Computational DEM Analysis of Stick-Slip Dynamics in the Vertical Lunar Regolith Conveyor under Earth and Lunar Gravity

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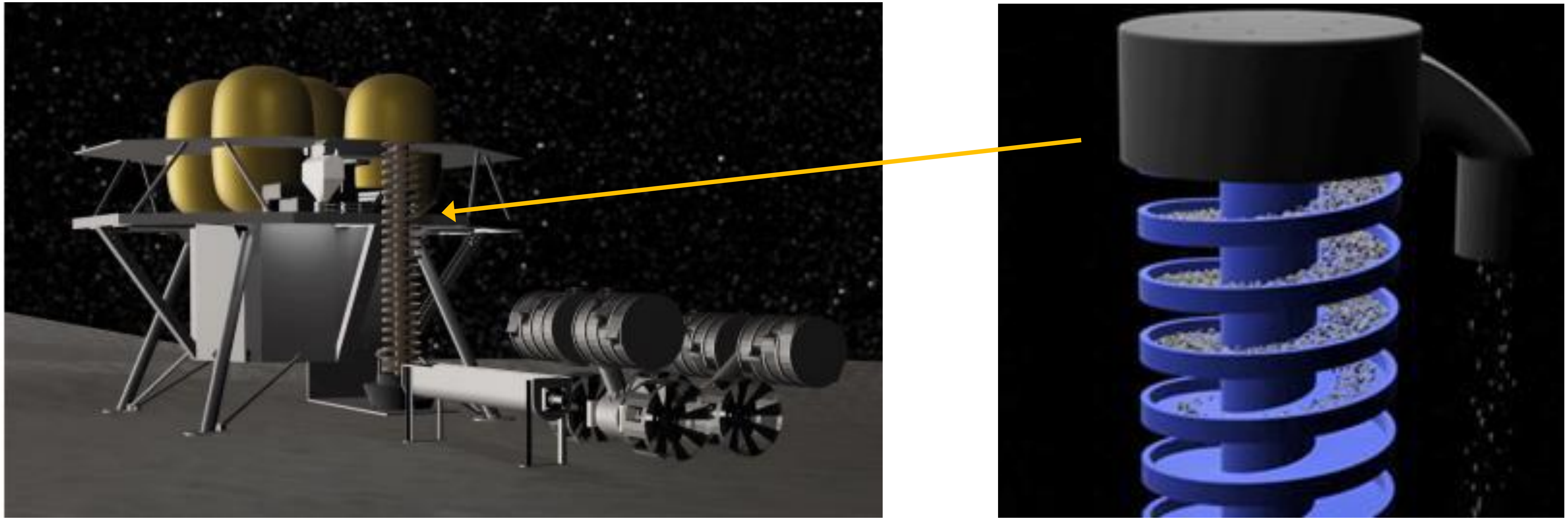
Vertical Lunar Regolith Conveyor (VLRC)

- VLRC is a helical vertical conveyor technology developed by NASA KSC, aiming to transport lunar regolith from ground operations into a surface processing facility.



VLRC Concept
(Credit: NASA KSC)

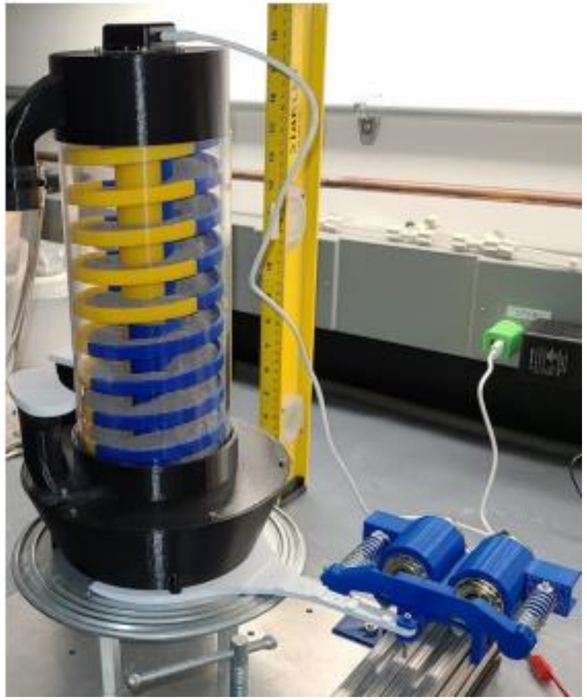
Research Question: How do gravity level, regolith properties, and stick-slip operating conditions affect regolith transport performance?

VLRC Progression and Experiments at KSC

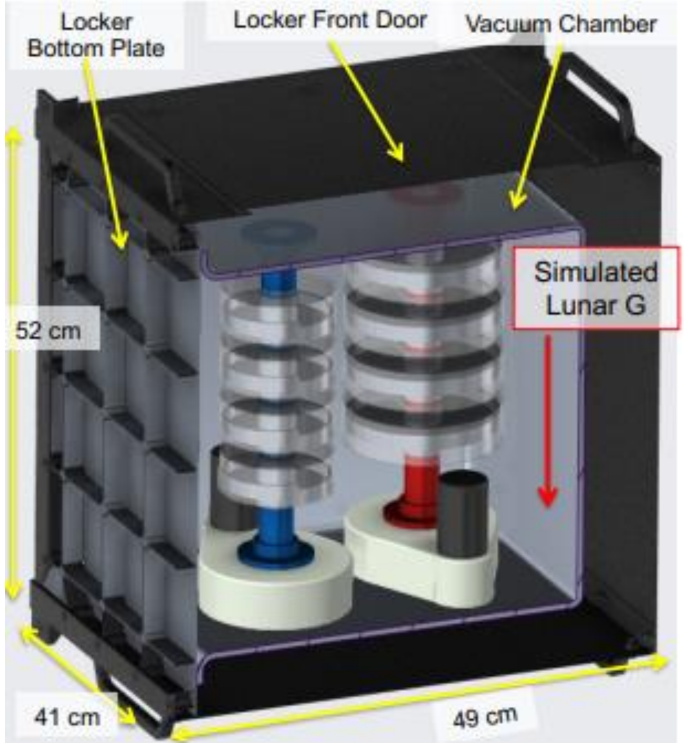
- The VLRC evolved from earlier vibratory concepts toward stick-slip operation because stick-slip offers
  - improved transport efficiency
  - lower wear
  - greater dust tolerance.

- Flight opportunities for lunar-gravity testing are limited and short in duration, making computational modeling an attractive complement to physical testing.

- Computational modeling enables thousands of virtual experiments that would be impractical in reduced-gravity testing.



Lab-scale VLRC Prototype
(Credit: Olson et al., KSC)

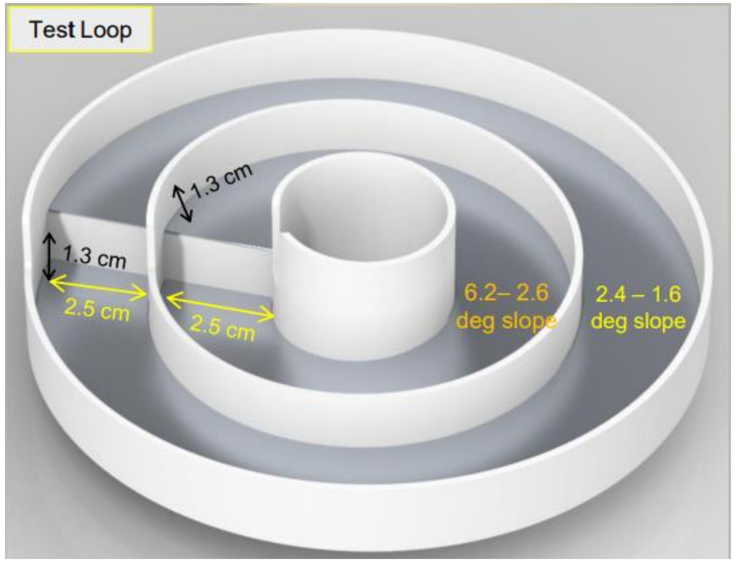


Two Stack VLRC Lunar Gravity Experiment Design
(Credit: Olson et al., KSC)

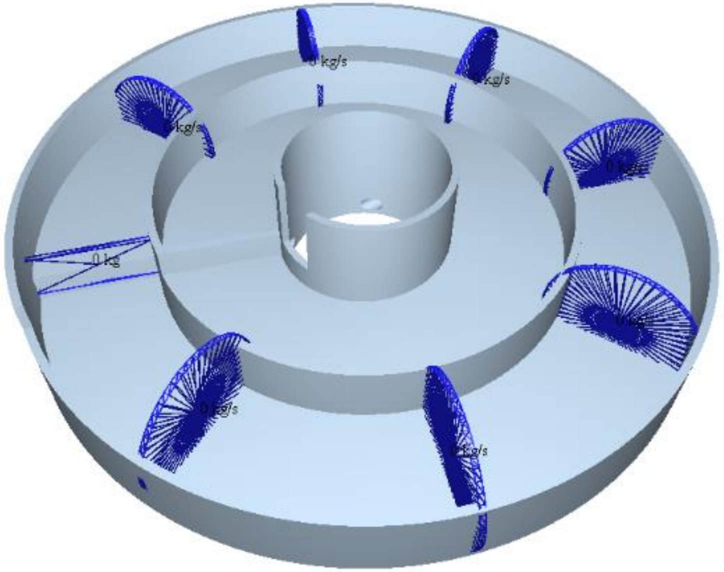
Vertical Lunar Regolith Conveyer (VLRC)

Our goal is to build a validated digital twin of the VLRC and use it to explore operational and material parameters. Research Objectives:

- **Quantify frequency effects**
- **Compare Earth and Lunar gravity**
- **Assess cohesion effects**
- Identify optimal operating ranges



Physical model & testing



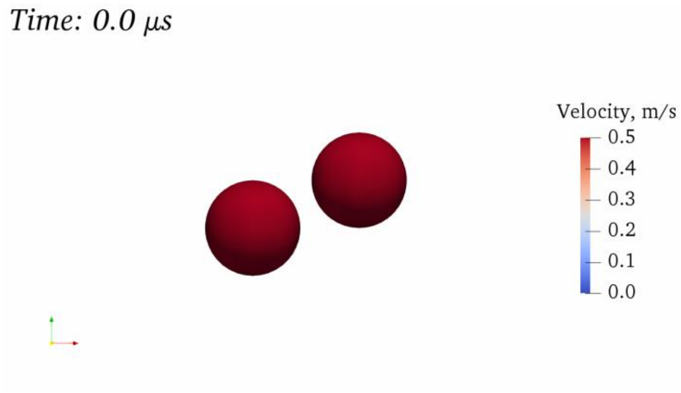
Digital twin & virtual testing

Outline

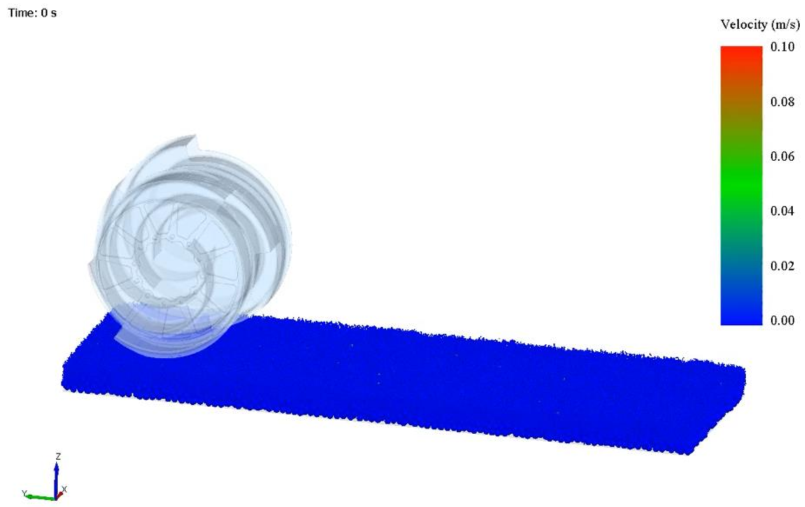
1. Introduction
2. Methodology
   i. Computational approach: the discrete element method
   ii. VLRC model setup
3. Results and Analysis
4. Ongoing Work & Summary

