

Design of Lunar Soil Simulant for Lunar Landing Applications and Its Mechanical Property Evolution under Impact Loading

Yi Sui

19136470@qq.com.com

Beijing Institute of Space Mechanics & Electricity

Article

Keywords: Landing Tests, Lunar Soil Simulants, Mechanical Properties

Posted Date: October 21st, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11172801/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Design of Lunar Soil Simulant for Lunar Landing Applications and Its Mechanical Property Evolution under Impact Loading

Yi Sui^{1,2*}

¹Beijing Institute of Space Mechanics & Electricity, Beijing100094, China

²Laboratory of Aerospace Entry, Descent and Landing Technology,
Beijing, 100094, China

Abstract: There is a critical shortage of lunar soil simulants (LSS) tailored for the far side of the Moon and the South Pole, and the evolution of lunar soil mechanical properties under realistic lander footpad impact conditions remains poorly understood, especially the response laws under different landing slopes. In this study, a dedicated LSS for landing impact tests was developed using Changbai Mountain volcanic ash as the base material, based on lunar soil characteristics from the far side and South Pole-Aitken (SPA) basin. The LSS was prepared through crushing, grinding, sieving and gradation optimization, and a 10 m × 10 m test bed was constructed. Impact simulation tests were performed using a four-legged lander on four typical slopes (0°, 4°, 8°, 12°). Combined with direct shear and consolidation compression tests, the spatial evolution of shear strength and compression properties of the LSS after impact was analyzed. The results show that the particle size distribution of the volcanic ash-based LSS falls within the range of natural lunar soil and matches the gradation trend of Chang'e-5

samples. Key mechanical parameters (dry density, cohesion, internal friction angle) agree well with those of Apollo and Chang'e real lunar soils. Landing slope significantly affects the spatial distribution of post-impact mechanical properties: shear strength weakens on the uphill side and strengthens on the downhill side, while void ratio shows the opposite gradient. This distribution pattern stabilizes when the slope exceeds 8° . The findings provide important experimental basis for lunar soil mechanical evaluation, lander stability analysis and ground verification of future lunar exploration missions.

Keywords: Landing Tests; Lunar Soil Simulants; Mechanical Properties

1 Introduction

With the advancement of global lunar exploration towards deep space landing and in-situ resource utilization, the far side of the Moon and the lunar South Pole have emerged as primary targets for international scientific and engineering missions [1,2]. The Chang'e-4 mission achieved the first soft landing on the far side of the Moon, and Chang'e-6 successfully returned lunar soil samples from this previously unexplored region. Upcoming missions including Chang'e-7 and Chang'e-8 will focus on lunar South Pole exploration and facilitate the development of a lunar surface research station. During lunar landing, the impact of lander footpads significantly disturbs the shallow subsurface lunar soil, altering its compaction state and mechanical properties, which directly governs landing stability and the safety of subsequent surface operations.

Therefore, developing lunar soil simulants (LSS) tailored for the far side and South Pole regions and elucidating the evolution of lunar soil shear and compression properties following landing impact are of critical engineering and theoretical importance for lunar landing safety assessment [3-5].

Due to the extreme scarcity and restricted access to returned lunar samples, which cannot satisfy the requirements for large-scale ground-based landing simulation tests, high-fidelity LSS have become indispensable materials for lunar geotechnical engineering research. Since the 1970s, numerous LSS formulations such as JSC-1A and MLS-1 have been developed and widely applied in landing impact experiments [4-6]. Subsequent research efforts have produced additional dedicated simulant materials, establishing comprehensive frameworks for LSS development and characterization [7-10]. Various research institutions have developed CAS-1, JLU, and other LSS series, achieving excellent agreement in mineral composition and particle size distribution, and providing essential support for ground verification of lunar exploration missions [11-14,18]. Engineering-oriented LSS designed for landing impact applications prioritize key geotechnical parameters including gradation [15], density [16], shear strength [17], and compression characteristics [18].

The lunar surface is continuously subjected to micrometeorite bombardment and solar wind irradiation. These natural processes, combined with anthropogenic impact loads from lunar landing and in-situ construction activities, induce particle breakage, gradation modification, and microstructural evolution in lunar soil, thereby altering its macroscopic mechanical behavior. Consequently, the evolution of lunar soil mechanical

