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Guest Editorial to the Special Issue Planetary Rock and Soil Mechanics

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1. Introduction

In recent years, there have been significant advancements in the scope and depth of space exploration. Challenging missions, such as returning to the Moon and exploring Mars, are gradually being implemented. In deep space exploration, understanding the mechanical behavior of planetary geomaterials is crucial for various missions, including mission planning, landing system design, drilling and coring, base construction, in-situ resource utilization (ISRU), and asteroid mining. Researchers from diverse backgrounds have been actively advancing knowledge and driving innovation in this field. Fifteen years ago, the mechanical properties of soil and rock samples brought back from the Moon by the Apollo missions were investigated experimentally [1]. The testing of meteorietes, which can be obtained on Earth, also helps us to understand the Moon and asteroids. Recently, Prof. Saydam at the University of New South Wales established the commission of 'Planetary Rock Mechanics' within the International Society for Rock Mechanics and Rock Engineering.

Our knowledge of planetary rock and soil mechanics is still insufficient, which leads to uncertainties in space missions. In August 2021, NASA's Perseverance rover encountered difficulties in drilling and capturing Martian rocks because these rocks fragmented rapidly and were difficult to handle [2]. Fortunately, in September 2021, the rover successfully obtained its first Martian rock sample [3]. In the near future, advancements in planetary soil and rock mechanics are expected to support more deep space missions, such as permenant base construction on Moon, planetary defense and space mining.

The rise of deep space exploration will undoubtedly drive the development of geotechnical sience and engineering. Solving problems and challenges encountered in the exploration of deep space is expanding the scientific boundaries of geotechnical engineering. Extraterrestrial geomaterials and environments differ significantly from those on Earth. Novel theories, technologies, and equipments are continually being developed for the exploration of the Moon, Mars, and asteroids.

This special issue aims to advance the theory and engineering technology associated to the planetary soil and rock mechanics, providing support for extraterrestrial missions to Mars, the Moon, and asteroids. This special issue includes 10 academic papers. Among them, 6 focus on lunar exploration, 2 on Martian exploration, and 2 on meteorite research. These papers address cutting-edge scientific issues in the mechanics of planetary rock and soil, directly supporting deep space exploration missions.

2. Moon

The Moon, as the closest celestial body to Earth, plays a crucial role in deep space exploration. Investigating and developing the Moon are essential steps for advancing further into space. This special issue presents 7 academic papers focusing on lunar exploration, briefly introduced below. They explore topics including lunar regolith simulants, sintered lunar regolith, lunar lava tubes for base construction, drilling and coring technology, and moonquakes.

Zou et al. [4] developed a high-fidelity PolyU-1 simulant by pulverizing, desiccating, sieving, and blending natural mineral materials on Earth, based on the physical, mineral, and chemical characteristics of Chang'e-5 (CE-5) samples. This simulant has a high degree of consistency with the CE-5 samples in terms of particle morphology, and mineral and chemical compositions. Direct shear tests were conducted on the simulant, and the measured internal friction angle and cohesion values can serve as references for determining the mechanical properties of CE-5 lunar regolith. The PolyU-1 simulant would contribute to experimental studies involving lunar regolith, as well as the development of in-situ resource utilization technologies.

Han et al. [5] investigated the properties of sintered HUST-1 lunar regolith simulant (HLRS) at different thermal loadings, which is potential building materials for lunar bases. The effect of sintering temperature on the compressive strength of sintered HLRS was investigated experimentally, and the exact value of the optimum vacuum sintering temperature was determined. Besides, this study reveals the effects of sintering temperature on the physical, mechanical and thermal properties of vacuum sintered HLRS, and these material parameters will provide support for the construction of future lunar bases.

Feng et al. [6] reviewed the geological origins, exploration history, and distribution locations of lunar lava tubes, which are special underground caves formed by volcanic eruptions and are

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considered ideal natural shelters for lunar base construction. Specially, the challenges and opportunities encountered in the field of geotechnical engineering regarding the establishment of lunar lava tube bases are discussed, encompassing cave exploration technologies, in-situ testing methods, geomechanical properties under lunar extreme environments, base design and structural stability assessment, excavation and reinforcement techniques, and simulated Earth-based lava tube base.

Hao et al. [7] designed an in-situ condition preserved coring (ICP-Coring) and analysis system was designed, for drilling and coring on the Moon. The system has the following characteristics: (1) Realizing of the large temperature difference in the lunar extreme environment (−185 to 200 ℃), with intelligent temperature alternation control; (2) Providing a 10^{-3} Pa scale vacuum environment under unloaded conditions in φ580 mm×1000 mm test space and loaded condition with φ400 mm × 800 mm lunar rock simulant, respectively; (3) Simulating different lunar rock depths - for axial pressure ≤4 MPa and confining pressure ≤3.5 MPa; (4) Satisfying sample rotation at any angle and sampling length for ≤ 800 mm; (5) Achieving multiple modes of rotate-percussive drill sampling controlled by penetrating speed/weight on bit (WOB).