Discrete Element Method (DEM)

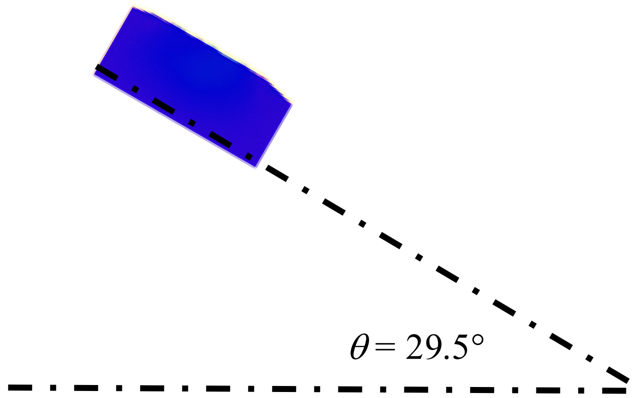
- A particle-based numerical method for modeling the mechanical behavior of particulate materials.
- DEM tracks every particle and contact, allowing us to capture flow behavior that continuum approaches cannot easily represent.



Particle interaction



Simulating KSC IPEx

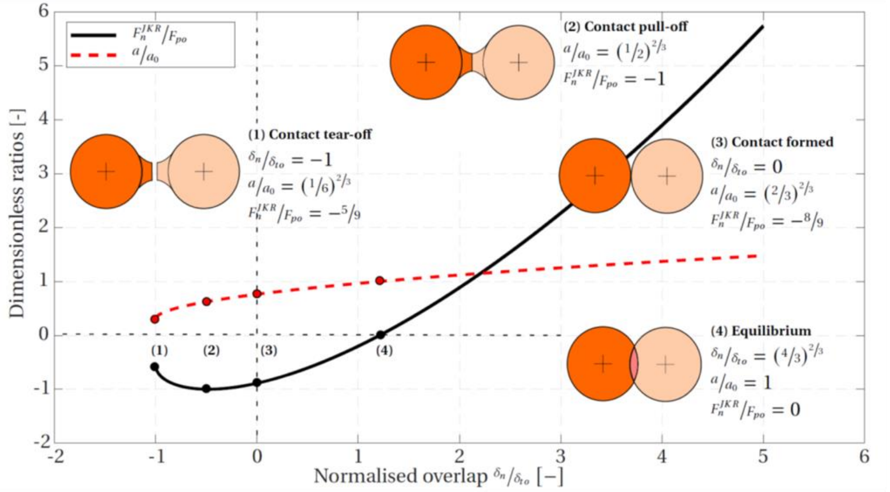


Granular flow

Discrete Element Method (DEM)

Particle-scale interactions captured through contact models

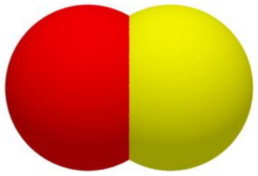
- Hertz – Mindlin with a JKR (Johnson-Kendall-Roberts) cohesive model
  - The Hertz-Mindlin contact model will determine the:
    - Tangential elastic force
    - Normal dissipation force
    - Tangential dissipation force
- Why JKR?
  - Represents cohesive regolith behavior
  - Enables parametric study of cohesion



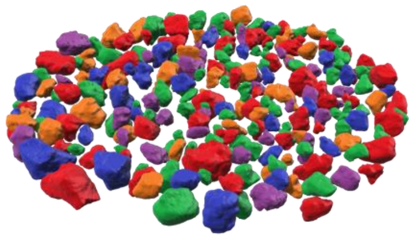
JKR model (credit: Itasca Software)

Particle shape template:

- Double sphere clumped particle
- More complex shape model is possible, but at the cost of increased computational time.



Two-sphere clump



Complex shape model
(Lai and Chen 2021)

Outline

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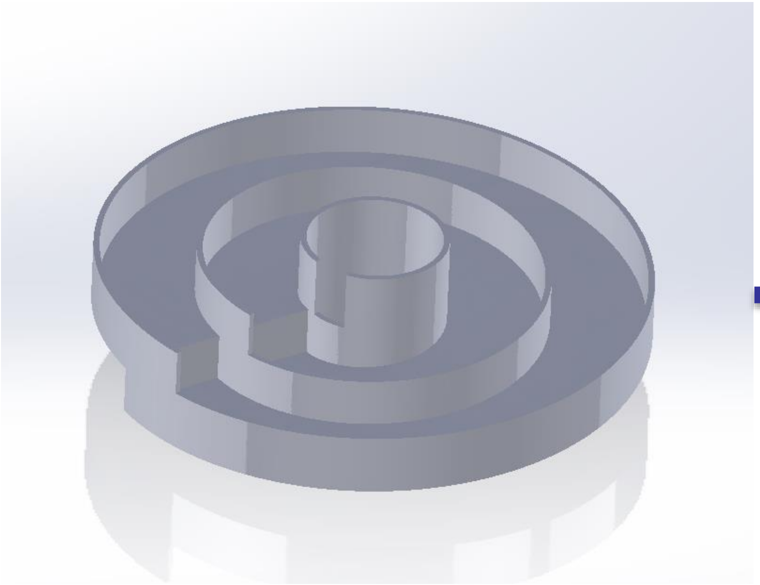
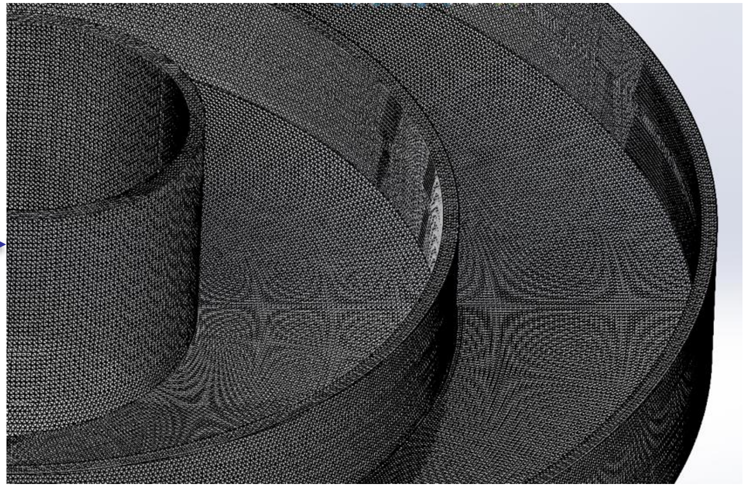
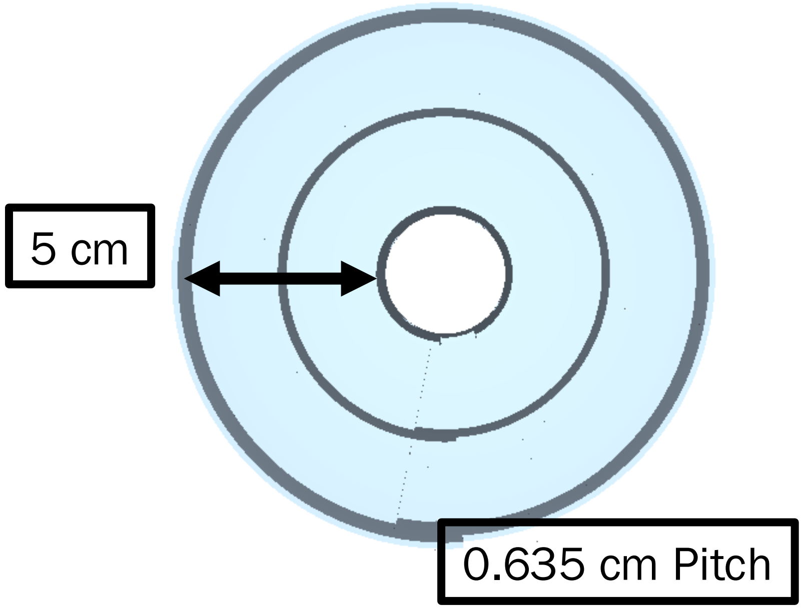
Model Setup – the VLRC Single-Loop



CAD design file
(from KSC)



STL triangular mesh



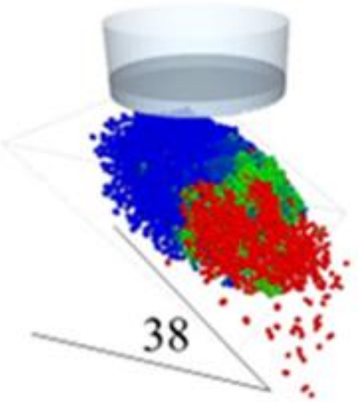
DEM model

Model Setup – Regolith Generation

- DEM contact parameters were calibrated using lab test data of BP-1 lunar regolith simulant
- Calibration reproduced bulk density, angle of repose, and inclined-plane behavior within experimental uncertainty.

