Advancements in Vibrational Segregation for Particle Size Classification

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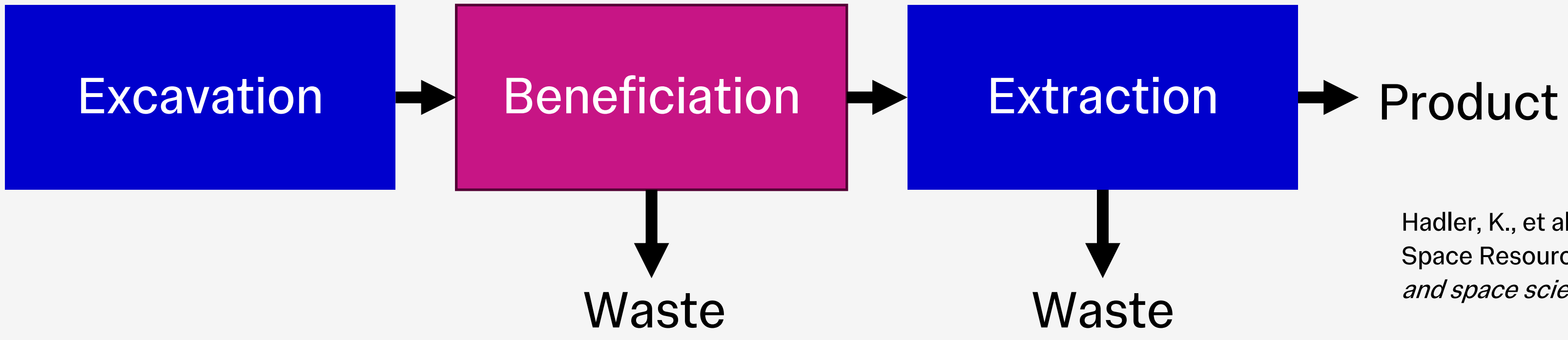
ISRU Context & Challenges
Motivation & Context

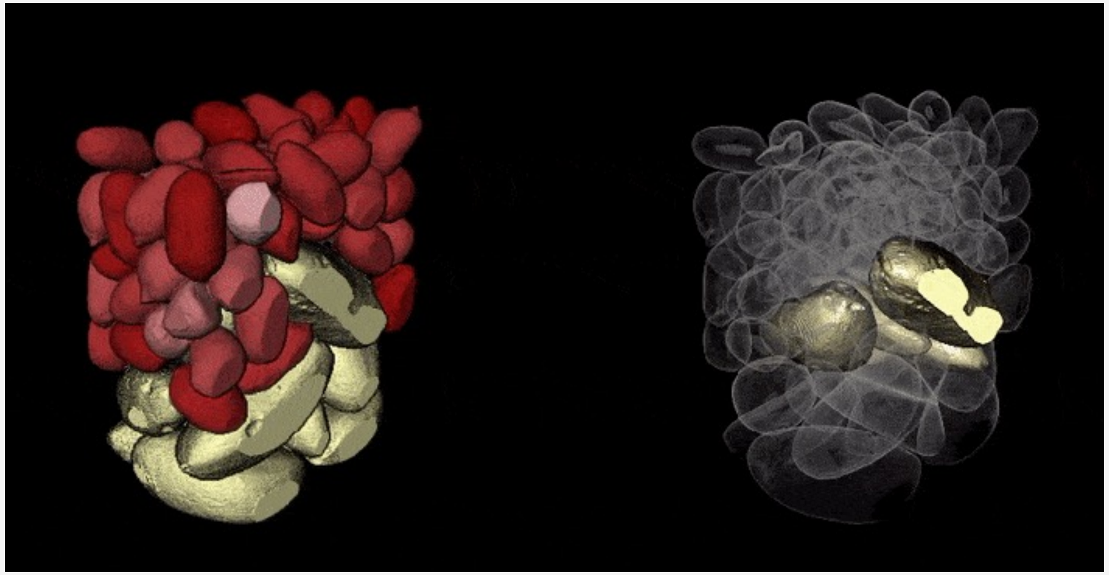
- Sustained lunar exploration depends on efficient ISRU.
- Dry beneficiation is ideal due to extreme environmental conditions on the Moon.
- Size classification is a key step for beneficiation: enables downstream mineral separation.
- Conventional wet processes unsuitable → need robust, low-power alternatives.



Hadler, K., et al. "A universal framework for Space Resource Utilisation (SRU)." *Planetary and space science* 182 (2020): 104811.

The Brazil Nut Effect (BNE)
Motivation & Context

- BNE = size segregation in vibrated granular media.
- Larger particles rise to the top due to convection and void-filling.
- Attractive for ISRU: passive, dry, low-maintenance.
- Limitations: Past studies relied on simplified intruder tests with spherical particles.