Peng et al. [8] presented the significant development and characterization of the new LSS NYUAD-1, the first regional soil simulant tailored for the planned Emirates lunar missions. The material and geotechnical properties of NYUAD-1, including chemical composition, mineralogy, particle size, morphology, specific gravity, density, shear strength, and compressibility behaviors, were assessed through laboratory tests conducted per ASTM standards. Comparative analysis with authentic lunar regolith and various regolith simulants confirms the significance and applicability of NYUAD-1 for lunar-based research, offering a promising step toward future lunar habitation.

Cao et al. [9] showed the effect of mineral composition and temperature on the frictional instability of basaltic faults on the Moon. They observe a transition from velocity-neutral to velocity-weakening behaviors with increasing obsidian content. They suggest that obsidian content dominates the potential seismic response of basaltic faults with the effect of temperature controlling the range of seismogenic depths. Thus, shallow moonquakes tend to occur in the lower lunar crust due to the corresponding anticipated higher glass content and a projected temperature range conducive to velocity-weakening behavior. These observations contribute to a better understanding of the nucleation mechanism of shallow seismicity in basaltic faults. Basalt is a major component of the earth and mooncrust.

3. Mars

Mars, the closest terrestrial planet to Earth after the Moon, has environmental conditions such as gravity and atmosphere that are relatively similar to those of Earth. Therefore, exploring Mars aids in preparing for future human missions and potential colonization, tackling challenges related to technology and sustainability.

Chen et al. [10] established a numerical model for soil erosion and crater formation based on computational fluid dynamics methods and Roberts' erosion model, demonstrate that an increase in cohesion and friction angle leads to a decrease in erosion rate and maximum crater depth, with cohesion having a greater impact. The influence of nozzle height on the erosion process is not clear, as it jointly controls the erosion process along with jet structure. Furthermore, concentrated erosion mode and dispersive erosion mode were classified based on the characteristics of crater morphology evolution. Finally, the mechanical properties of soil at Tianwen-1 landing site were estimated. These results provide an explanation for deeper landing craters on Mars and serve as a reference for risk avoidance and other aspects of the future Mars exploration missions.

Yin et al. [11] proposed a fast and accurate probability distribution method for predicting the macroscale elastic modulus of Martian rocks by integrating the microscale rock mechanical experiments (micro-RME), accurate grain-based modeling (AGBM) and upscaling methods based on reliability principles. The microstructure and microscale mechanics of NWA12564 Martian sample were achieved experimentally. Secondly, based on the best distribution function of each mineral, the Monte Carlo Simulations (MCS) and upscaling methods were implemented to obtain the probability distribution of upscaled elastic modulus. The correlation between the upscaled elastic modulus and macroscale elastic modulus obtained by AGBM was established. The accurate probability distribution of the macroscale elastic modulus was obtained by this correlation relationship.

4. Meteorites

Meteorite study is a crucial way to understand the Moon, Mars, and asteroids. However, in the past, research on the mechanical properties of meteorites has been limited because meteorites are often irregularly shaped and difficult to process into standard specimens for traditional macroscale rock mechanics experiments. The following introduces two advanced methodologies for investigating the mechanical properties of meteorites at multiple scales.

Peña-Asensio et al. [12] explored the application of machine learning algorithms in predicting the mineralogical and mechanical properties of DHOFAR 1084, JAH 838, and NWA 11444 lunar meteorites based solely on their atomic percentage compositions. Leveraging a prior-data fitted network model, the authors achieved near-perfect classification scores for meteorites, mineral groups, and individual minerals. The regressor models, notably the K-Neighbor model, provided an outstanding estimate of the mechanical properties-previously measured by nanoindentation tests—such as hardness, reduced Young's modulus, and elastic recovery. The findings underscore the potential of machine learning in enhancing mineral identification and mechanical property estimation in lunar exploration, which pave the way for new advancements and quick assessments in extraterrestrial mineral mining, processing, and research.

Liu et al. [13] provide a critical review of the micromechanical testing and property upscaling for analyzing planetary rocks, such as scarce and irregular meteorites. The authors discuss several methods for analyzing the mineralogy and microstructure of planetary rocks and provide a comprehensive review of non-destructive micromechanical testing techniques. The paper also introduces several feasible upscaling methods that bridge the micro-measurements of meteorite minerals to the strength of the intact bulk mass. These discussions aim to broaden the understanding of the microscale mechanical properties of planetary rocks and their significant role in deep space exploration.

5. Summary

The authors of this special issue come from the Italy, Spain, United Arab Emirates, Egypt, United States and China. They present a range of cutting-edge achievements in planetary geomechanics, including fundamental theories, experimental methods, engineering equipment development and potential base construction plans. This special issue aids readers in understanding both the theoretical and engineering challenges of deep space exploration, while also providing the latest theoretical and technological knowledge in planetary solid and rock mechanics. As human space exploration advances, planetary geomechanics is expected to play an increasingly pivotal role.

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