Bulk Density

Angle of Repose



Inclined Plane

Parameter	Value	Unit
Poisson's Ratio	0.25	-
Solids Density	2750	kg/m^3
Shear Modulus	1.00E+07	Pa
(P-P) Resitution Coefficient	0.3	-
(P-P) Static Friction Coefficient	0.85	-
(P-P) Rolling Friction Coefficient	0.8	-
(P-G) Restitution Coefficient	0.3	-
(P-G) Static Friction Coefficient	0.7	-
(P-G) Rolling Friction Coefficient	0.1	-
JKR Surface Energy	0	J/m^2

Model Setup – Stick-Slip Dynamics

- **Stick:** Slow forward stroke → particle advancement
- **Slip:** Fast backward stroke → conveyor reset
- In DEM, motion is specified through calculated angular acceleration and velocity

(Slow rotation) $$\alpha_1 = \frac{2*\Delta\theta}{(\Delta t_1^2)} = \text{124.62 deg/s}^2$$

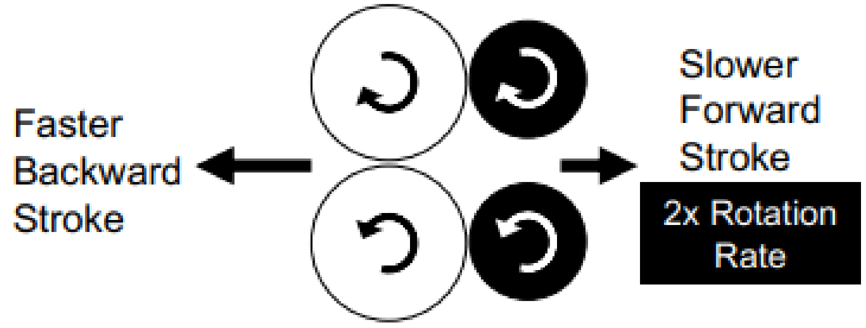
Δt_1 = 0.4 s
$\Delta\theta$ = 0.1745 rad (or 10 deg)

(Slip rotation) $$\alpha_2 = \frac{2*-\Delta\theta}{(\Delta t_2^2)} = \text{-1993.893 deg/s}^2$$

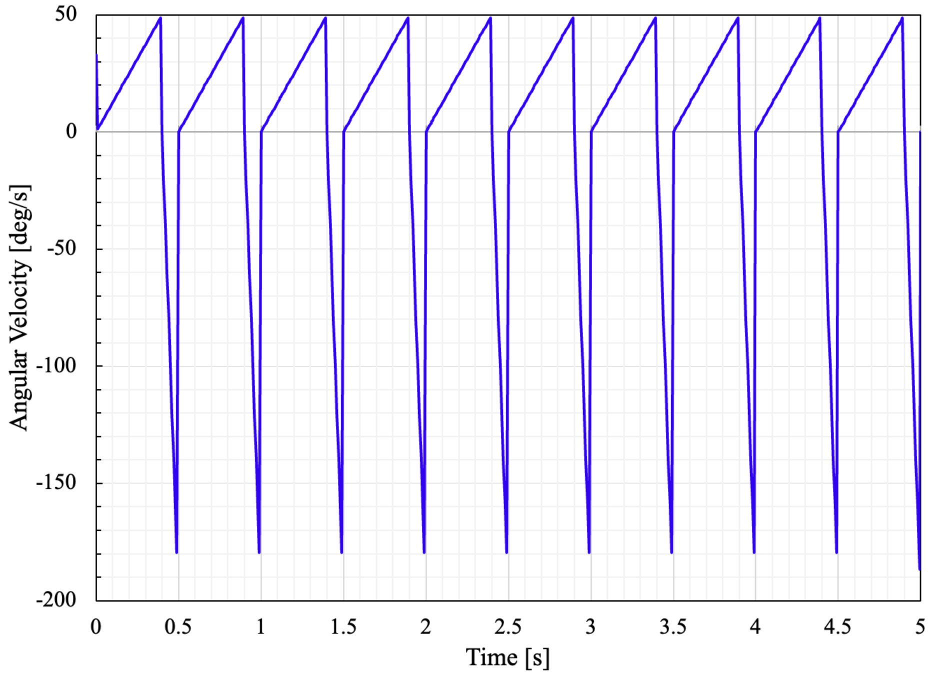
Δt_2 = 0.1 s
$\Delta\theta$ = 0.1745 rad (or 10 deg

(4Hz case, one "stroke" is 10 deg)

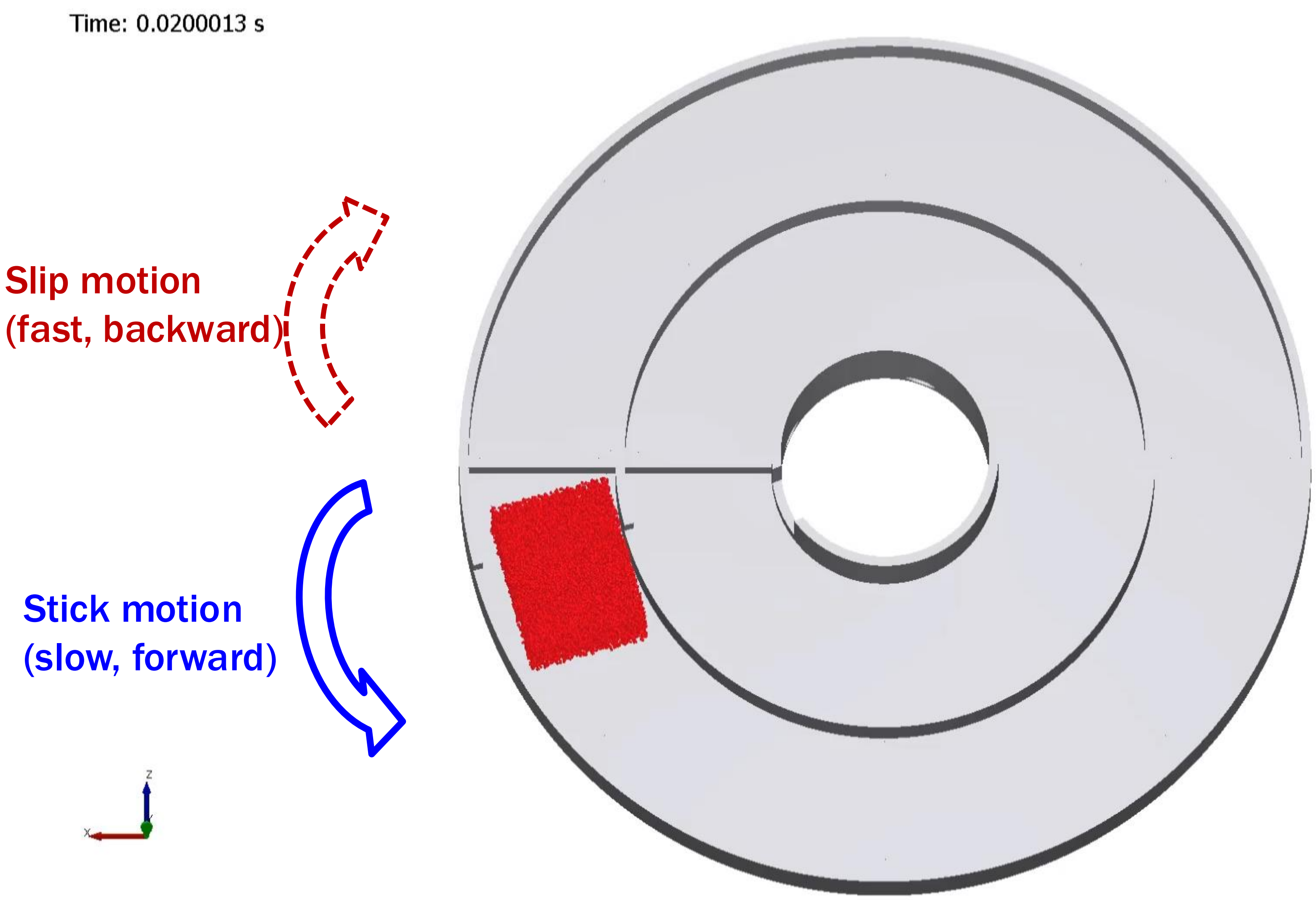
- The stick-slip motion selected for its efficiency has a specified range of frequencies (per KSC)
  - 1.7 Hz – 4.4 Hz



Rotating unbalanced stick-slip drive Concept



Model Setup – Stick-Slip Demo



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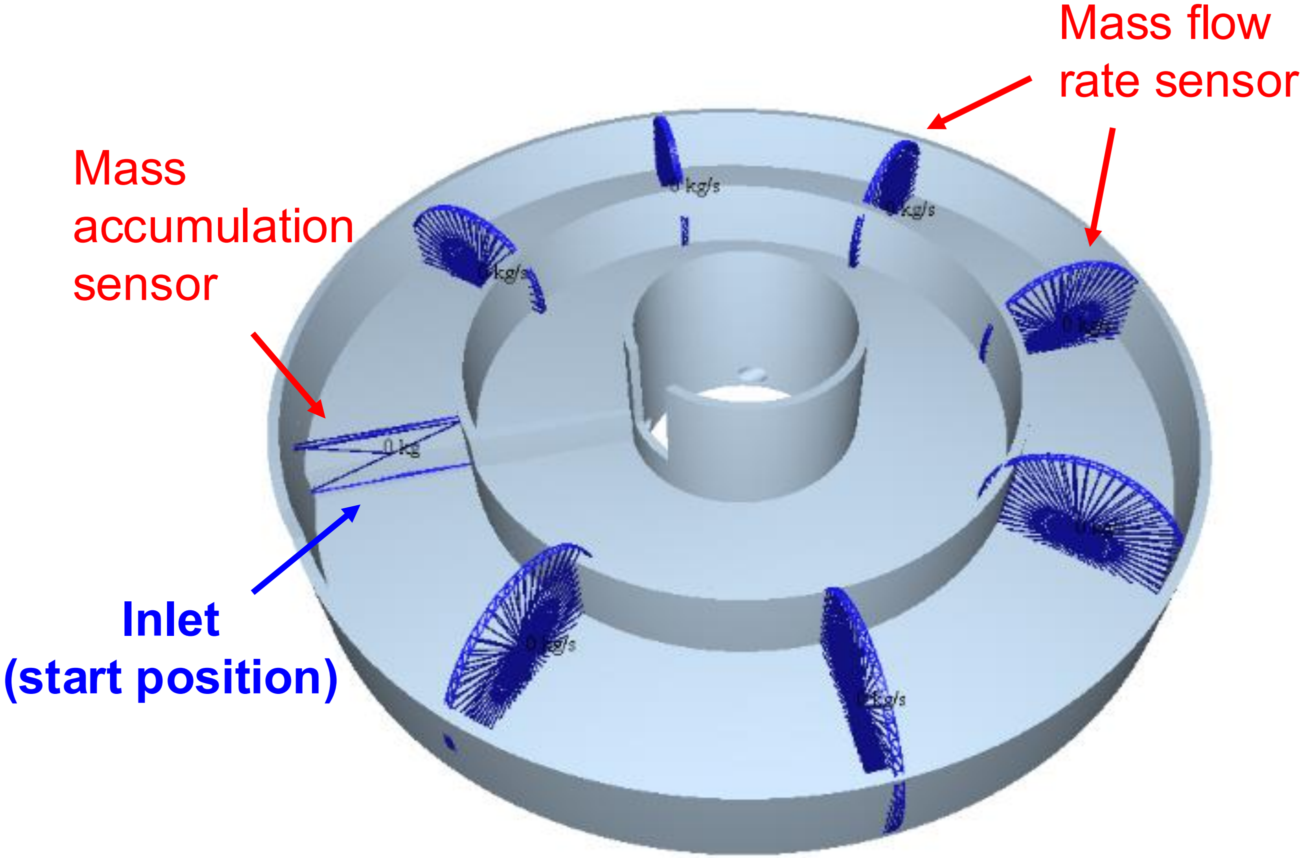
Performance Metric

- To quantify transport performance, we placed virtual mass accumulation and mass flow rate sensors around the loop.

