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Influence of Particle Morphology on the Mechanical Characteristics of Lunar Soil via Numerical Simulation

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Abstract: The mechanical properties of lunar regolith are fundamental to extraterrestrial resource utilization and deep space exploration, directly influencing the safety of lunar infrastructure and base construction. Traditional discrete element method (DEM) simulations often oversimplify particle morphology as spherical, leading to biased mechanical predictions, while in-situ lunar testing remains cost-prohibitive. This study investigates the effects of realistic particle morphology—using CE-6 lunar regolith scanned into 2 distinct shapes (i.e., near-spherical and platy particles)— on the mechanical behavior via triaxial shear DEM simulations. Results show that platy specimens exhibit higher peak strength than spherical simplifications, with strain hardening dominating except for spherical specimens under high confinement. Micromechanically, platy particles demonstrate complex force chains, stress concentration, and anisotropic contact forces, whereas spherical particles yield uniform distributions. These findings advance lunar soil-structure interaction models, inform simulated regolith development, and provide methodological insights for planetary soil studies, supporting China's lunar exploration and deep space endeavors.

Keywords: ***Chang'e 6 lunar, Particle morphology, Mechanical behavior.***

Introduction

With the increasing depletion of Earth's resources and the rapid advancement of deep space exploration technologies, nations worldwide have formulated various deep space exploration plans, competing to establish technological superiority in this field. International lunar exploration programs have accumulated valuable sample data. During six crewed missions (1969–1972), NASA's Apollo program collected a total of 382 kg of lunar rocks and soil, comprising 2,196 individual samples. The Soviet Union's Luna missions, through three unmanned sampling missions (Luna 16, 20, and 24, 1970–1976), obtained subsurface core samples via drilling, returning approximately 321 g of lunar regolith. China's Chang'e-5 mission retrieved 1,731 g of lunar samples, while the Chang'e-6 return capsule made a groundbreaking achievement by successfully bringing back 1,953.3 g of samples from the Moon's far side (Li et al. 2024). However, the global total remains less than 400 kg, and due to the scarcity and non-renewability of these samples, destructive mechanical testing is severely limited.

Discrete Element Method (DEM)-based numerical simulations have become a crucial approach for investigating the mechanical mechanisms of lunar regolith. Essentially, lunar soil resembles discontinuous granular materials like sand. DEM constructs numerical models of discontinuous media, effectively simulating complex mechanical behaviors in granular systems and demonstrating advantages in handling nonlinear and large-deformation problems. Through DEM-based numerical simulations, researchers can accurately represent the true mechanical properties of lunar regolith—a dry, discontinuous granular medium devoid of liquid water.

Lunar regolith consists of highly irregularly shaped particles. Traditional discrete element numerical simulations often simplify regolith particles into regular geometric shapes such as circles or spheres, neglecting the influence of realistic particle morphology on the mechanical properties of lunar soil. This simplification also limits the comparability between numerical simulations of granular flow and the actual mechanical response of lunar regolith.

To improve the accuracy of numerical simulations and obtain more reliable computational results, this study integrates high-resolution morphological data of Chang'e-6 (CE-6) lunar regolith particles and employs the Particle Flow Code (PFC) to construct a discrete element model that accounts for realistic particle shapes. Through a series of triaxial shear simulations, we systematically analyze the influence of particle irregularity on macro-mechanical parameters and micro-scale mechanisms, thereby revealing the critical role of particle shape irregularity.

Methodology

Utilizing the micro-CT facilities at the Institute of Geology and Geophysics, Chinese Academy of

Sciences (IGGCAS), we obtained the 3D morphological data of 22 lunar regolith particles and reconstructed them into STL-format files compatible with PFC3D. These STL files were then imported into PFC3D, where the "clump" command was employed to generate particle clusters approximating the realistic grain morphology (Figure 1). Based on these clusters, a cylindrical specimen model was assembled, and a series of triaxial compression tests were conducted under confining pressures of 10 kPa, 40 kPa, and 120 kPa to obtain the stress-strain curves and strength parameters.

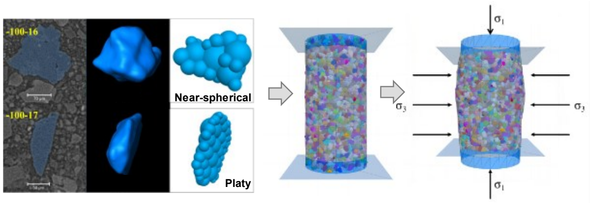

Figure 1, Scanning pictures and PFC modelling.

Results

Figure 2 presents the stress-strain and volumetric strain curves for the two models with distinct particle morphologies. The results demonstrate that specimens with both particle shapes exhibit strain softening behavior, which becomes more pronounced with increasing confining pressure. Compared to near-spherical particles, specimens composed of more irregular platy particles display higher strength, manifesting significantly greater deviatoric stress at equivalent strain levels.

The platy particle specimens exhibit stronger interparticle friction and interlocking effects than their near-spherical counterparts. Consequently, the stress-strain curves of platy particles show more noticeable serration phenomena. However, this serration effect diminishes with increasing confining pressure in both cases, consistent with the general observation.

The volumetric strain curves reveal distinct behaviors between the two particle morphologies. The near-spherical particle model exhibits contractive behavior, with increasing contraction magnitude at higher confining pressures, consistent with typical volume change characteristics of normally consolidated soils. In contrast, the platy particle specimens demonstrate markedly different responses. Under low confining pressure, initial contraction is followed by significant dilation. As confining pressure increases, the initial contraction phase becomes more pronounced while subsequent dilation diminishes, further confirming the suppressive effect of confining pressure on dilatant behavior.

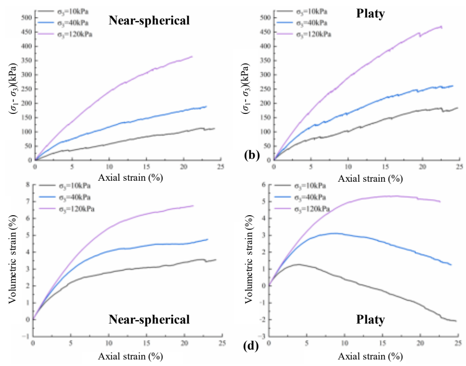

Figure 2, Stress-strain and volumetric strain curves for models with near-spherical and platy particle morphologies

Figure 3 compares contact force chains (thickness/redness indicates force magnitude) between near-spherical and platy particle systems. All specimens show: (1) denser/stronger chains with higher confining pressure; (2) uniform distribution at low pressure; (3) vertical alignment at high pressure; (4) longer chains fragment under pressure. Platy particles show stronger anisotropy due to interlocking.

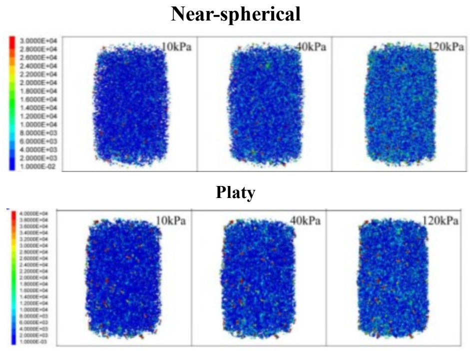

Figure 3, Contact force chains in the two models with near-spherical and platy particle morphologies.

Conclusion

The platy specimen exhibits higher peak strength than the near-spherical specimen, with strain hardening dominating except for near-spherical specimens under high confinement. Micromechanically, platy particles have complex force chains, stress concentration, whereas near-spherical particles yield uniform distributions.

Reference

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