ADVANCEMENTS IN VIBRATIONAL SEGREGATION FOR PARTICLE SIZE CLASSIFICATION.

R. Franks[1,*], S.R. Wang[1,*], M. Albino[2,*], G. Paneiro[2], J.J. Cilliers[1], L.E. Salinas Faran[1], J.N. Rasera[1]
[1]Imperial College London, Exhibition Road, London, SW7 2AZ, United Kingdom, j.rasera@imperial.ac.uk,
[2]Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1, 1049-001, Lisboa, Portugal.
[*]Denotes equal contribution.

Introduction: In-situ resource utilisation (ISRU) on the Moon necessitates efficient beneficiation methods for lunar regolith to concentrate resources essential for sustained lunar missions. Previously, we proposed using the Brazil Nut Effect (BNE)—the tendency of larger particles to rise in a vertically vibrated granular medium—as a dry size-classification method suitable for lunar regolith processing [1]. However, lunar regolith characteristics, including composition, particle size distribution (PSD), agglutinate content, and container geometry, substantially influence segregation performance. This work synthesises findings from experimental simulant tests, controlled geometry experiments, and numerical discrete element method (DEM) simulations, to comprehensively investigate these factors and inform the design of efficient, low-maintenance particle separation techniques for lunar applications.

Methodologies: Simulant segregation experiments were conducted using six different lunar regolith simulants representative of highlands and mare (LMS-1/1D/1-25A, LHS-1/1D/1-25A) and spherical soda-lime glass beads (ballotini). Samples were vibrated vertically at fixed amplitude and frequency within cylindrical containers and subsequently analysed via high-resolution micro-CT imaging to examine internal particle stratigraphy. This allowed precise characterisation of segregation influenced by mineralogical composition, morphology, size, and agglutinate content (25 wt.%).

In parallel, geometry and PSD experiments systematically isolated the effects of container geometry and fine particle content using ballotini. Containers with circular, square, and triangular cross-sections were tested under controlled amplitude and frequency conditions, comparing two distinct particle size distributions: a fines-free fraction (90–1000 µm) and a broader fraction including fines (0–1000 µm). This methodology allowed the clear evaluation of geometric effects without confounding factors introduced by irregular particle shapes or compositions.

DEM simulations complemented these experimental studies, providing deeper insight into particle interactions and convective behaviour within vibrated granular systems. The model explicitly tracked convection cell formation, void-filling events, and particle trajectories under varying vibration amplitudes and frequencies, comparing terrestrial and lunar gravity conditions.

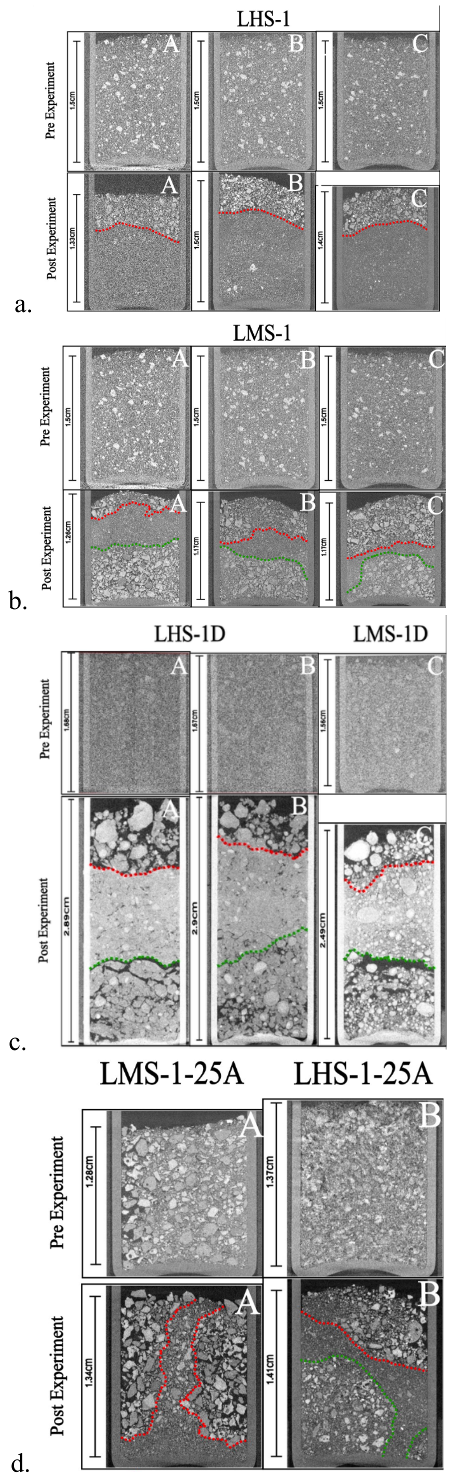

Fig. 1 – 2D slices from micro-CT demonstrating segregation performance.

This enabled the exploration of gravitational effects on segregation mechanisms, extending the relevance of experimental findings to anticipated lunar environmental conditions.