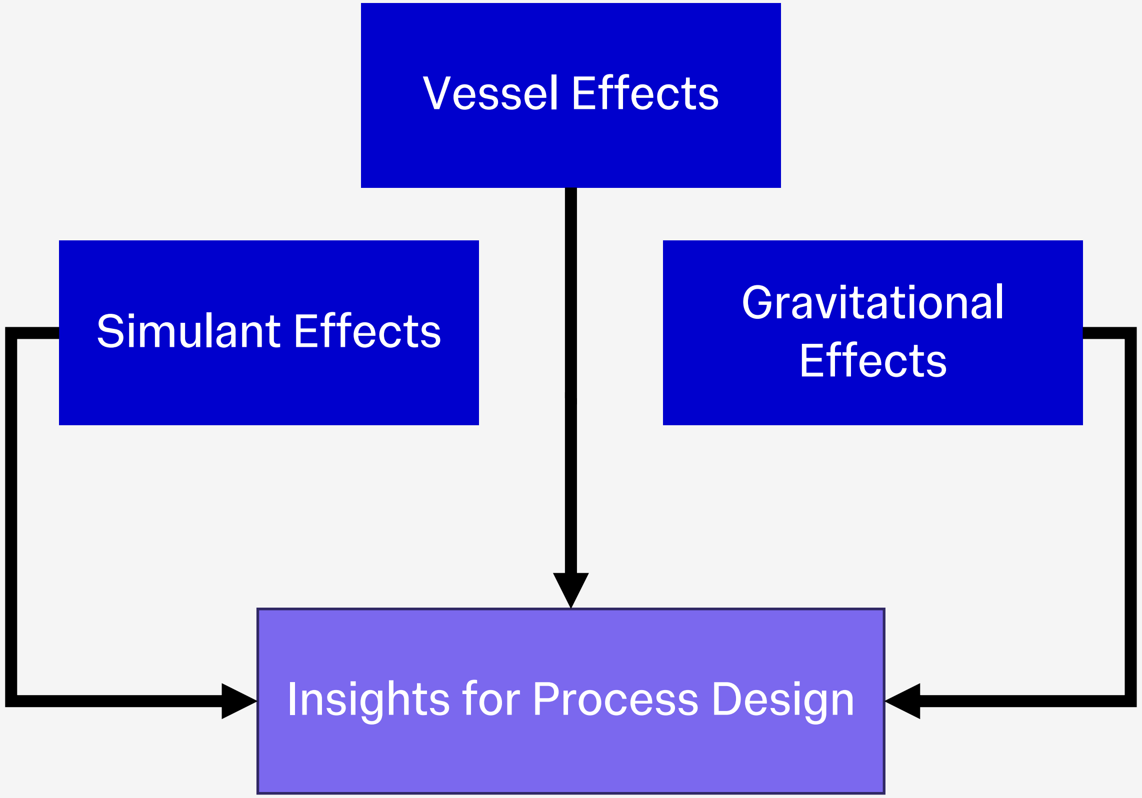


Gajjar, P., Johnson, C. G., Carr, J., Chrispeels, K., Gray, J. M. N. T., & Withers, P. J. (2021). Size segregation of irregular granular materials captured by time-resolved 3D imaging. Scientific reports, 11(1), 1-6.

Study Design: Integrated Approach

Study Overview

- Objective: Evaluate key equipment and environmental parameters influencing the BNE.
- Three parallel investigations studied:
    1. The role of simulant morphology and composition.
    2. The impact of vessel geometry.
    3. Performance variations between terrestrial and lunar gravity conditions (using DEM).



Experimental Parameters

Study Overview

- Both experimental studies employed fixed amplitude/frequency
- Micro-CT used for post-shake characterisation of PSD.
- Outputs: Segregation efficiency, compaction, layering.

Particle Effects Study

- Samples: 7 simulants (LMS-1, LHS-1, with dust/agglutinate variations), and Ballotini (spherical glass beads)
- Setup: 1.5g per sample

