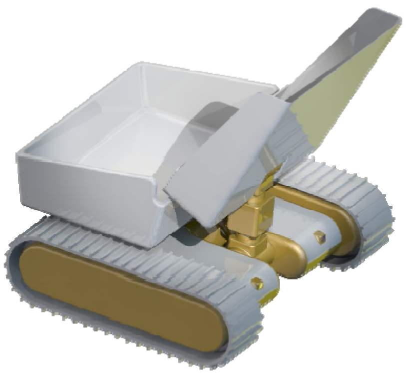
<u>Regolith cohesion</u> is the most significant parameter that is outside the designer's control

- **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

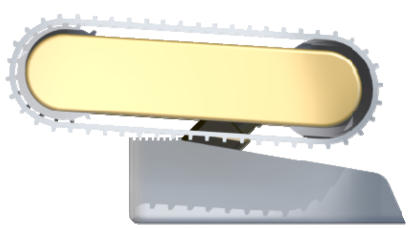
- **Are there innovative ways to accomplish site preparation and surface stabilization utilizing native lunar materials?**

Include a dump bed to achieve sufficient payload ratio



Perform rock paving to stabilize surface using native lunar materials

Use vibration and downforce to compact regolith for strength



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.)

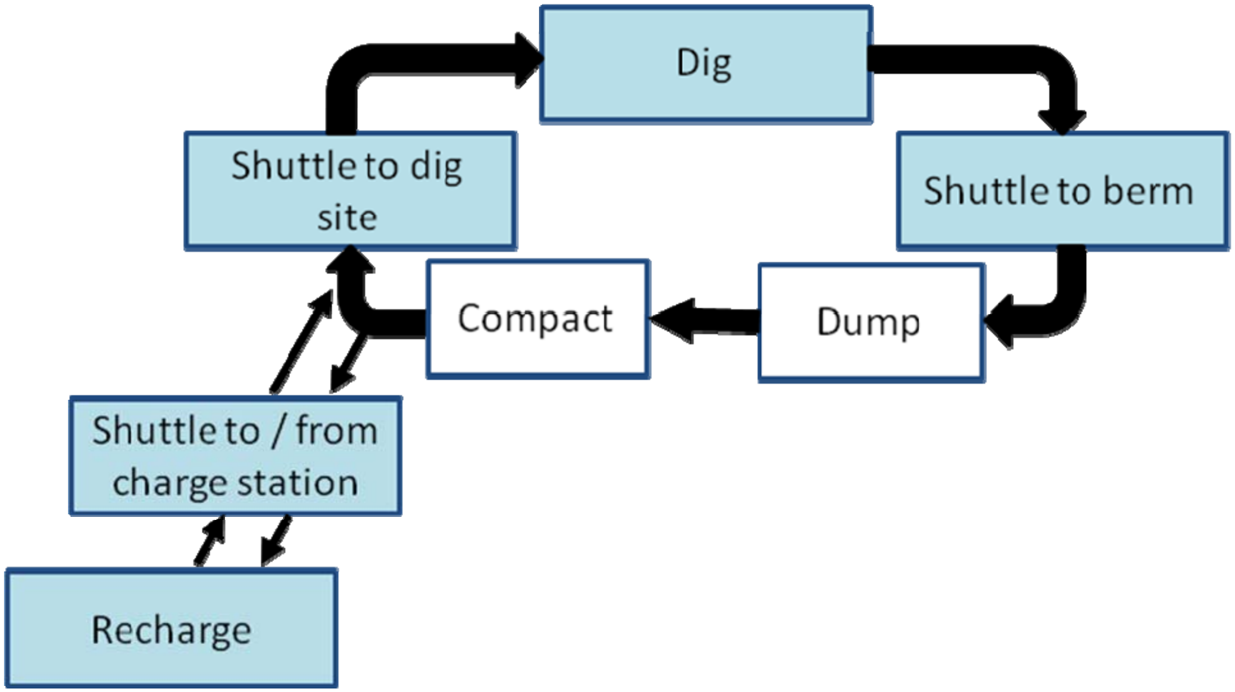
Distribution and abundance of rocks at the lunar poles is unknown