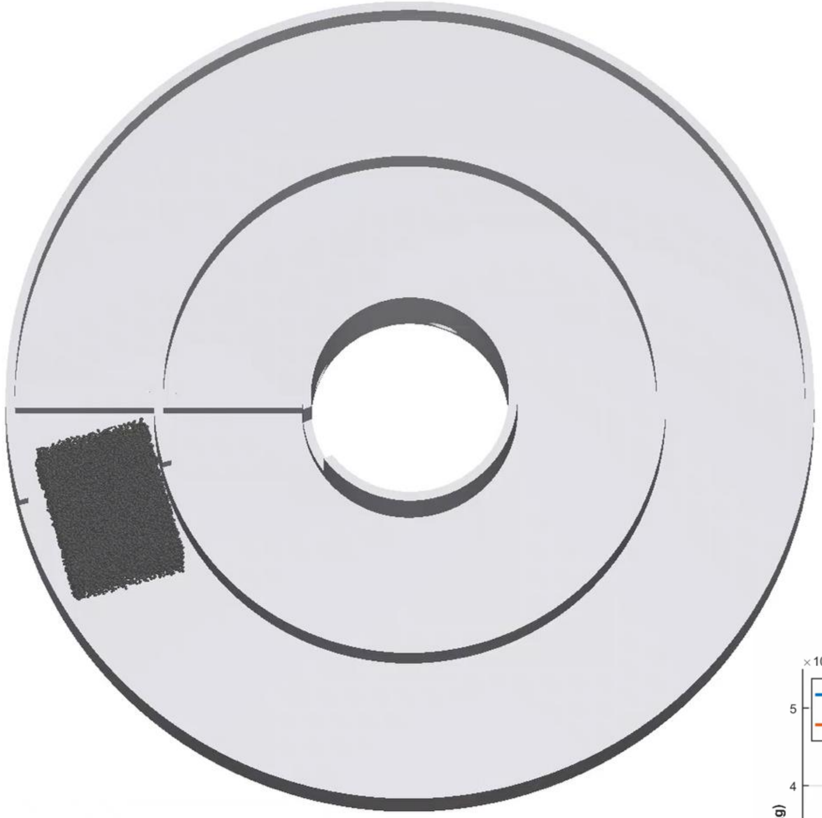
- Performance metrics: mass accumulation over time and mass transport rate



Research Question: How do gravity level, regolith properties, and stick-slip operating conditions (stroke frequency) affect regolith transport performance?

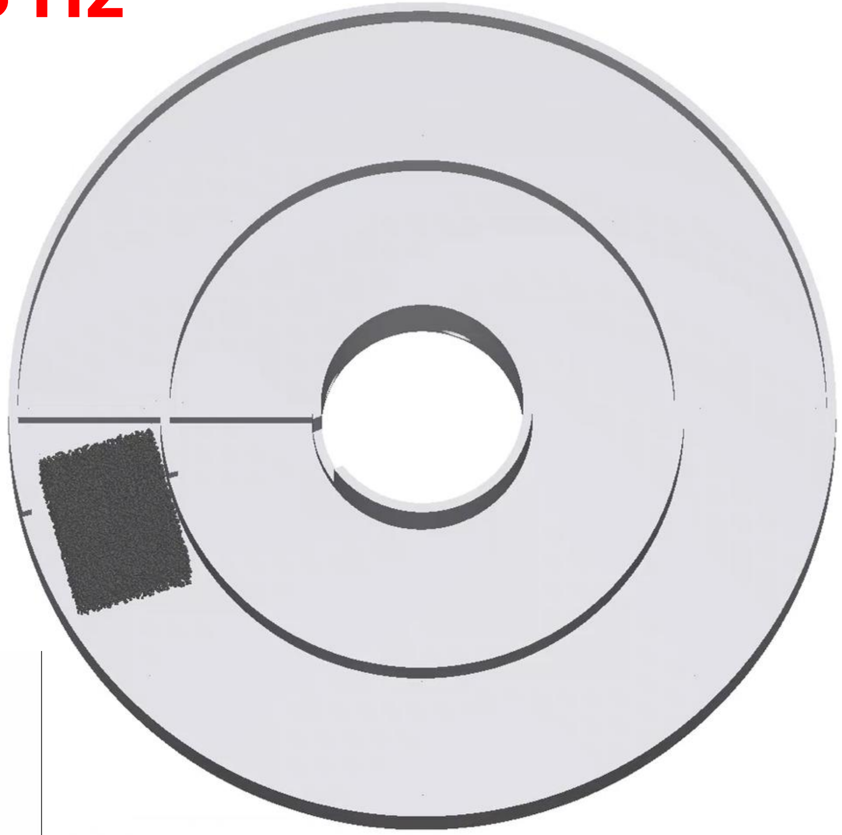
Results – 4 Hz vs 3 Hz (Earth Gravity)

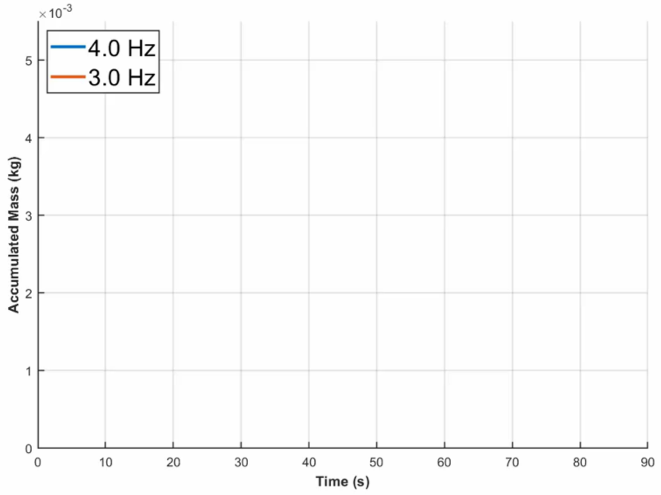
4 Hz



Time: 0.030002 s

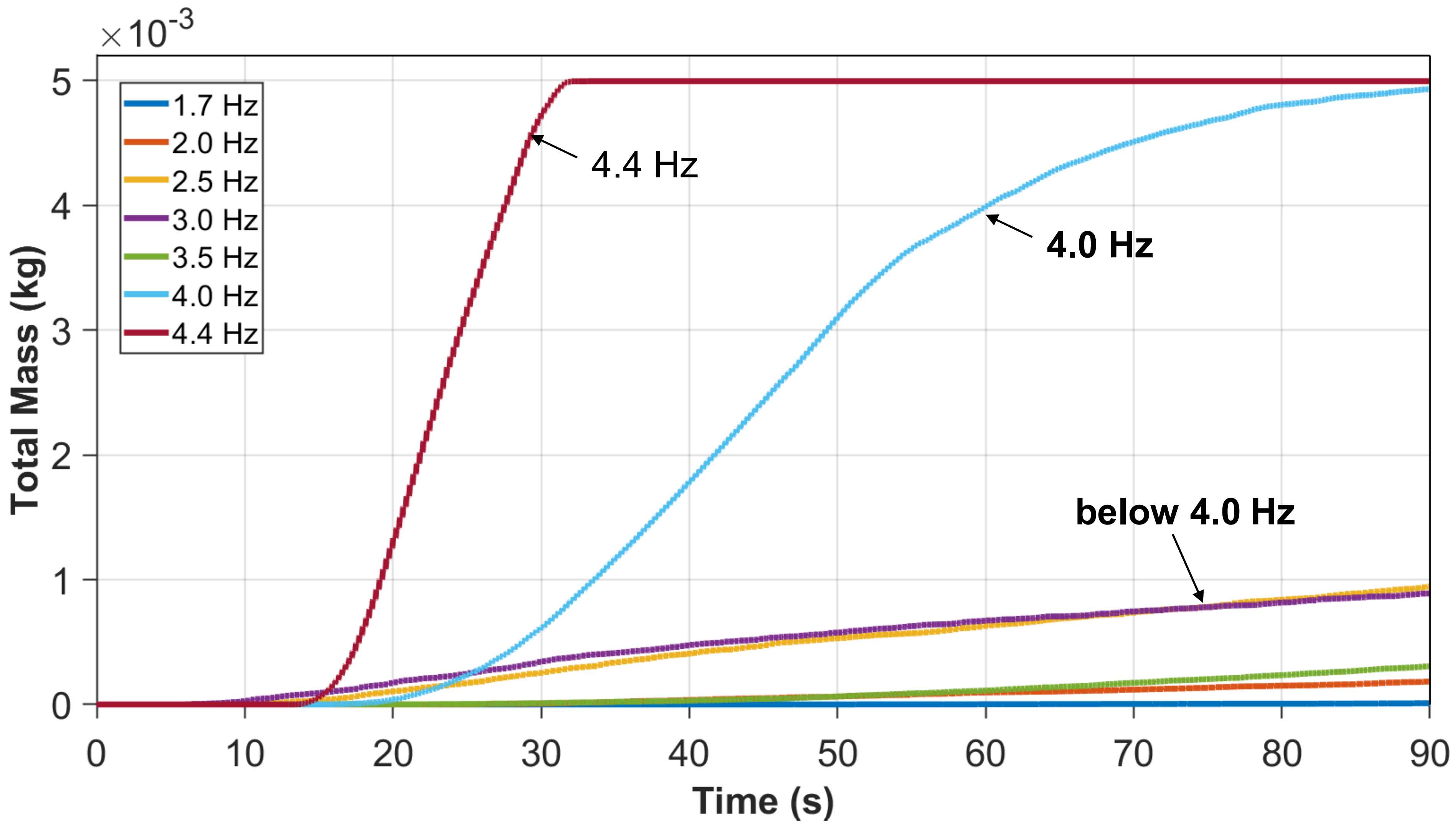
3 Hz





Mass Accumulation

Results – Varying Stroke Frequency (Earth-G)