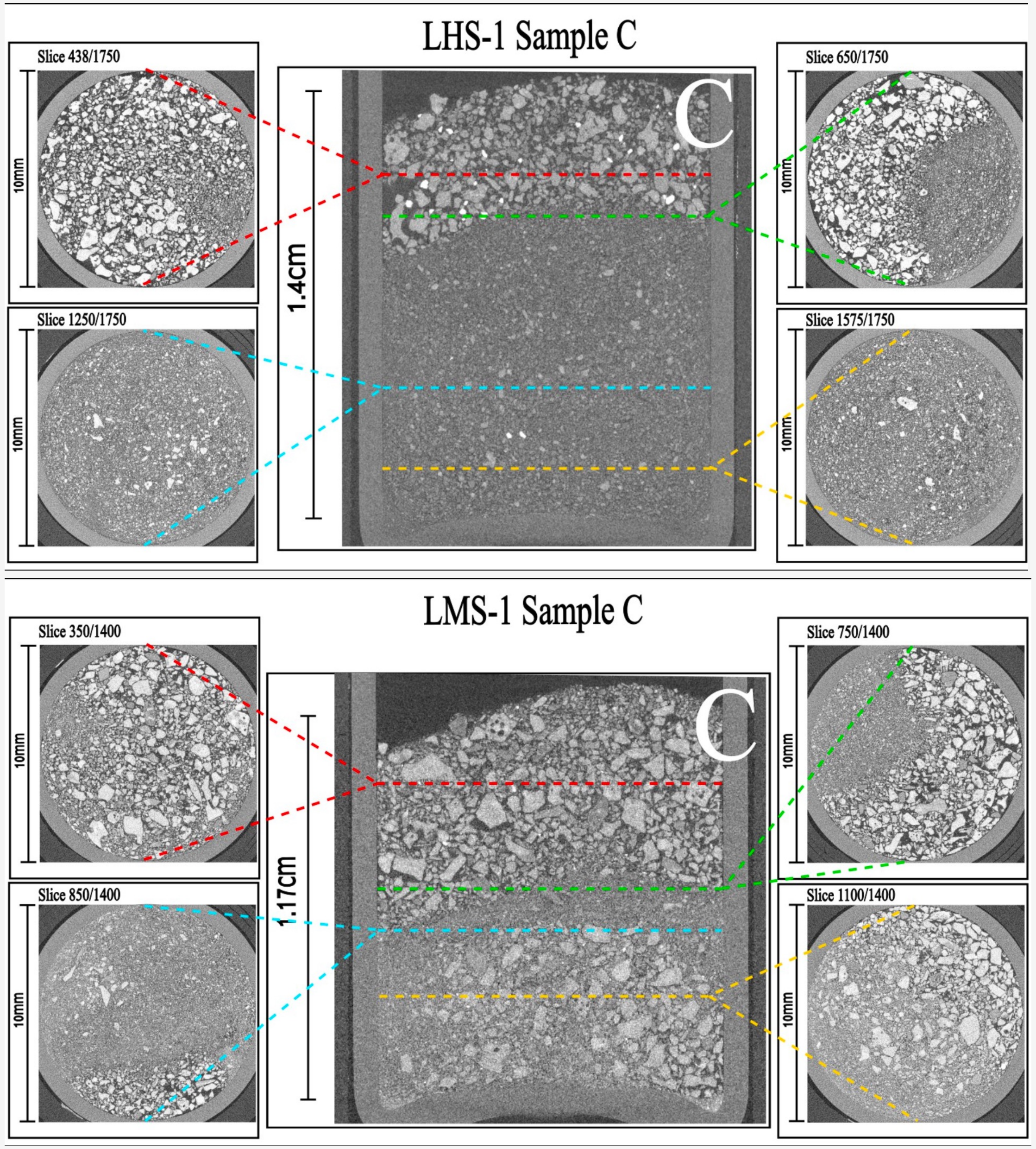
Geometry Effects Study

- Samples: Ballotini sized to Coarse (90-1000 μm), Fine (0-90 μm), and Mixed (0-1000 μm)
- Setup: vessels had same base area and a constant bed height (2 cm)
- 3 container geometries: cylindrical, square, equilateral triangular

Regolith Composition Effects

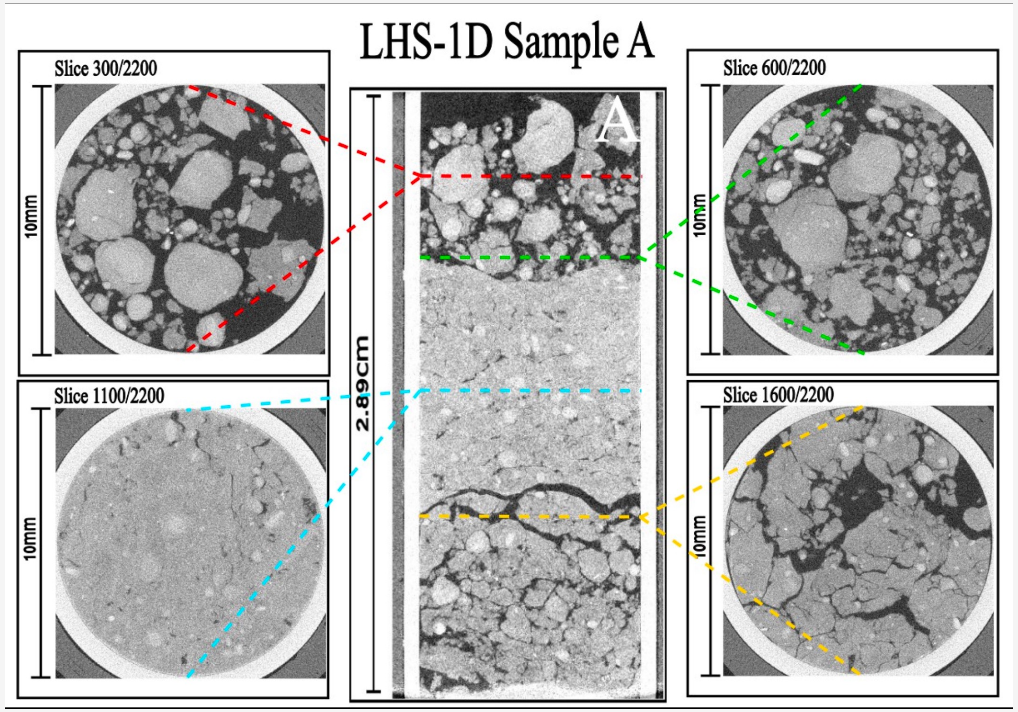
Key Experimental Results

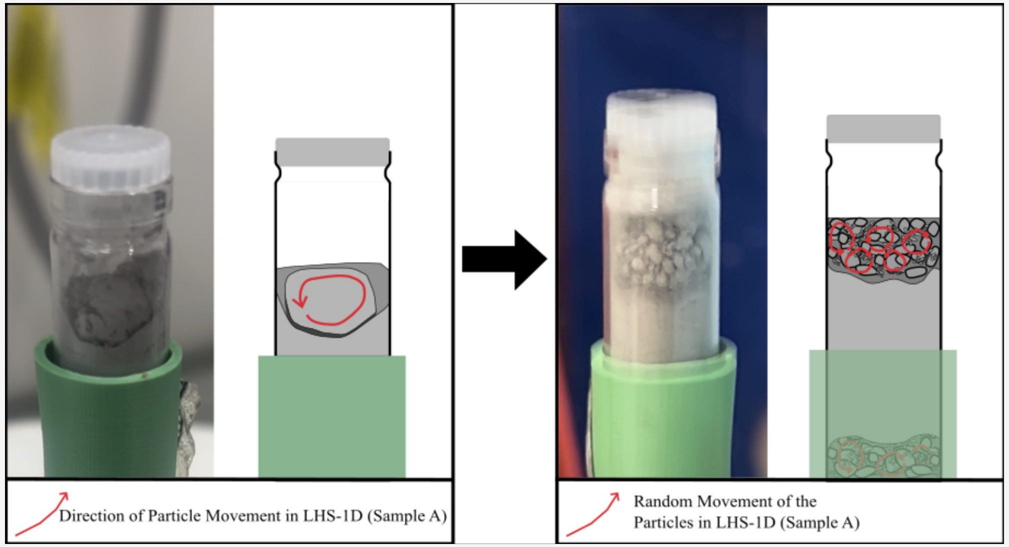
- **Key Findings:**
  - LHS-1 demonstrated **bimodal segregation**
  - LMS-1 stratified into **three-layers**, with a lower unsegregated region
  - LHS-1's top layer consisted of **coarser basaltic particles**, trapped by **void-filling.**
- **Why the difference?**
  - LMS-1 has varied particle densities & shapes, leading to **tighter packing, high cohesion, and particles becoming jammed.**
  - LHS-1 has larger, less compact particles, resisting tight packing.
  - LMS-1 compacted by **20.9%** due to vibrations, while LHS-1 only compacted by **3.28%.**