- 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**

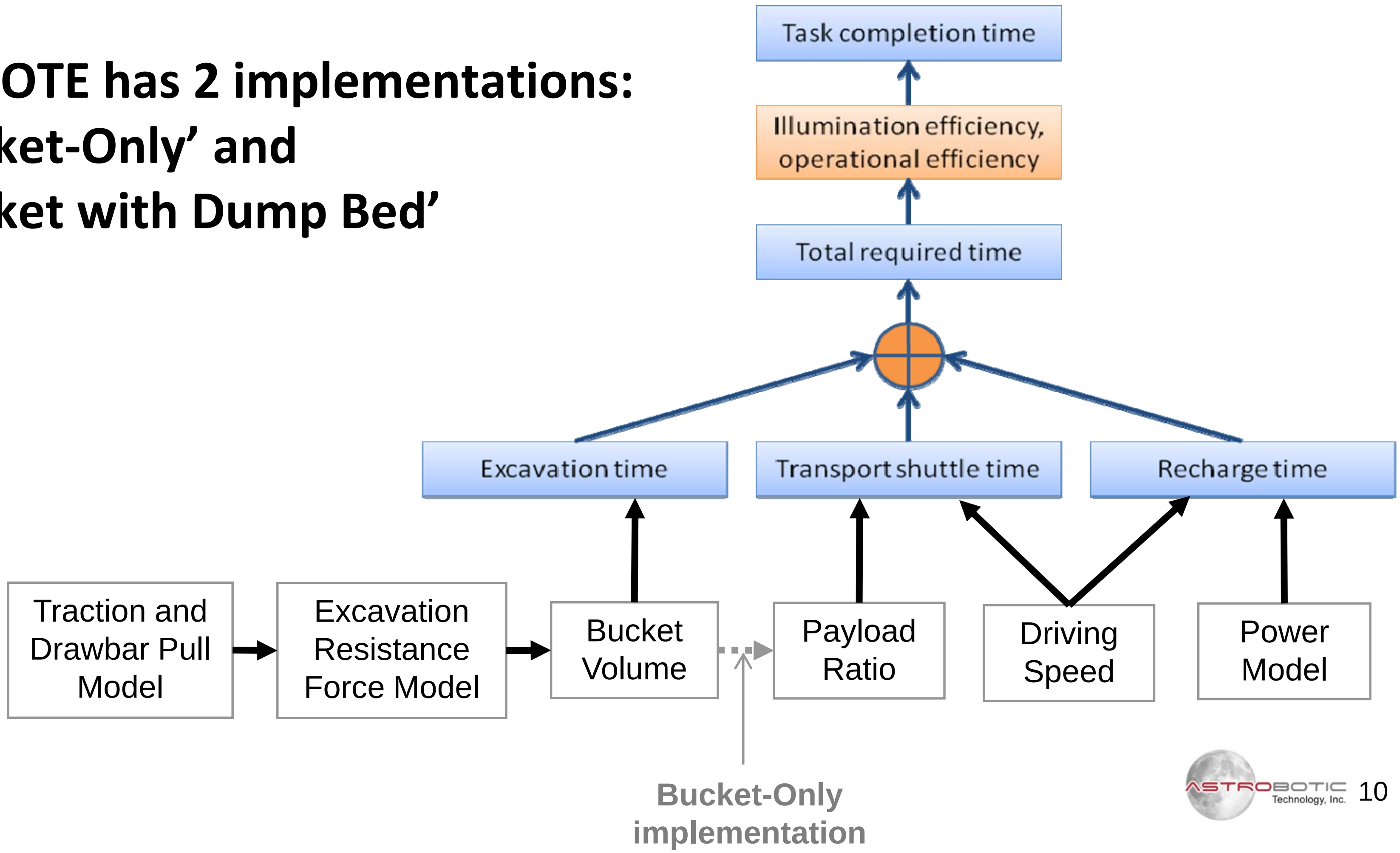
- **REMOTE characterizes performance of machines within site-level tasks such as berm building, trenching, and road building**
  - **Creates a comprehensive context for a task from the elemental actions of digging, transporting, and shuttling for recharge**



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.**

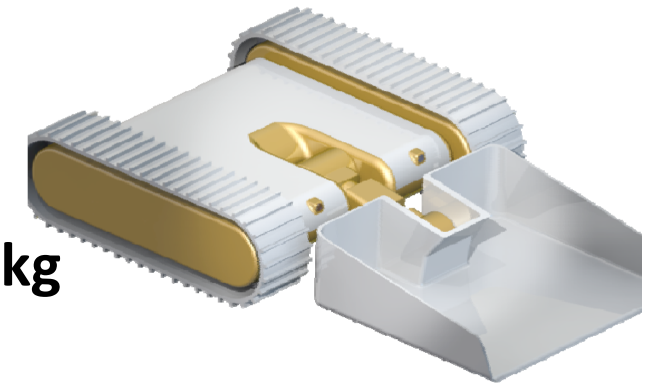
- **REMOTE has 2 implementations:**
  'Bucket-Only' and
  'Bucket with Dump Bed'