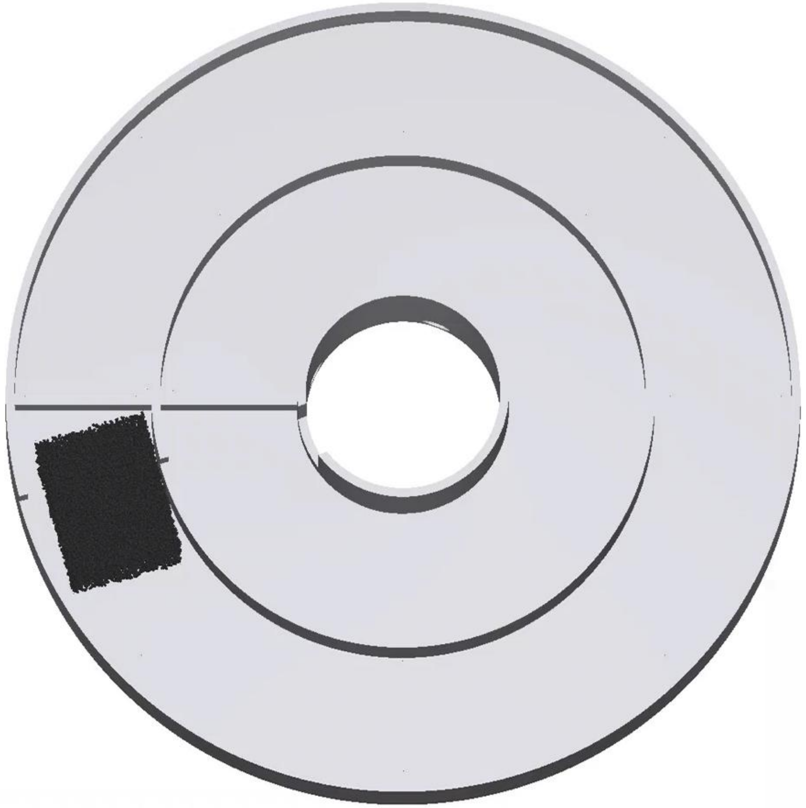


- **In Earth gravity, transport efficiency is highly sensitive to frequency.**
- **Frequencies below 4 Hz result in dramatically slower transport, while 4.0–4.4 Hz produce efficient circulation.**

Earth-G threshold ≈ 4 Hz

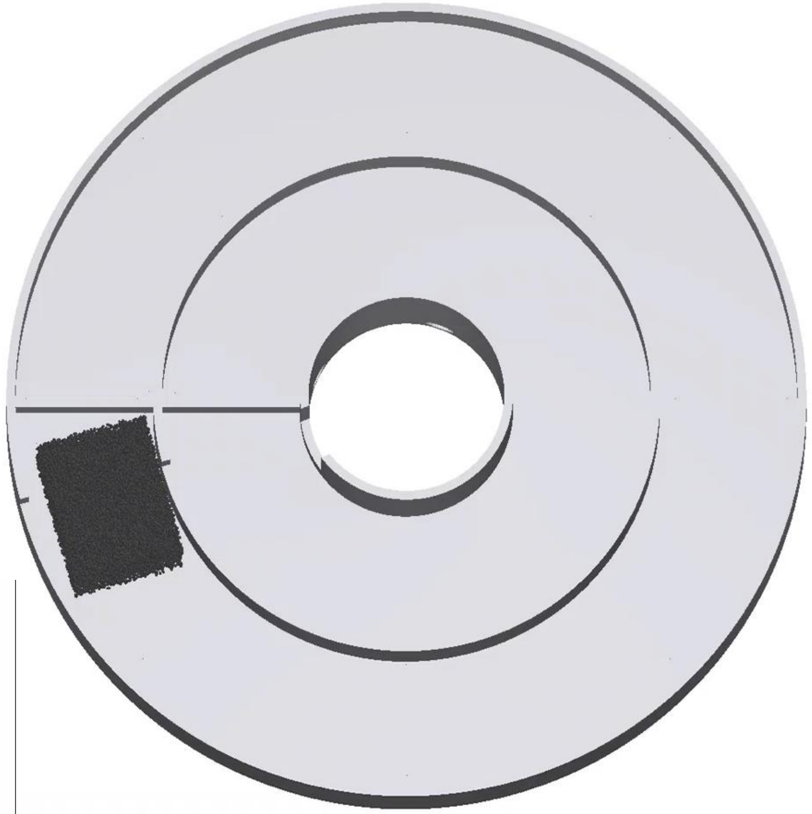
Results – 4 Hz vs 3 Hz (Lunar Gravity)

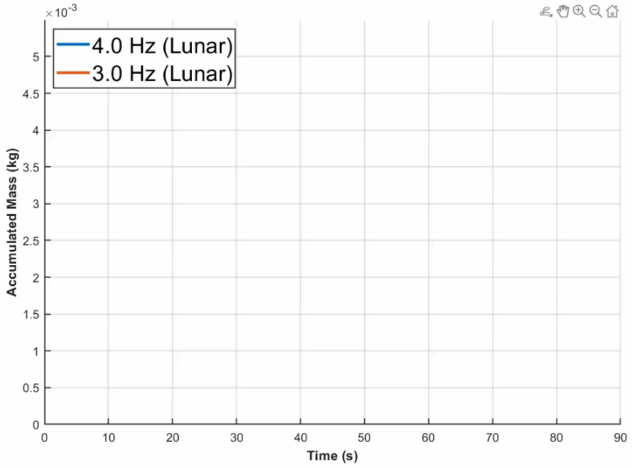
4 Hz



3 Hz

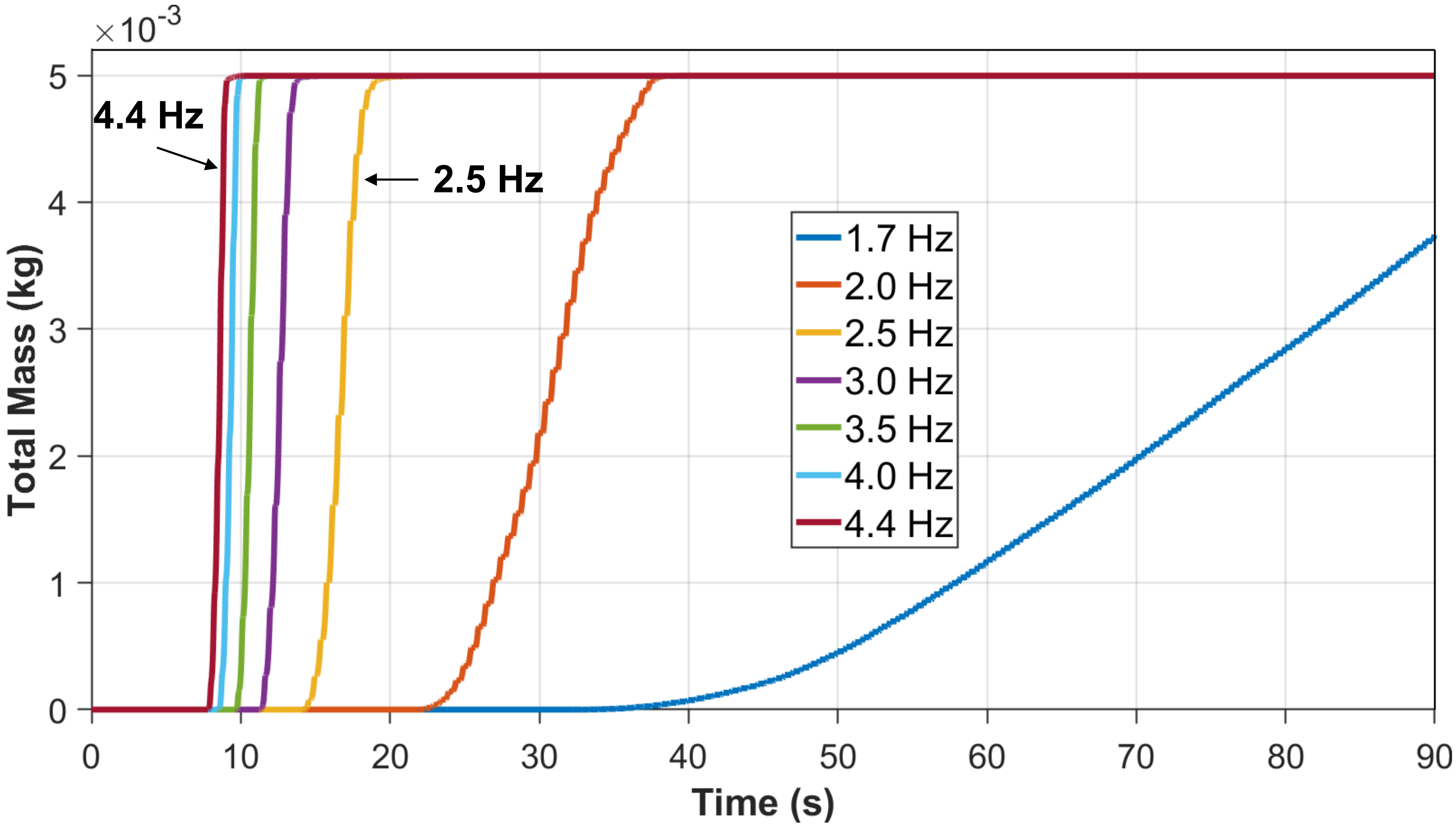
Time: 0.030002 s





Mass Accumulation

Results – Varying Stroke Frequency (Lunar-G)



- Significantly **more efficient transport** under Lunar-G
- Reduced gravity lowers normal loading and resistance, enabling more efficient particle transport during each stick-slip cycle.
- Performance saturates around 2.5 Hz, meaning higher operating frequencies provide little additional benefit

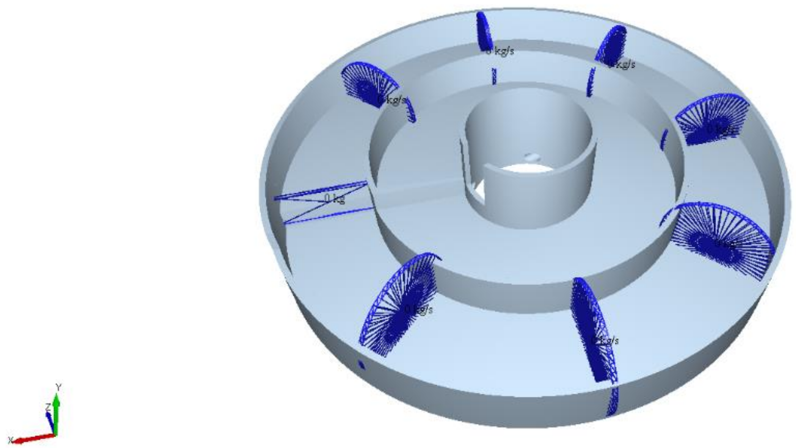
Lunar-G optimum ≈ 2.5 Hz

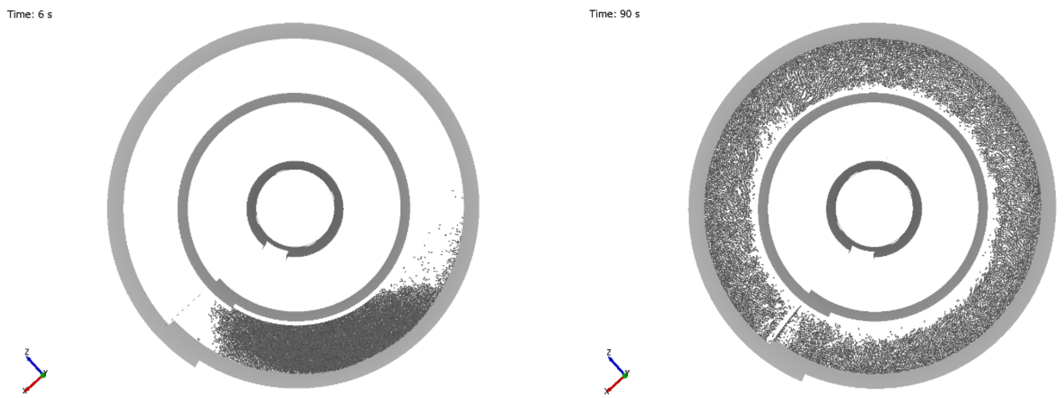
Results – Cohesion on Regolith Transport

- Lunar regolith exhibits cohesion even in the absence of moisture (0.1 kPa to 1 kPa, higher for deeper regolith)

- Typically attributed to electrostatic, Van der Waals forces, and angular, interlocking particles.