PSD Effects – Dust Fraction
Key Experimental Results

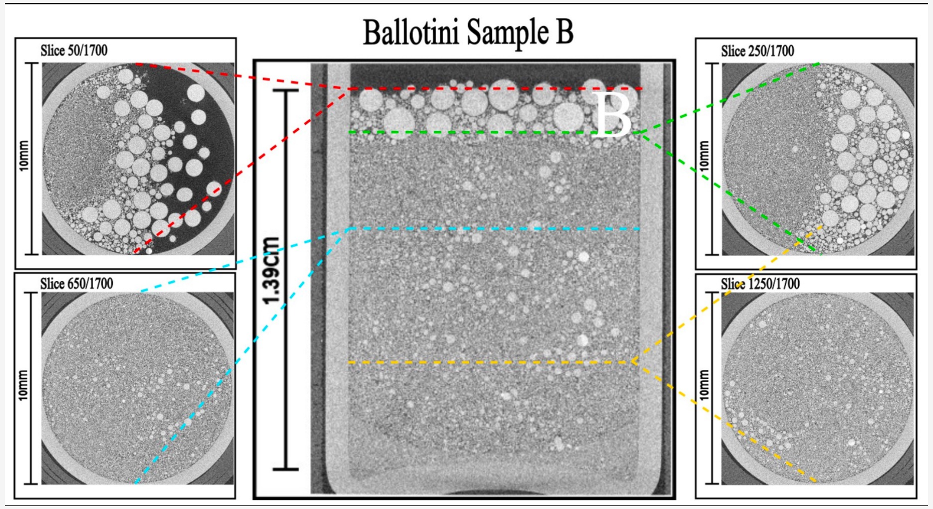
- **Key Findings:**
  - LHS-1D & LMS-1D exhibited **poor segregation** due to **cohesion and clumping.**
  - **Fine particles formed aggregates**, limiting percolation.
  - **Dense middle layer** prevented full segregation.
- **Why the Difference?**
  - Smaller particles have **high surface area-to-volume ratios,** increasing **inter-particle forces.**
  - **LHS-1D & LMS-1D compacted by 11.4%,** compared to **3.28% for LHS-1.**
  - **Segregation was minimal;** fine particles formed clumps rather than distinct layers.

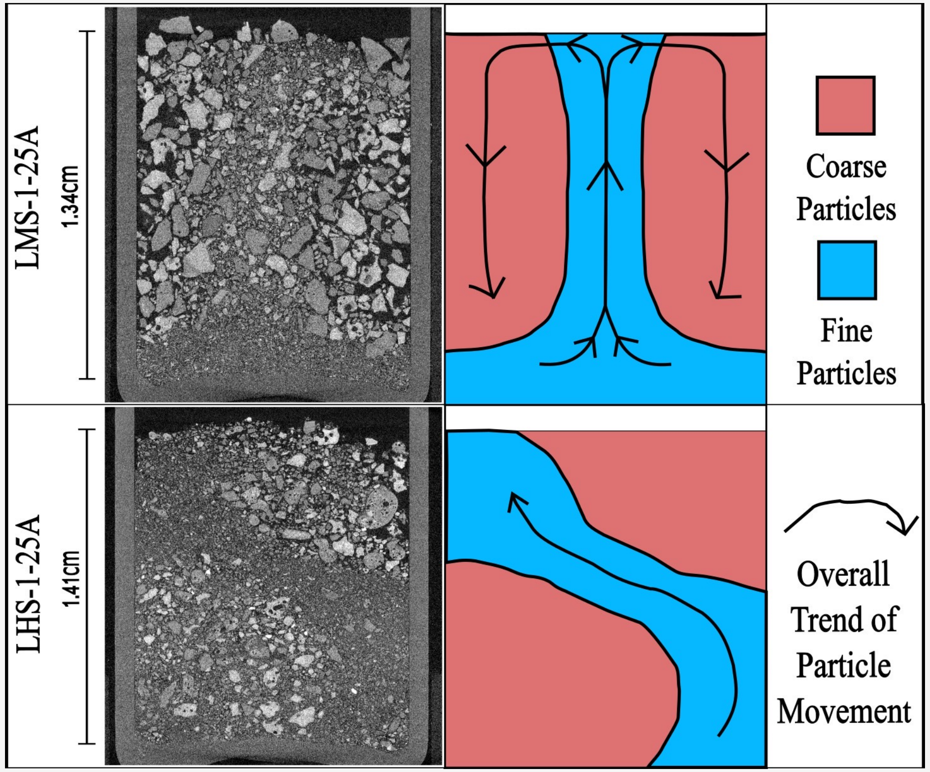




Agglutinates & Shape
Key Experimental Results

- **Key Findings:**
  - The **spherical ballotini** segregated more effectively than irregular simulant
  - LHS-1-25A & LMS-1-25A exhibited **irregular segregation patterns**
- **Why the Difference?**
  - Spherical particles have **lower friction & interlocking**, facilitating ascension/percolation.
  - **Stronger interlocking** from irregular agglutinates disrupted convection & void-filling
- **Key Takeaways:**
  - **Particle shape** plays a critical role in vibration-based segregation performance.
  - **High agglutinate content** in lunar regolith may reduce BNE performance