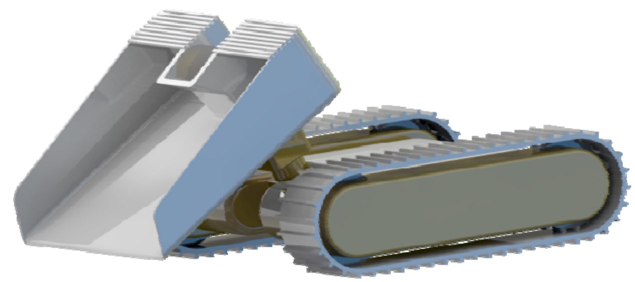


Berm Construction Simulation: Bucket-Only

- 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

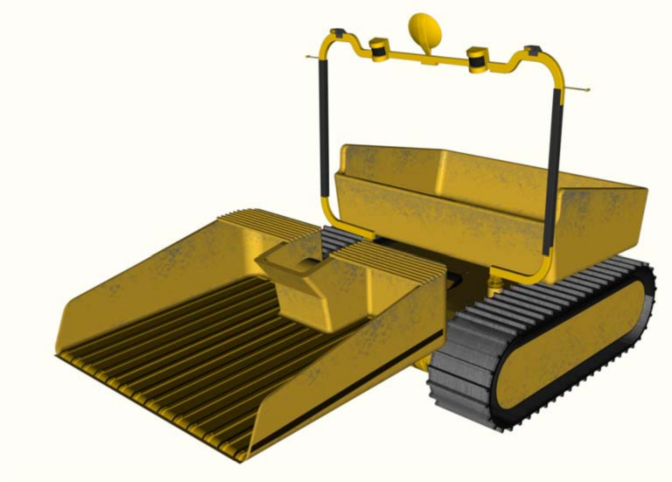


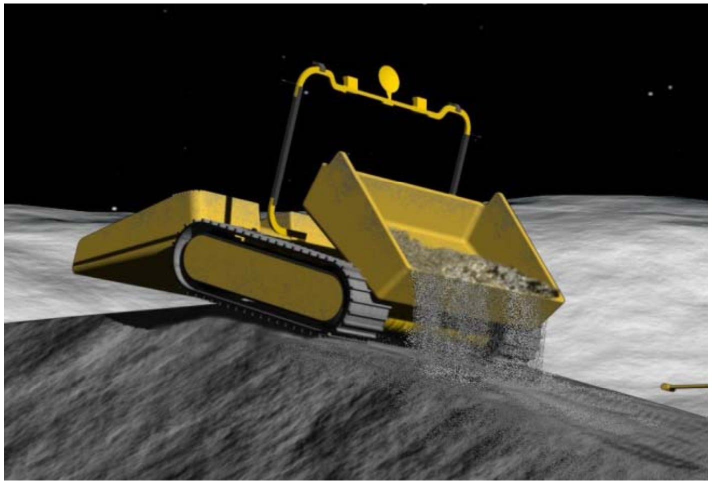


Berm Construction Simulation: Dump Bed

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

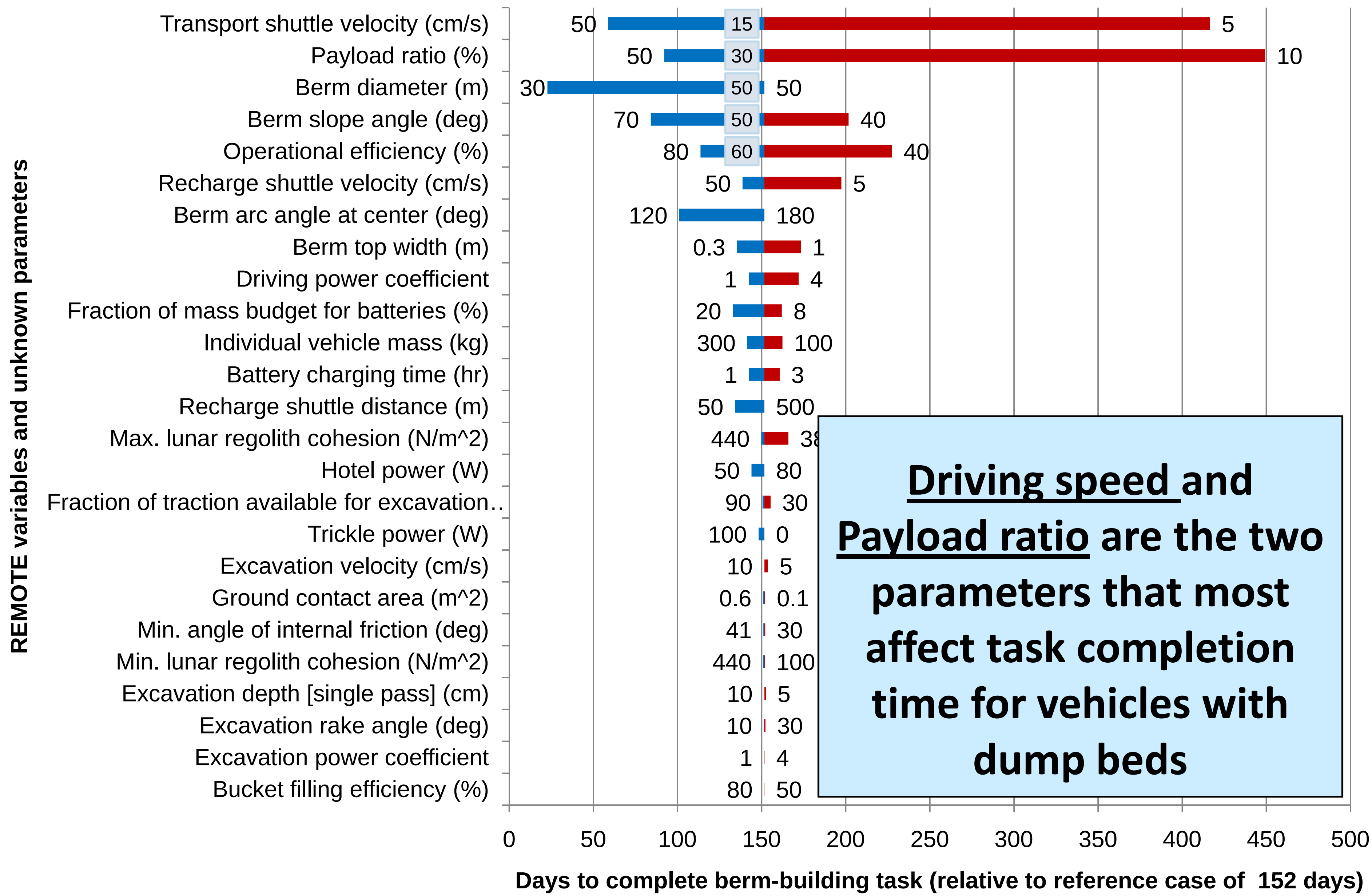
- **Parameters and values that lead to this result are the same as for the Bucket-only case, except for Payload ratio:**
  - **2 excavation robots, each of mass 150 kg**
  - **1,200,000 kg of regolith to transport**
  - **Transport shuttle velocity of 15 cm/s**
  - **30% Payload ratio set as a design parameter**





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

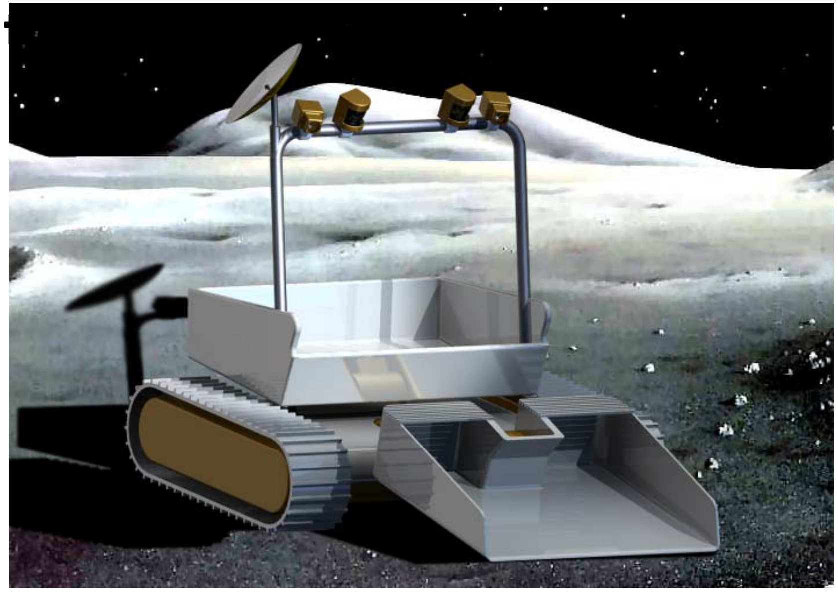
Sensitivity Analysis of Dump Bed Implementation