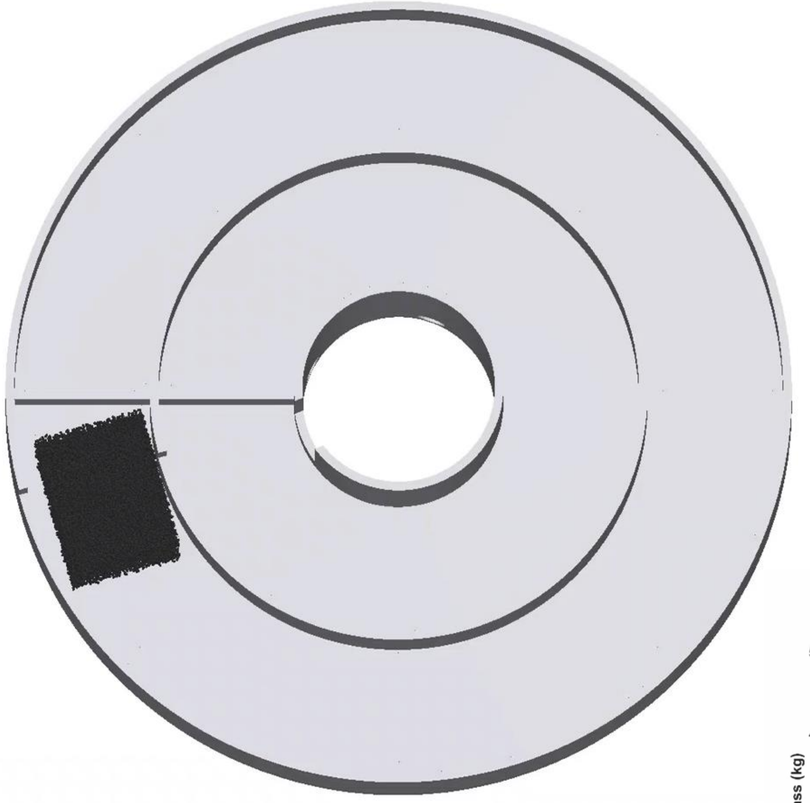
- We introduced cohesion through JKR surface energy and examined its impact on transport
    - 0.1, 0.3, 0.5, 0.7, and 0.9 J/m2 trials were completed





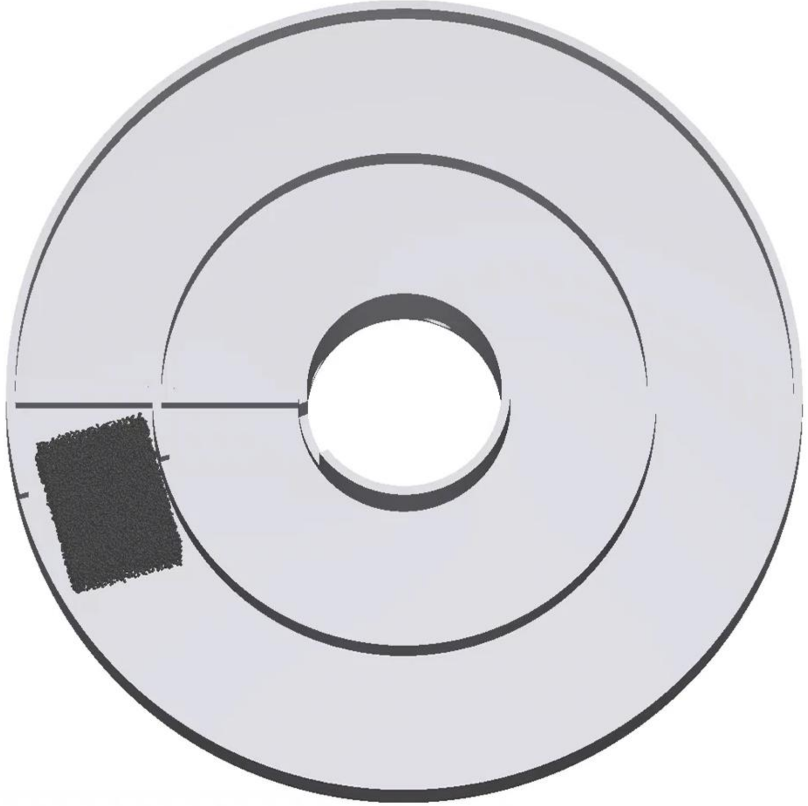
Results – 4 Hz (w/ and w/o Cohesion) (Earth-G)

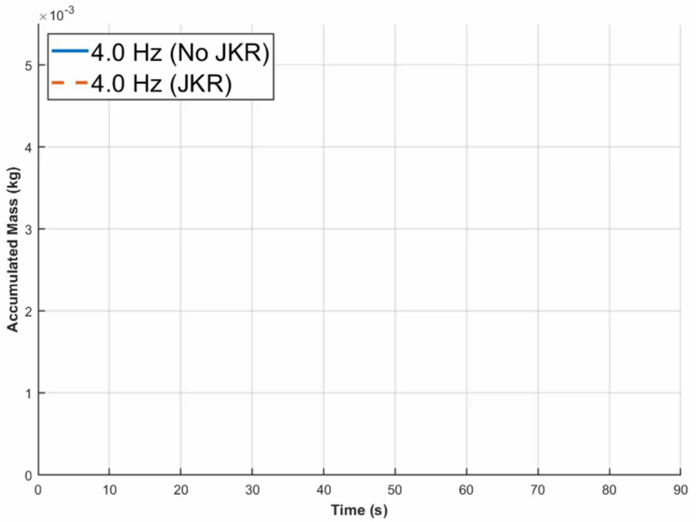
With cohesion



No Cohesion

Time: 0.030002 s





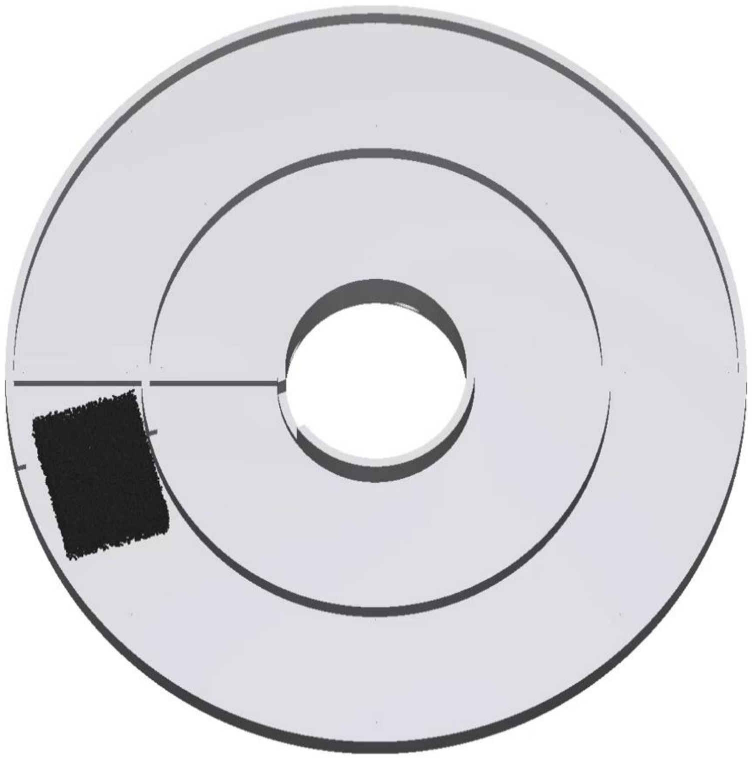
Mass Accumulation

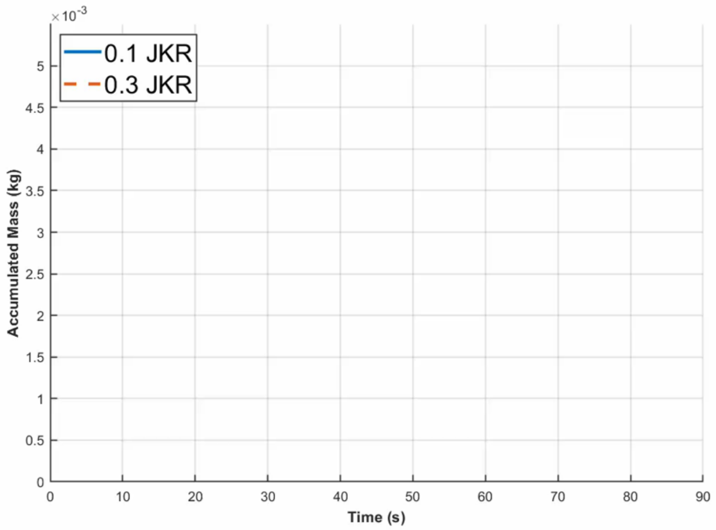
Results – 4 Hz (0.1 vs 0.5 JKR) (Earth-G)