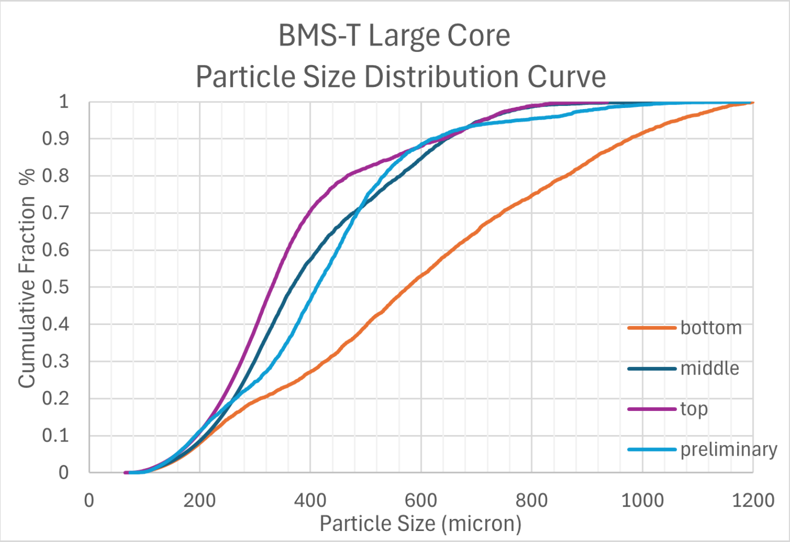


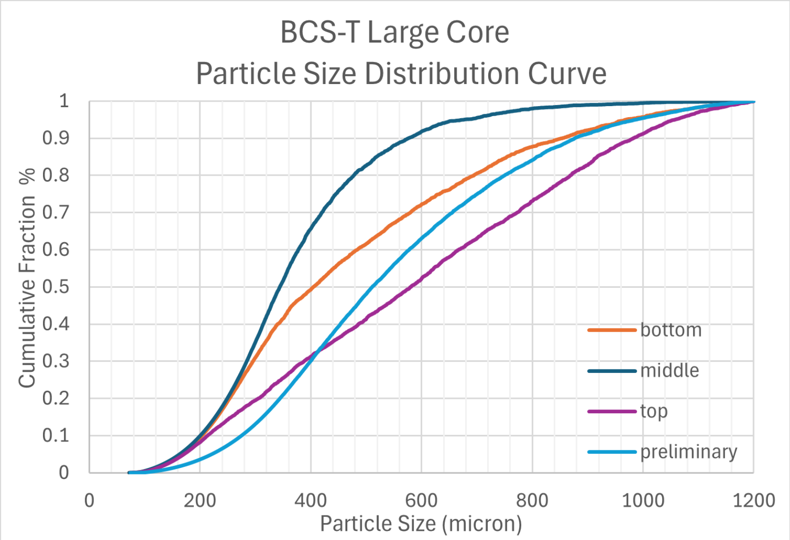


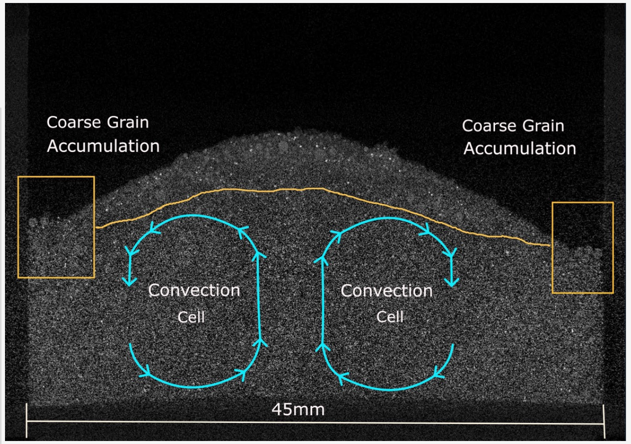
Vessel Geometry & PSD Effects

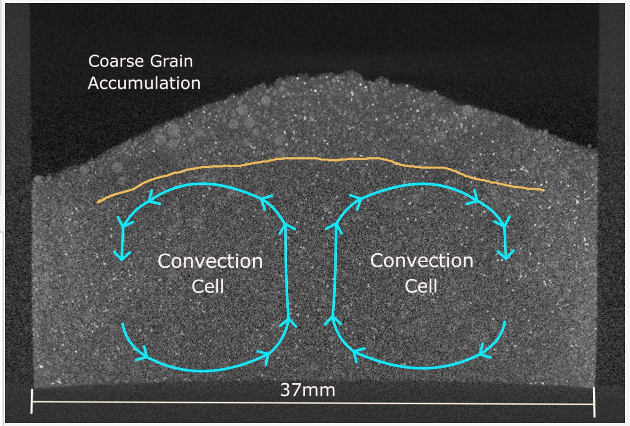
Key Experimental Results

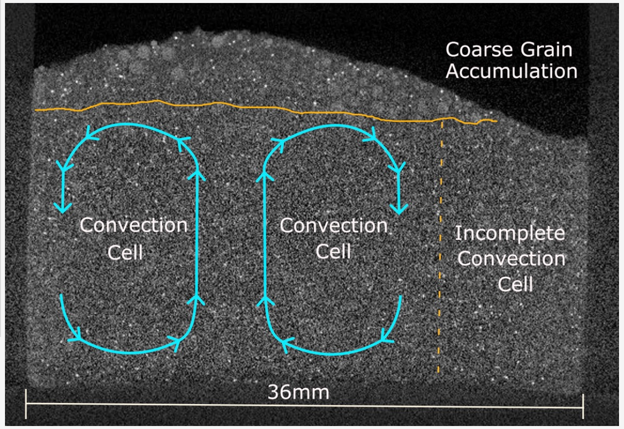
- **Key Findings:**
  - BNE not observed in Fine class
  - Mixed and Coarse classes displayed BNE in circular and square vessels
  - BNE observed in triangular vessel with Coarse class, and reverse BNE displayed in Mixed class
  - Bulges formed with Mixed class only
- **Key Takeaways:**
  - BNE performance is tied to PSD and vessel geometry.
  - Fine (-90 µm) particles modify geomechanical properties, resulting in higher internal friction and bulging