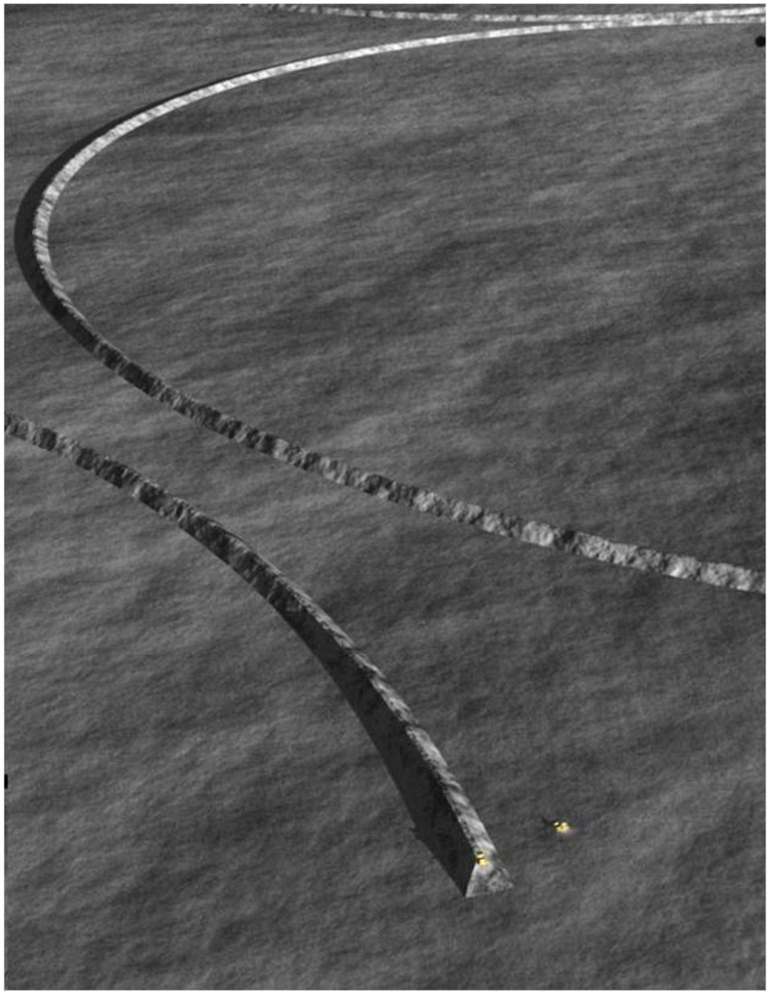


<u>Driving speed</u> and <u>Payload ratio</u> are the two parameters that most affect task completion time for vehicles with dump beds

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 autonomy**

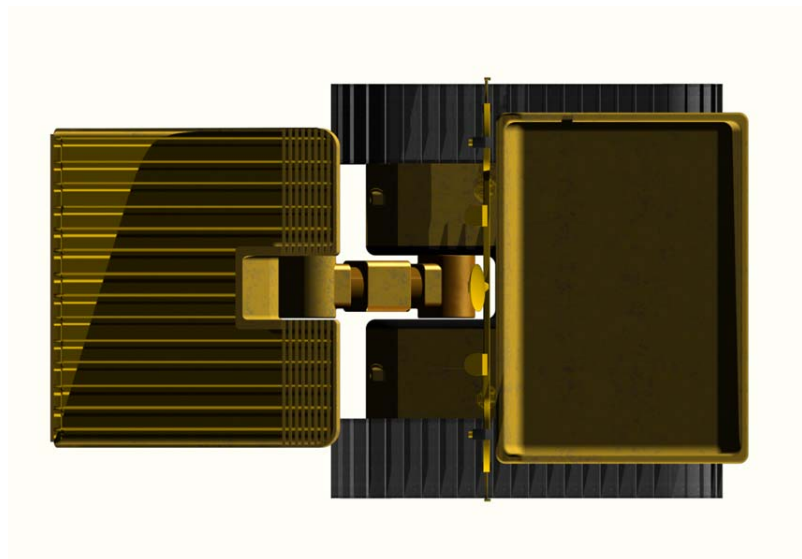




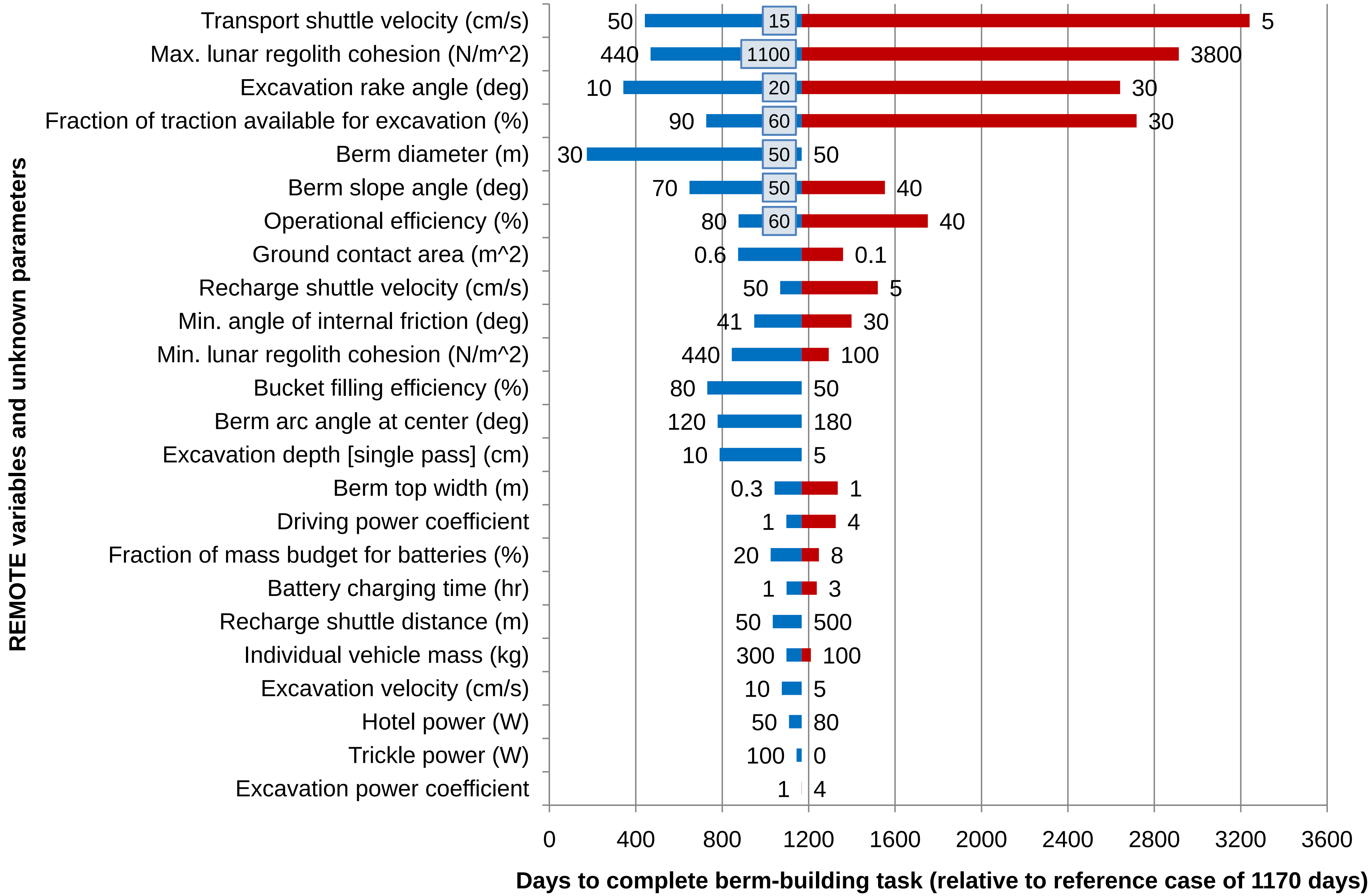
An extraterrestrial vehicle cannot be expected to drive this fast…