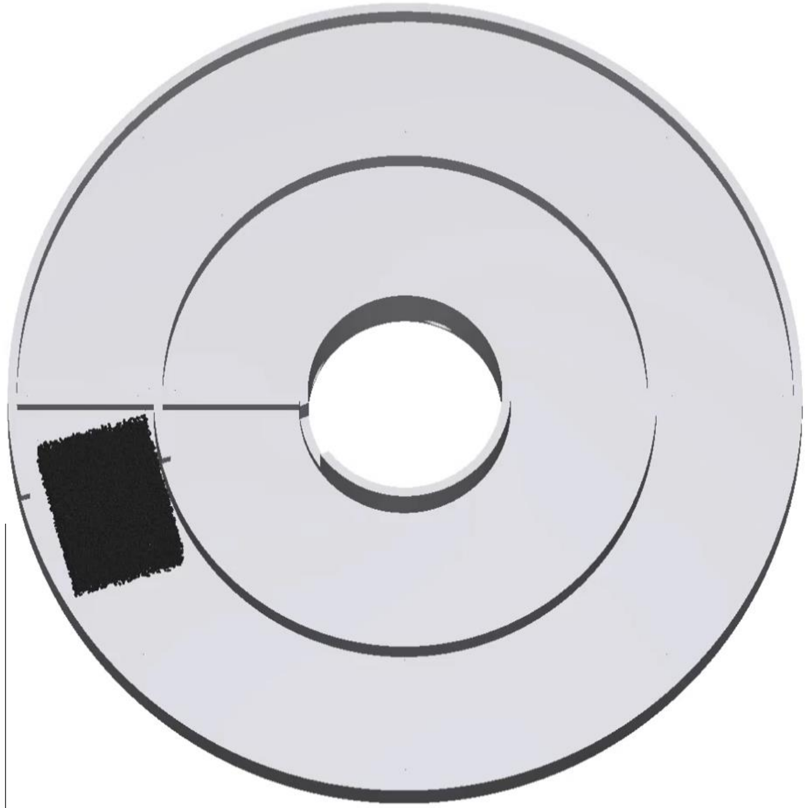
0.1 J/m²

0.3 J/m²

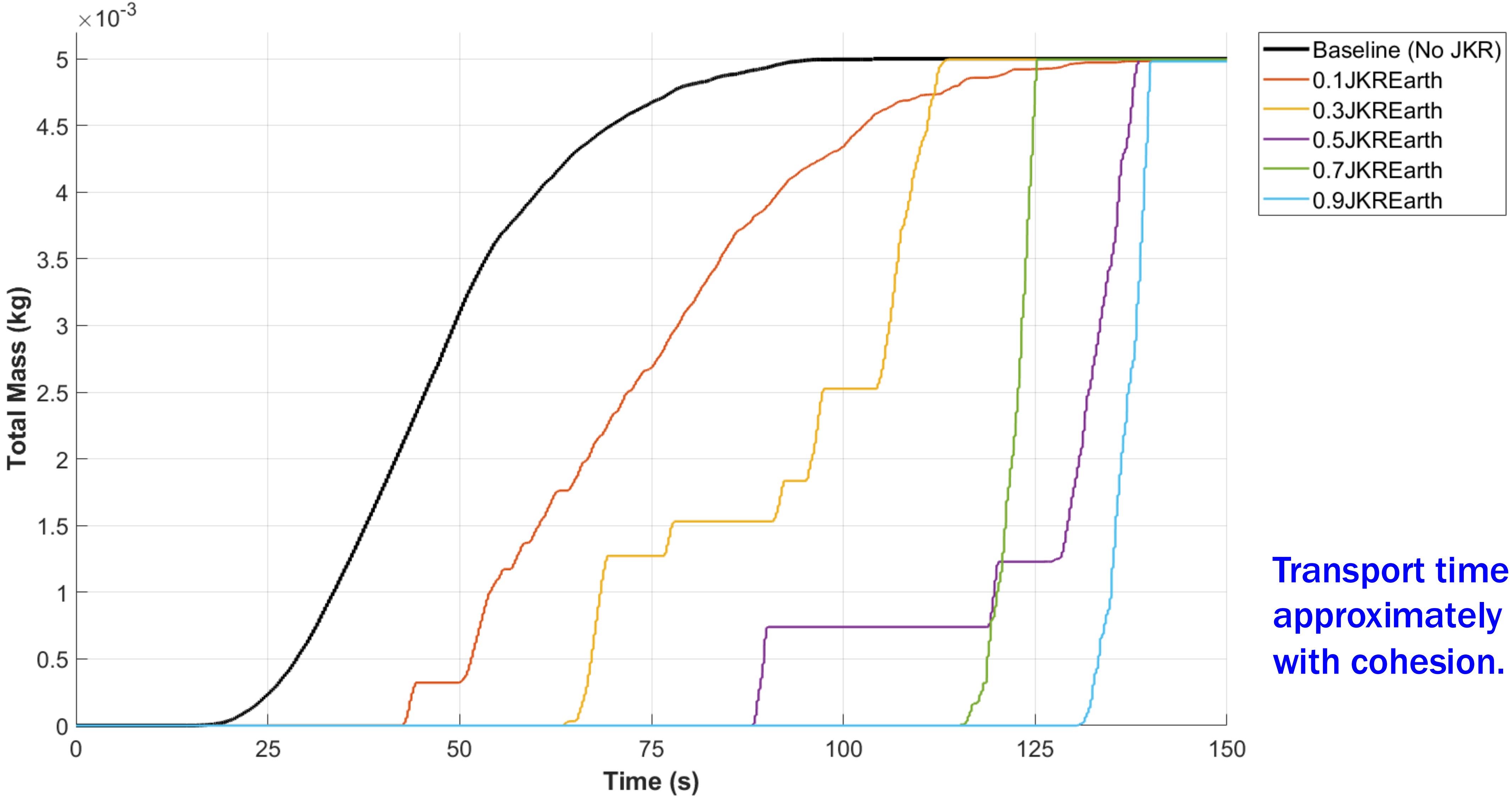
Time: 0.030002 s





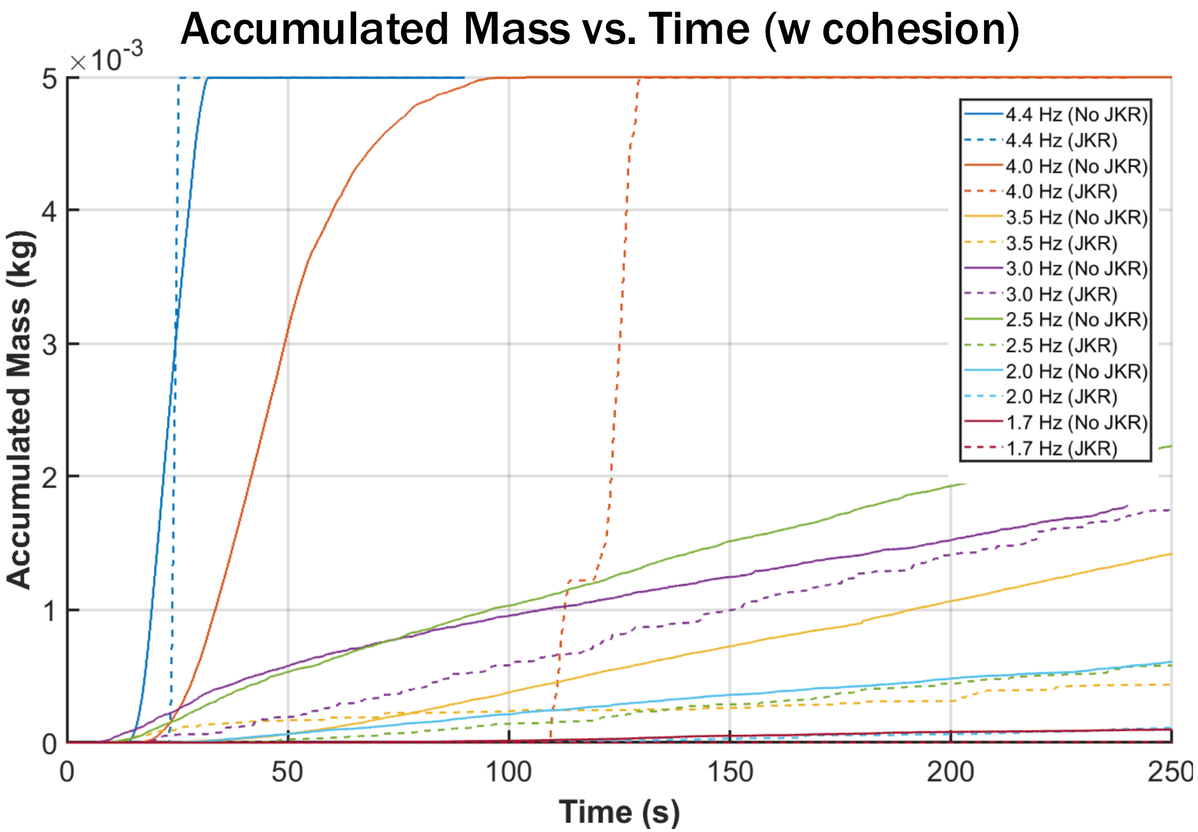


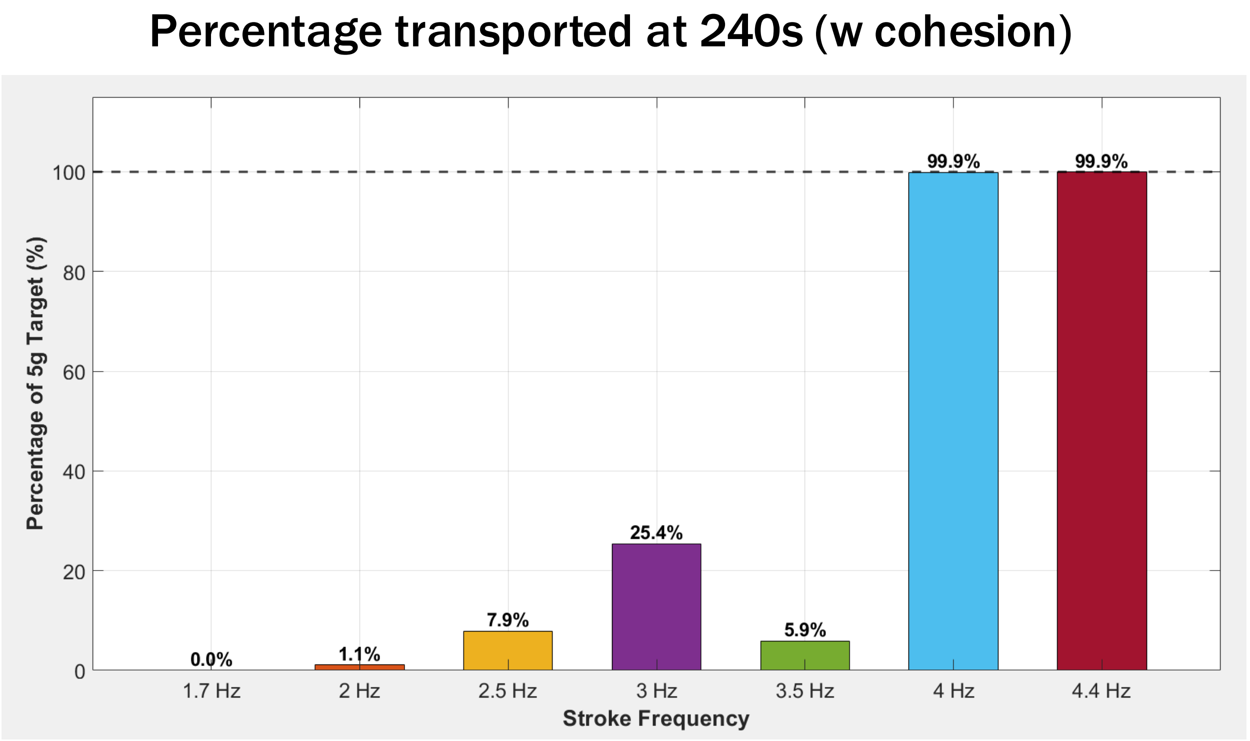
Results – Scaled Cohesion (Earth-G)



Transport time increases approximately monotonically with cohesion.