Results: Experimental results indicated clear differences in segregation performance driven by regolith simulant properties. The more angular highland simulant, LHS-1, consistently achieved near-complete two-layer segregation, clearly separating coarse particles from fines (Fig. 1a). Conversely, LMS-1 demonstrated partial segregation with a distinct three-layered stratigraphy, reflecting complexity due to finer particle presence and greater particle cohesion (Fig. 1b). The dust fractions (LMS/LHS-1D) of LMS and LHS formed three distinct layers: a loosely packed upper layer of large aggregates, a tightly packed middle layer, and a loosely packed lower layer also containing aggregates (Fig. 1c). Incorporating agglutinates (LMS/LHS-1-25A) into the simulants dramatically altered segregation patterns, with intensified convection and increased void formation, creating complex segregation profiles—most notably in the mare simulant, which exhibited pronounced convective mixing and incomplete segregation (Fig. 1d).

Container geometry experiments demonstrated significant effects on segregation efficacy (Fig. 2), with the square container producing optimal segregation through a single, stable convection cell. Cylindrical containers also supported segregation, but with less efficiency compared to the square geometry. The triangular geometry exhibited a striking reversal of segregation (reverse BNE) with increased fines, attributed to complex convection cell patterns generated by the sharp angular geometry.

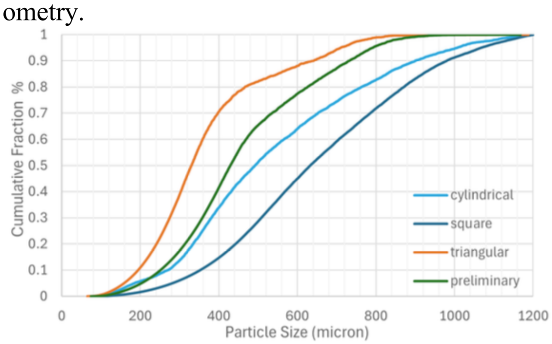

Fig. 2 – PSD comparison of top segment from 3 geometries compared to the preliminary PSD.

DEM simulations validated and expanded on experimental findings, demonstrating how changes in vibration amplitude or frequency influenced particle dynamics. High amplitude or frequency conditions led to fluidisation and chaotic convection patterns, reducing segregation effectiveness. Critically, DEM predictions under lunar gravity (0.16g) indicated faster and more effective segregation due to enhanced void-filling mechanisms (Fig. 3). Under lower gravitational conditions, void-filling dominates, facilitating the migration of small particles downward and thus promoting coarse particle ascent

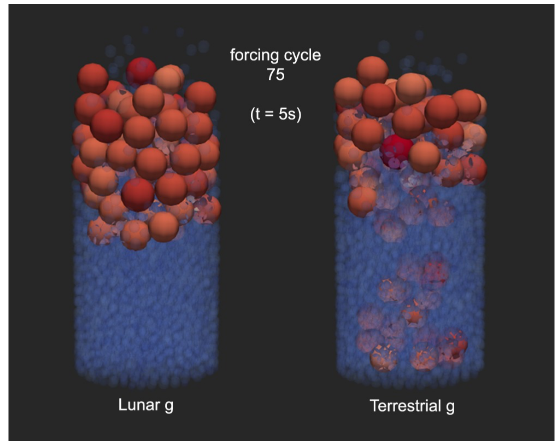

Fig. 3 – Comparison of two simulations at the same time value (forcing cycle). The lunar case has separated while the terrestrial one has not.

Conclusions: Vibration-induced segregation leveraging the Brazil Nut Effect is confirmed as a promising dry beneficiation approach for lunar regolith, but its implementation requires careful consideration of regolith properties, vibration conditions, and container design. Mineralogical homogeneity and angular morphology facilitate efficient segregation, whereas abundant fines and cohesive components significantly complicate the process. Agglutinate content intensifies these challenges by enhancing both convection and void-filling, resulting in complex intermediate stratifications. This suggests that a staged approach may be beneficial to maximise overall size segregation performance. Container geometry plays a critical role in determining segregation efficiency, with optimal geometries promoting stable, single-cell convection patterns.

DEM modelling provided essential mechanistic insights into the segregation process, confirming the dual importance of void-filling and convection mechanisms. Simulations under lunar gravity predicted slower yet potentially more efficient segregation through increased dominance of void-filling. These findings highlight the necessity of tailored designs to accommodate lunar-specific conditions, ensuring effective size sorting in future lunar ISRU operations. Ongoing research aims to explore staged processing, as well as to validate these insights under lunar gravity and vacuum conditions.

References: [1] Rasera et al. (2025), Sci. Rep. (Under review); [2] Franks, R. (2025), MSci Thesis, Imperial College London; [3] Wang, R.S. (2025), MSci Thesis, Imperial College London; [4] Albino, M. (2025), MSc Thesis, Univ. de Lisboa.