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**

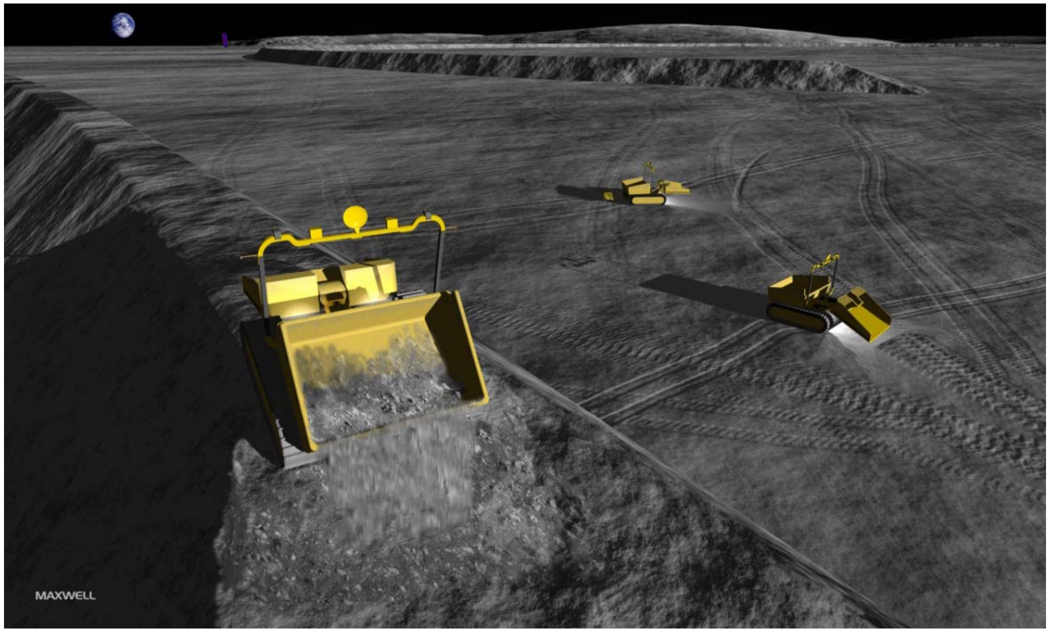


Sensitivity Analysis of Bucket-only Implementation



Innovative Regolith Moving: Dump Bed

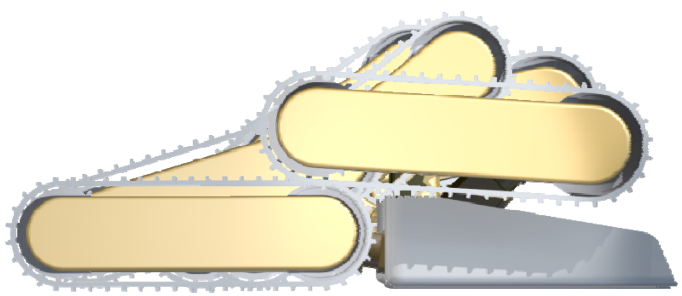
- **A dump bed…**
  - ➢ **Reduces the number of transport shuttle trips required, making 6 month berm construction feasible**
  - ➢ **Makes payload ratio a design parameter, instead of being dependent on the excavation reaction forces**
  - ➢ **Reduces the effect of regolith cohesion on task completion 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 require**
- **Vibration and downforce are effective means to compact**
- **Loader/Compactor Concept: Combine a flat bottomed excavation bucket with robot weight and a vibratory actuator**