Results – Cohesion (Earth-G)



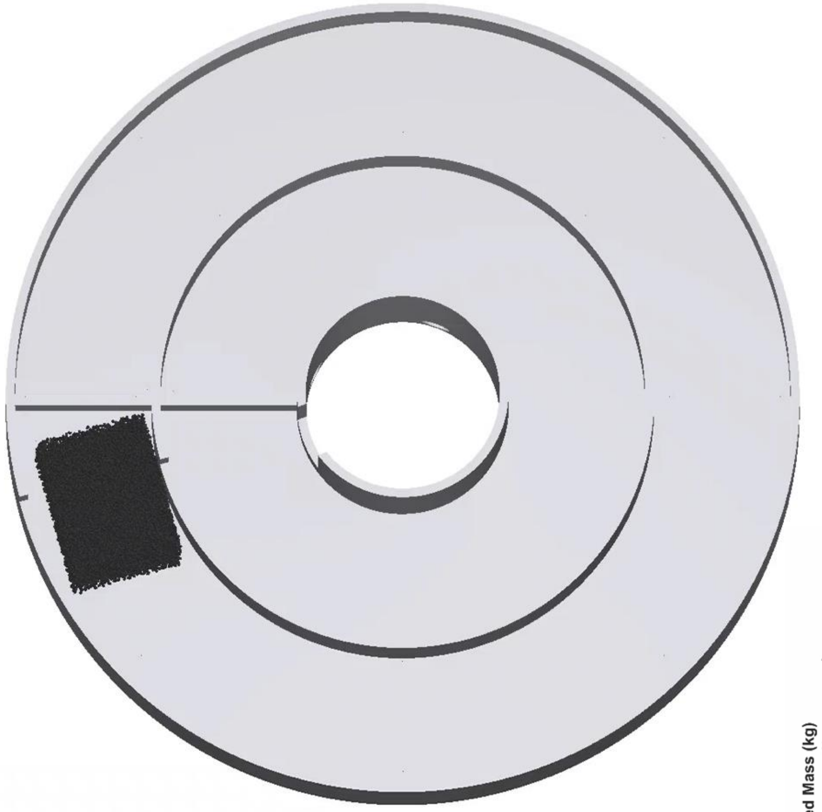


Earth-G cohesion findings

- Cohesion promotes particle clustering and increases resistance to transport and reduces efficiency
- Effect strongest below 4 Hz
- High-frequency operation partially offsets cohesion penalties

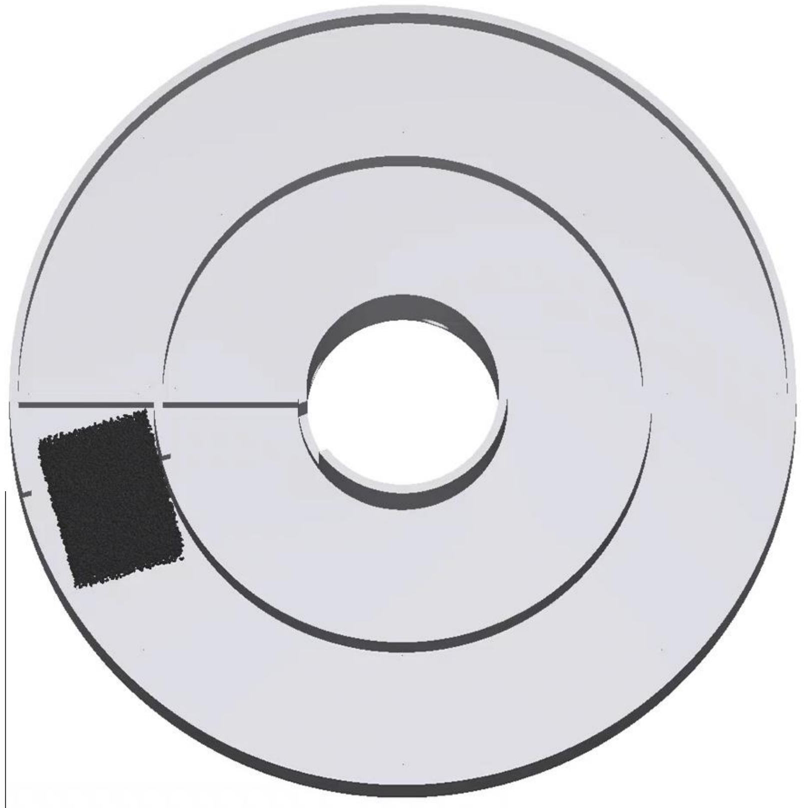
Results – 2.5 Hz (w/ and w/o Cohesion) (Lunar-G)

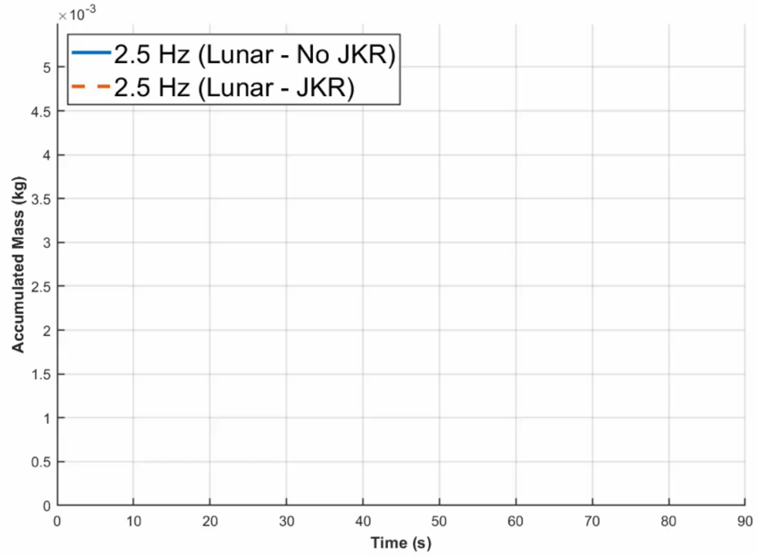
With cohesion



No Cohesion

Time: 0.030002 s





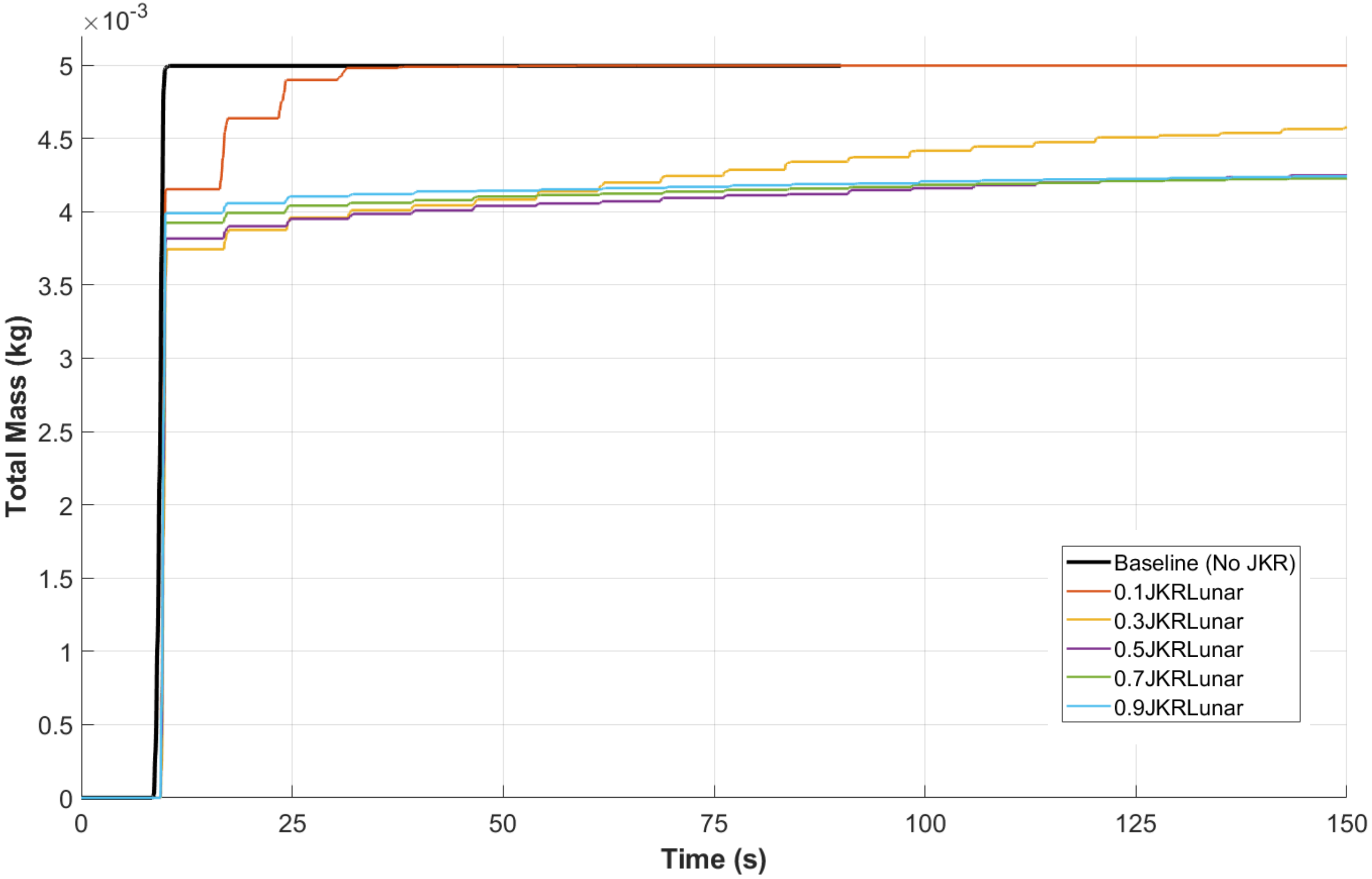
Mass Accumulation

Results – Scaled Cohesion (Lunar-G)

Lunar-G cohesion findings

- Cohesion remains detrimental but transport is still significantly more efficient than Earth gravity

- The collection of plotted lines shows that a clump of particles crosses the accumulation sensor around 10 seconds



Key Takeaways

Condition	Recommended Frequency
Earth-G	4.0–4.4 Hz
Lunar-G	~2.5 Hz
Higher Cohesion	Expect reduced throughput

DEM suggests lunar operation can achieve similar transport performance at substantially lower operating frequencies than Earth-based operation.

Summary & Future Work

Main Findings:

1. Lunar gravity dramatically improves VLRC transport efficiency.
2. Earth-G requires ≈4 Hz for efficient transport.
3. Lunar-G performance saturates near ≈2.5 Hz.
4. Cohesion generally reduces transport efficiency.
5. DEM provides a virtual testbed for VLRC optimization.

Engineering Implication: Lunar VLRC systems may achieve efficient regolith transport at lower operating frequencies, potentially reducing actuator demands and energy consumption.

Future Work

- Influence of realistic lunar regolith particle size distributions and particle morphology
- Validate DEM predictions against future reduced-gravity and flight-test data from the VLRC program.
- Extend the digital twin framework to evaluate throughput, energy efficiency, and design optimization for lunar surface operations.

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Thank you!

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- **Additional Slides**