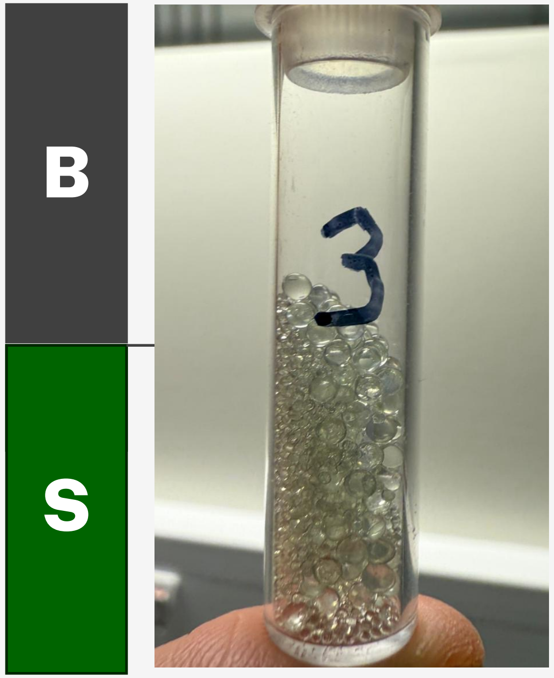




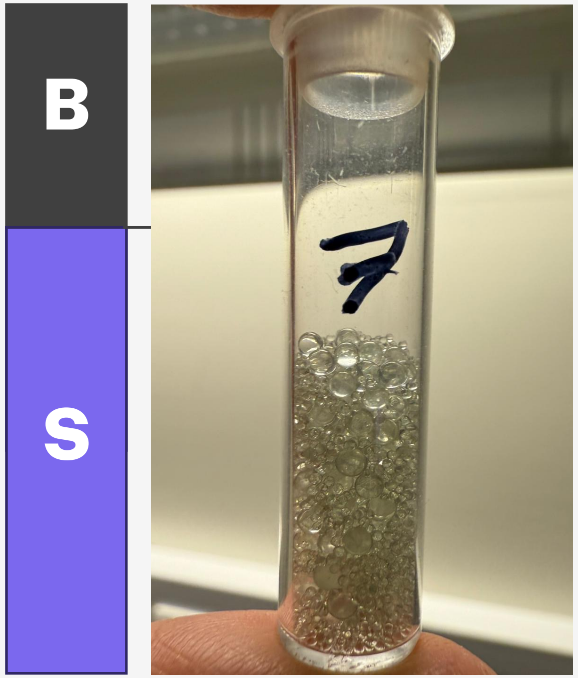
DEM Setup & Validation
Simulation Insights

- DEM implemented for comparative analysis under Earth vs Moon gravity using YADE.
- Use of spherical particles facilitated comparison with experimental data
- Variables:
  - Amplitude (0.5–1.5 mm),
  - Frequency (7.5–45 Hz),
  - Sample mixture ratios.
- Outputs: particle trajectories, velocity fields, stratigraphy.
- Models validated against XCT results.