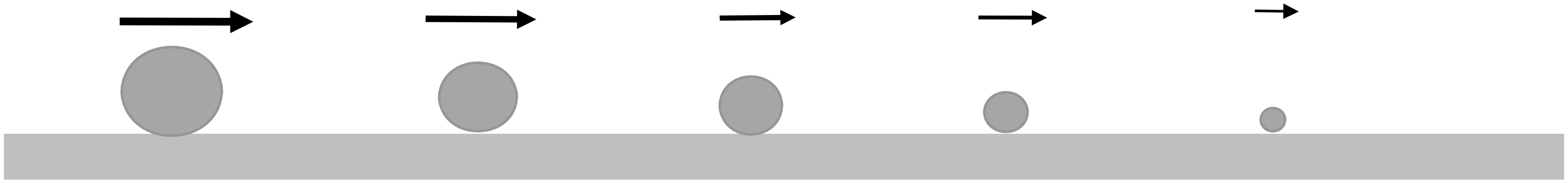


Innovative Surface Stabilization: Rock-Paving

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

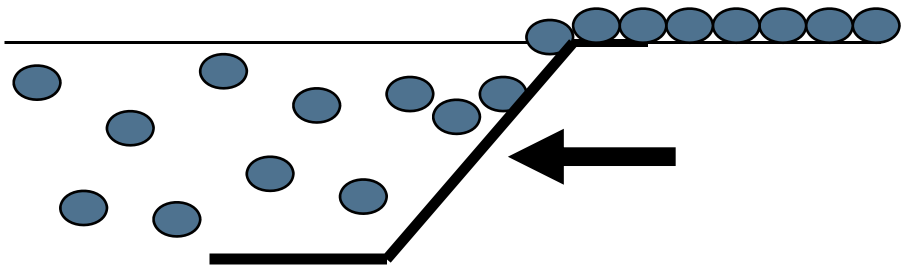
- **This technique is used for constructing stream-crossings, spillway linings and road-edges on Earth, and may have utility on the Moon**

- **Rocks resist erosion more than gravel; gravel resists erosion more than sand; and sand resists erosion more than silt**

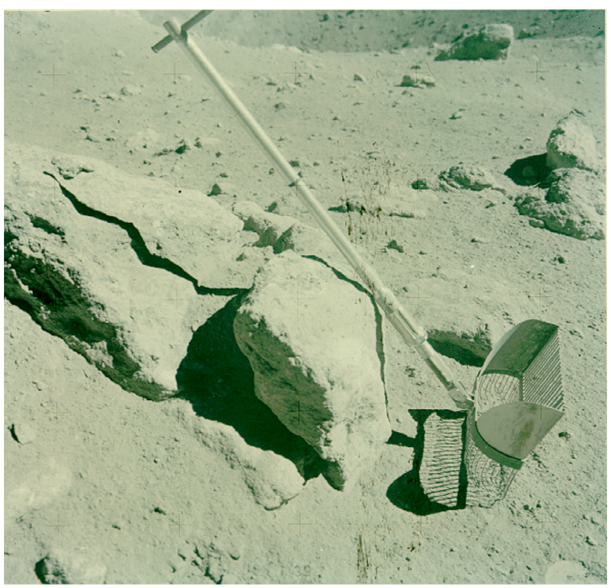


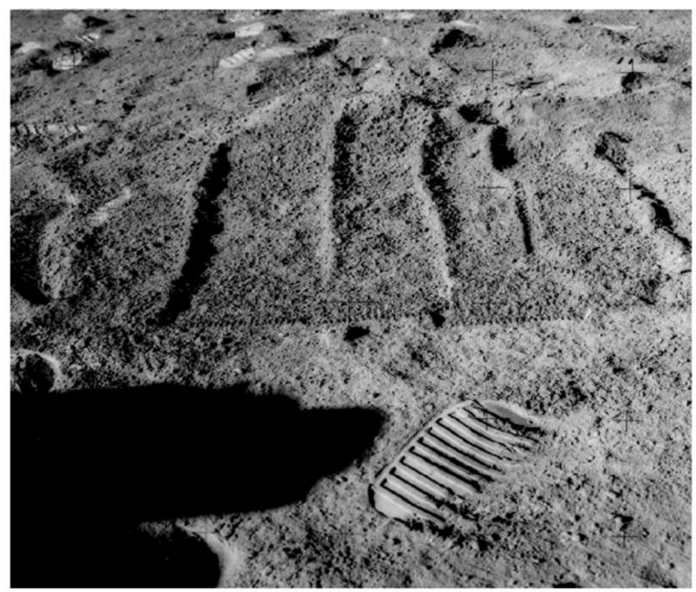
Rock-Paving Rake

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



- **Rock rakes were used for sample collection during Apollo**



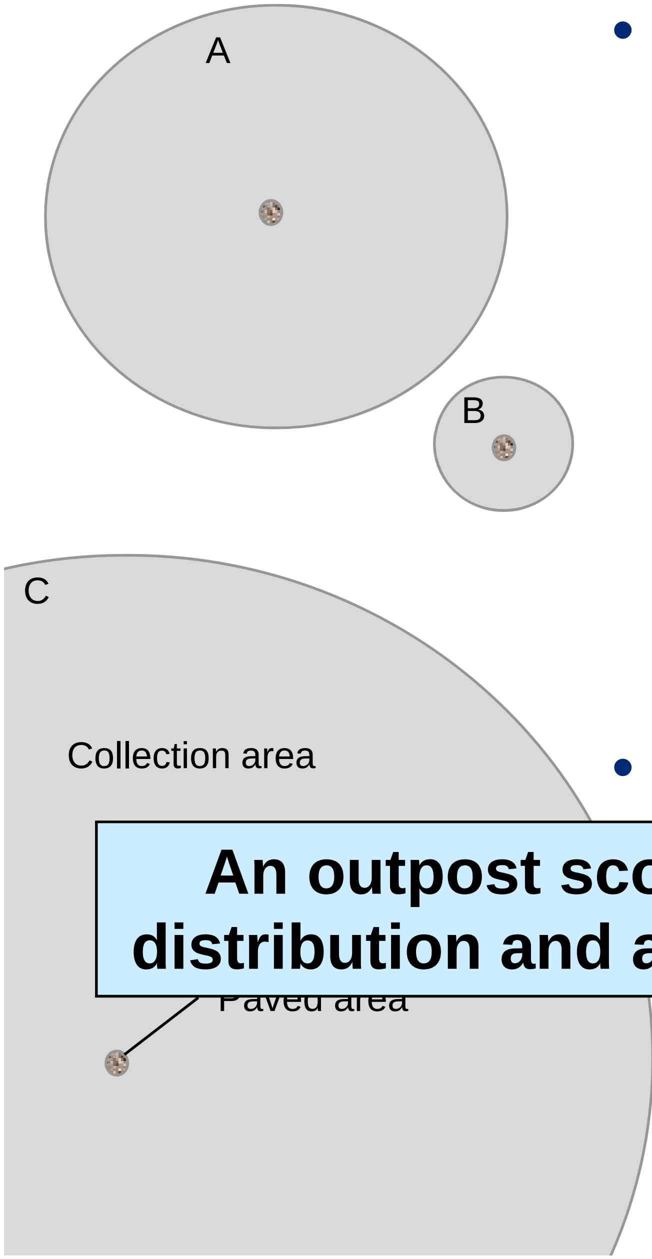


Rock Rakes, Windrowers and Rock-Pickers

- **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)

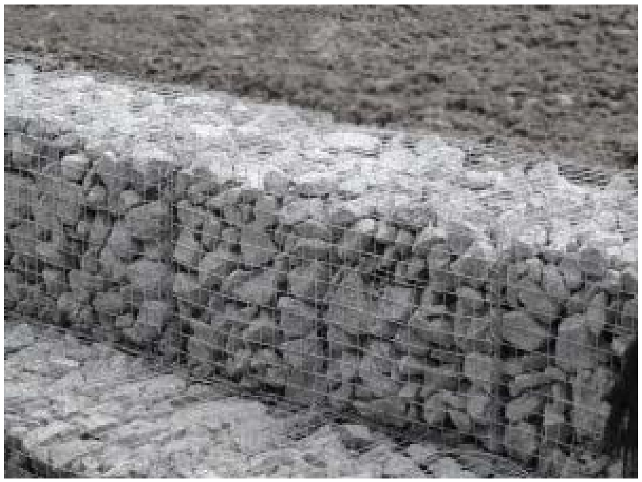
- **Sample cases based on rock distribution data**

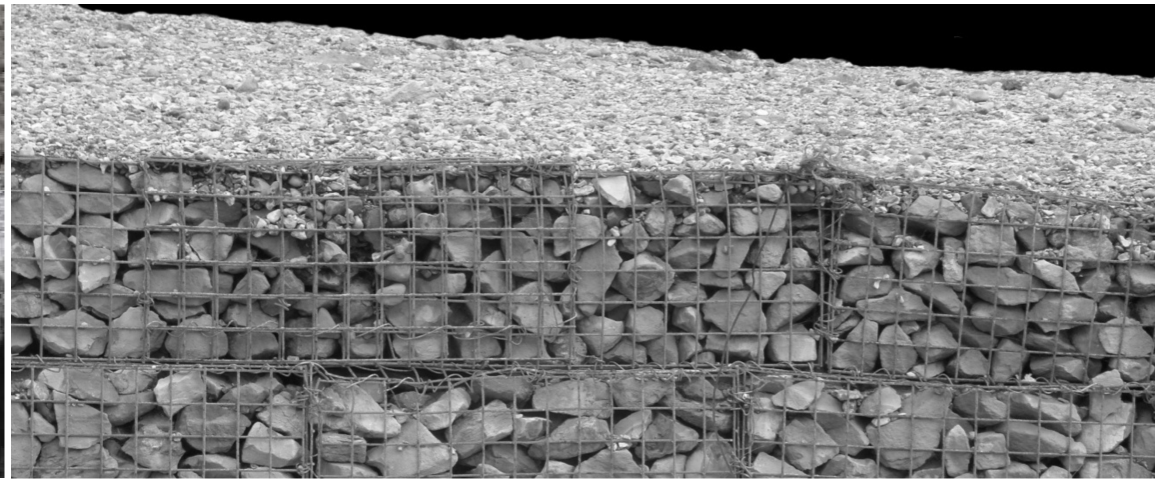
An outpost scouting mission could determine the distribution and al

Case	Rock size	Rake Depth	Drive Distance
A	1 – 2 cm	Surface	1400 km
B	1 – 2 cm	15 cm	180 km
C	10 – 15 cm	Surface	11,000 km

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

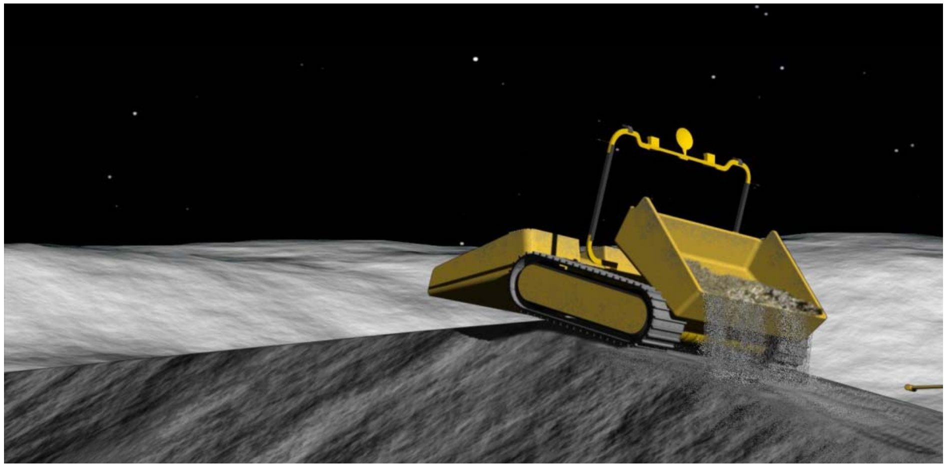
TABLE 9.12. Recommended typical values of lunar soil cohesion and friction angle (intercrater areas).