1B/1S

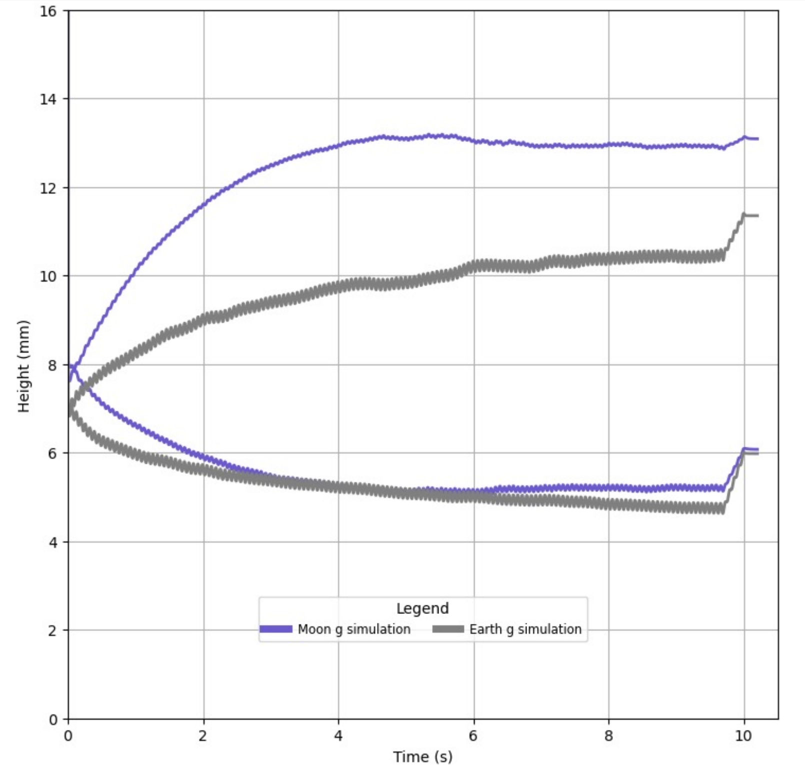


1B/2S

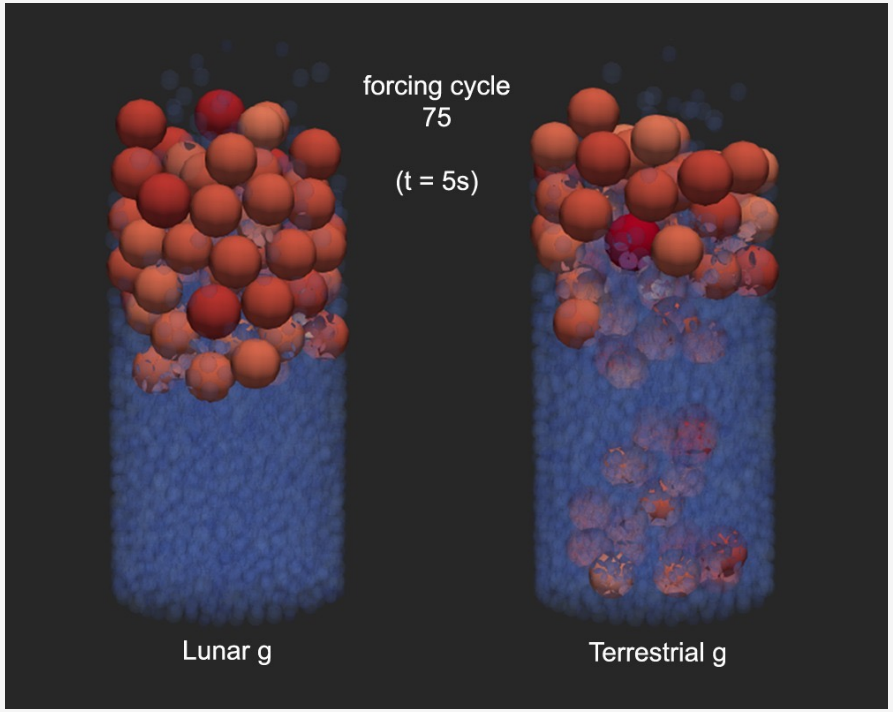


	1B/1S				1B/2S			
Test nº	1	2	3	4	5	6	7	8
Amplitude (mm)	0.50	0.75	1.00	1.50	0.50	0.75	1.00	1.50
Amplitude peak to peak (mm)	1.00	1.50	2.00	3.00	1.00	1.50	2.00	3.00
Frequency (Hz)	15							

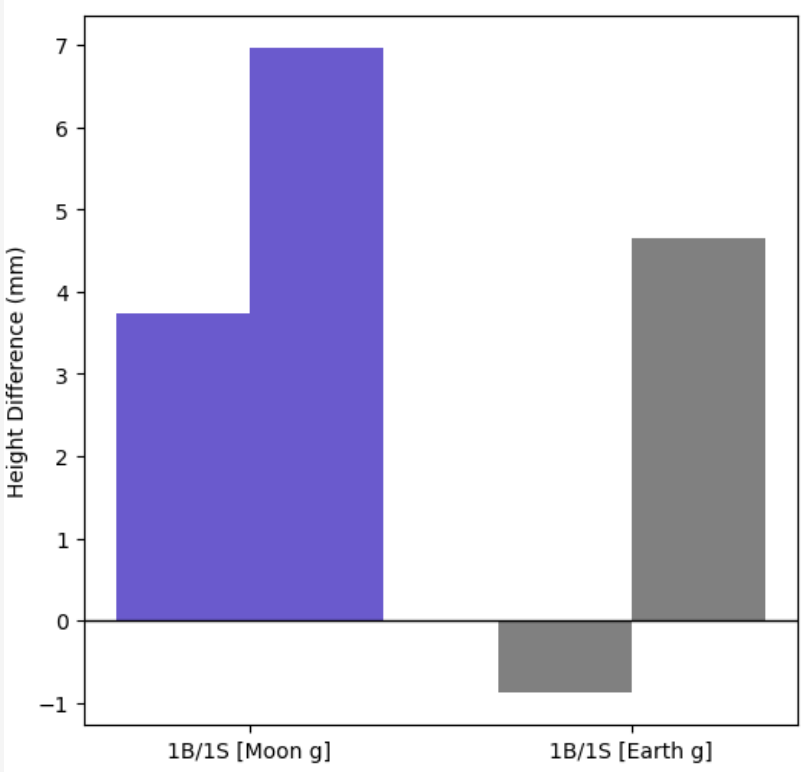
Earth vs Lunar Gravity
Simulation Insights



Comparison between terrestrial (in grey) and lunar (in purple) results for sample 1B/2S with A = 1.5 mm



Comparison of two simulations at the same time value (forcing cycle). The lunar case has separated while the terrestrial one has not.



Comparison between terrestrial (in grey) and lunar (in purple) height differences between size fractions.

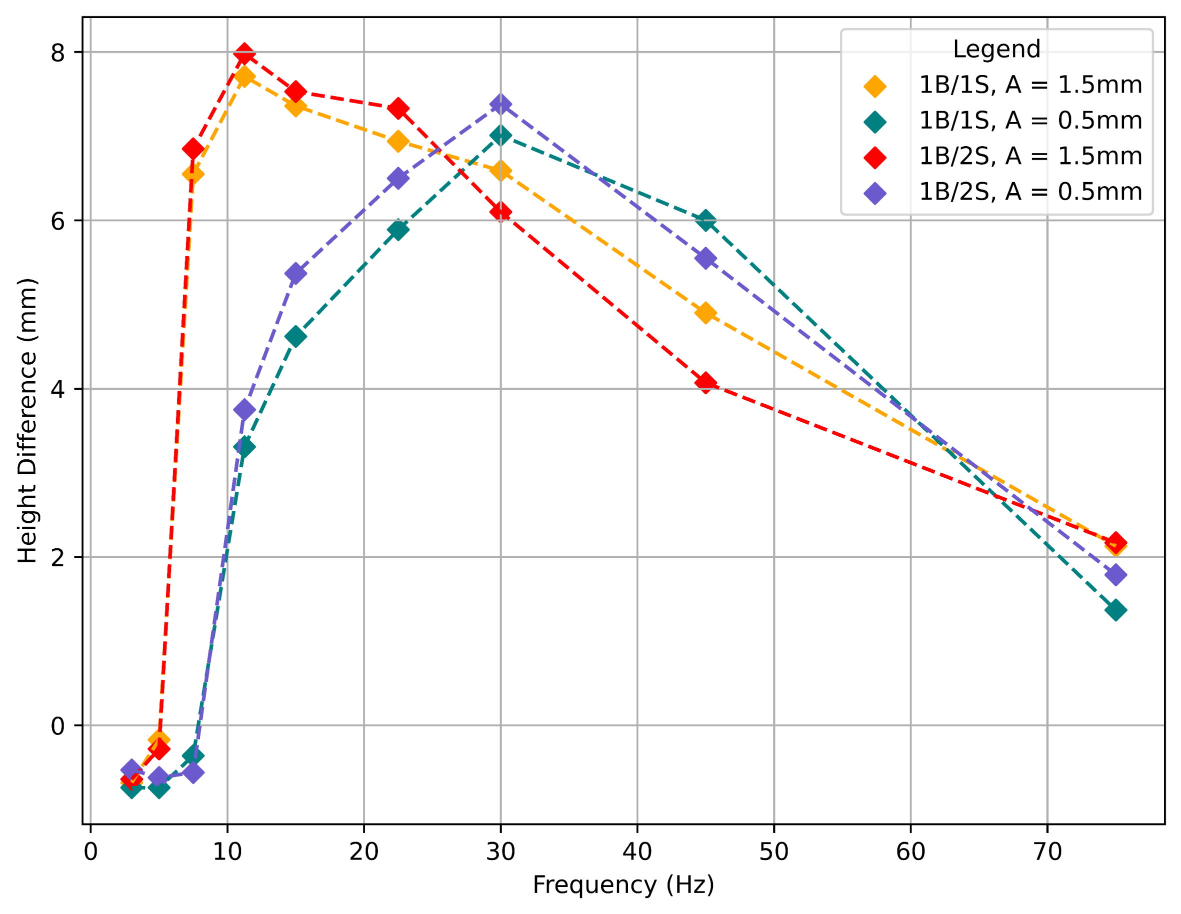
Optimisation of Vibrational Settings
Simulation Insights

- High amplitude simulations reveal an initial spike, proportional with the increase in frequency
- Very low frequencies produce no BNE
- There is a frequency value from which BNE quality reduces
- Results suggest is an optimal frequency for each amplitude value:

A = 0.5 mm ▶ $f_{optimal}$ = 30 Hz

↓ 3x increase ↓ ~ 3x reduction

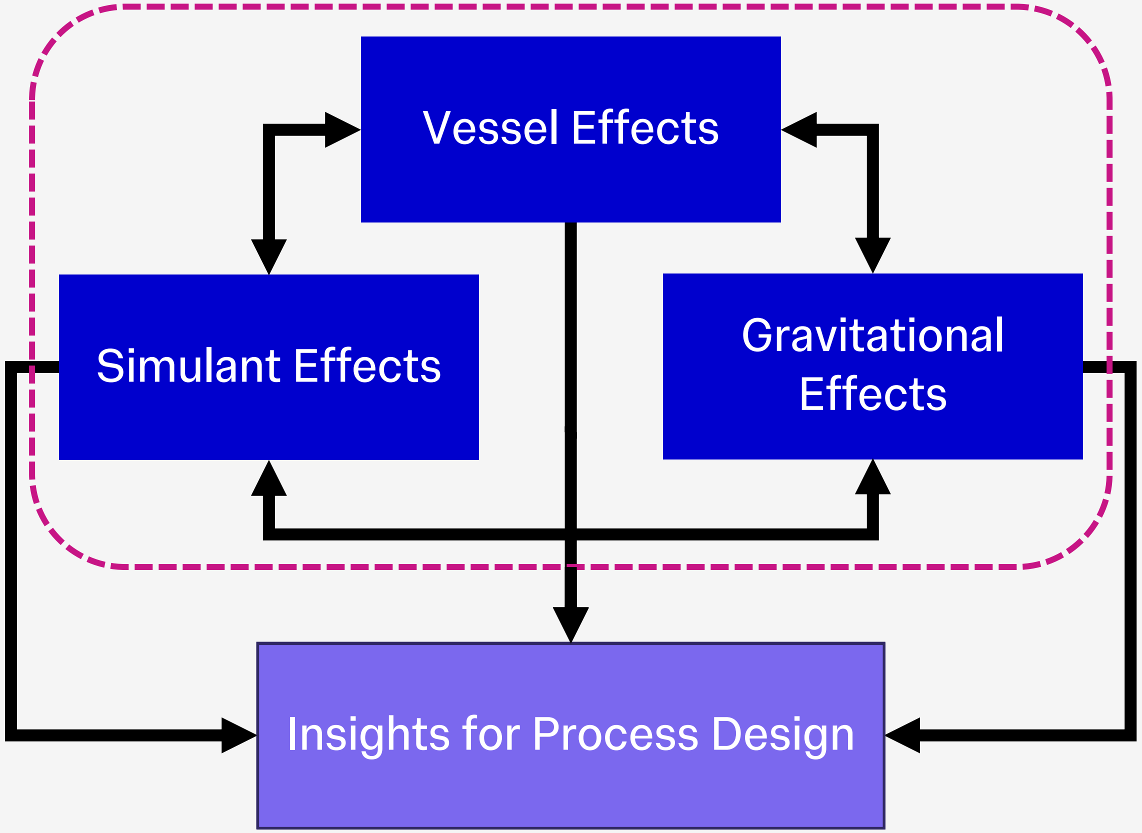
A = 1.5 mm ▶ $f_{optimal}$ = 11.25 Hz



Key Takeaways & ISRU Implications

Conclusions & Outlook

- BNE viable for lunar beneficiation, but challenges still to overcome.
- Particle composition, morphology, PSD, and vessel geometry all impact performance greatly
- DEM shows promise for predicting performance under lunar gravity conditions.
- Future work:
  - Integration of simulant, gravitational, and vessel effects experimentally and with DEM
  - Validate under vacuum
  - Develop staged/continuous processing.



IMPERIAL

Thank you

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