Depth Range (cm)	Cohesion, c (kPa)		Friction Angle, ϕ (degrees)	
	Average	Range	Average	Range
0 – 15	0.52	0.44 – 0.62	42	41 – 43
0 – 30	0.90	0.74 – 1.1	46	44 – 47
30 – 60	3.0	2.4 – 3.8	54	52 – 55
0 – 60	1.6	1.3 – 1.9	49	48 – 51

[Lunar Sourcebook]

Summary

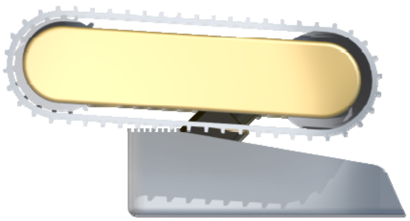
- **Robots with mass of 300 kg or less could construct a berm in less than 6 months, if equipped with dump beds**
  - REMOTE simulates task-level operations, such as berm construction, by combining analytical models of elemental actions such as excavation and mobility



- **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

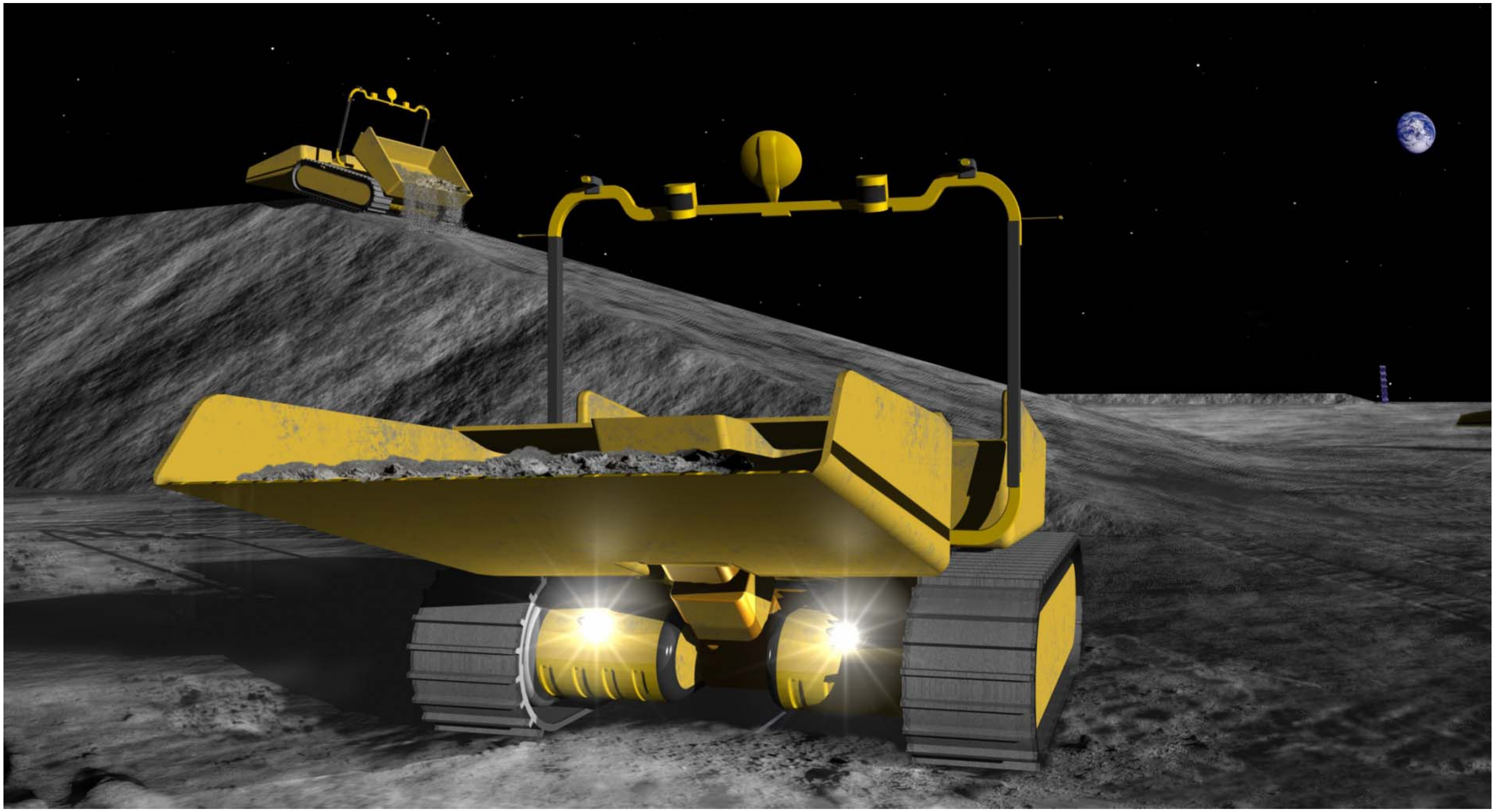
- Innovative regolith moving techniques include:
  - Using vehicles equipped with dump beds
  - Compacting with a dual loader/compactor
  - Stabilizing a landing pad by rock paving



- Effectiveness of construction and rock paving depend on further lunar data:
  - Measuring excavation resistance force directly
  - Determining distribution of lunar rocks

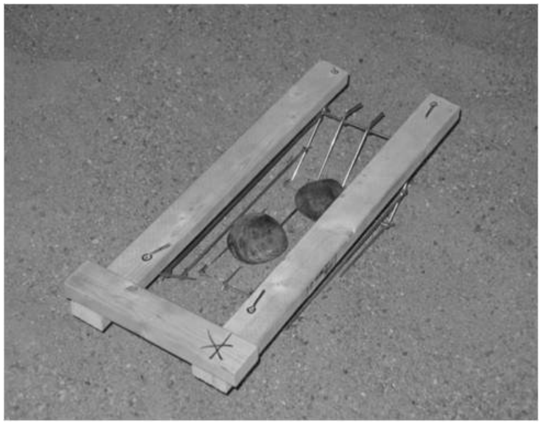
Opportunities for Follow-on Work: Moon Digger

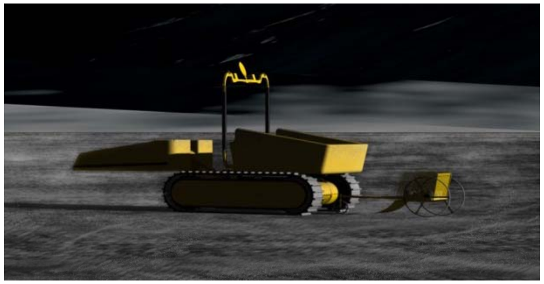
- **Analyze, prototype, and evaluate:**
  - **Technical implementations for bucket and dump bed designs**
  - **Teleoperation and automation of regolith moving with time delay**
  - **Compaction using downforce and vibration**



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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