properties before and after impact loading has become a prominent research focus worldwide. Frew et al. [19] demonstrated the strain rate strengthening effect of lunar soil using Split Hopkinson Pressure Bar (SHPB) tests, establishing the foundational experimental methodology for this field. Patel et al. [20] quantified the changes in lunar soil void ratio and shear strength before and after impact specifically for landing scenarios. Park et al. [21] observed through drop weight impact tests that low-amplitude repeated impacts enhance lunar soil compaction and strength, while high-amplitude impacts result in strength degradation. Li et al. [22] simulated micrometeorite bombardment using a light gas gun and developed a quantitative relationship between impact energy and lunar soil strength reduction. He et al. [23] integrated impact and direct shear tests to reveal the mechanisms by which impact history influences lunar soil cohesion and internal friction angle. The design and analysis of landing gear systems for manned lunar missions have also been extensively investigated. Wang et al. [24] developed a full-scale prototype of a four-legged landing gear system using multi-stage aluminum honeycomb as the primary energy-absorbing material, and validated through ADAMS-based simulations that the landing impact overload remained below 4 gn across 15 typical landing scenarios. Liang et al. [25] employed the discrete element method (DEM) to investigate the buffering effect of lunar soil itself, independent of the lander's structural buffers. Their parametric study revealed that the peak impact force increases linearly with both landing velocity and lander mass, and that lunar soil particles absorb energy in an approximately linear relationship with the impact energy.

Extensive research has also been conducted on the mechanical behavior of LSS

under various loading conditions. Jiang et al. [26] investigated the effects of water content and particle size distribution on the mechanical properties of TJ-1 LSS, establishing correlations between strength parameters and water content. Li et al. [27-28] developed a predictive model relating the degree of particle breakage to lunar soil mechanical strength. Xue et al. [29] constructed a discriminant model for evaluating lunar soil mechanical state using the PLSDA method, incorporating lunar rover rut characteristics, wheel loads, slip ratios, and optimized diagnostic indicators. Importantly, recent investigations have confirmed that lunar soil on the far side exhibits substantially different mechanical properties compared to near-side lunar soil due to prolonged intense impact processes, indicating that existing near-side research findings cannot be directly extrapolated to these regions. Alberquilla et al. [30] characterized the basalts from the Peñas de Tao geosite in Lanzarote (Canary Islands, Spain) through multi-analytical techniques and developed a new lunar soil simulant, LZS-1, whose mineralogical, geochemical, and petrophysical properties closely match the Apollo 14 regolith from the Fra Mauro mixing zone, supporting its use for in-situ resource utilization and lunar habitability studies. Go et al. [31] investigated the soil disturbance of a lunar regolith simulant bed during depressurization in a dusty thermal vacuum chamber, established a criterion based on the critical pressure difference (CPD) between the top and bottom of the bed, and provided guidelines on the optimal depressurization rate to maintain the initial bed conditions for reliable surface-mission testing.

Despite the extensive body of research on LSS development and impact mechanics, significant knowledge gaps persist. Most existing LSS formulations are calibrated

against near-side lunar soil characteristics, and high-fidelity simulants specifically adapted for the far side and South Pole regions remain limited. Furthermore, previous studies have predominantly focused on either the static mechanical properties or dynamic responses of LSS, while systematic investigations into the post-impact shear and consolidation compression properties of lunar soil under realistic lander footpad impact conditions—particularly at varying landing slopes—are notably lacking. This deficiency impedes accurate geotechnical characterization and stability analysis of potential landing sites.

To address these limitations, this study develops a dedicated LSS for landing impact testing using volcanic ash as the base material, with gradation and composition optimized to match lunar soil characteristics from the far side and South Pole-Aitken (SPA) basin. A large-scale test bed was constructed to perform impact simulation tests using a four-legged lander at four representative slopes. Direct shear and consolidation compression tests were conducted on LSS samples collected before and after impact to analyze the effects of impact loading on key mechanical parameters and to elucidate the relationship between landing slope and the spatial evolution of lunar soil mechanical properties. The results provide essential experimental data for geotechnical evaluation of lunar soil in far side and South Pole landing areas, and offer valuable insights for landing stability analysis and ground verification of future lunar exploration missions.

2 Raw materials and test methods

2.1 Materials

The target lunar soil in this study is the regolith from the far side of the Moon,

whose benchmark characteristics were determined based on in-situ measurements from the Chang'e-5 mission and authentic lunar soil sample data [30-33]. The lunar soil particles exhibit irregular shapes with low sphericity (average value of only 0.74) and prominent angularity, along with relatively small aspect ratios, resulting in strong interparticle interlocking.

Mineralogically, the soil is dominated by plagioclase (32.6%), clinopyroxene (19.7%), and amorphous glass (29.4%), with minor contents of ilmenite (1.6%) and olivine (0.5%). It is classified as a mixed type of low-titanium basalt and highland material. In terms of physical and mechanical properties, the soil has a dry density of approximately 0.983 g/cm³, characterized by high porosity and loose texture. The internal friction angle is about 47.96° and the cohesion is 1.08 kPa. The target values of specific mechanical parameters are presented in Table 1.

Subjected to long-term impact modification, the lunar soil in this region exhibits high degree of fragmentation, low cementation, and significant compressibility. These properties differ substantially from those of lunar soil on the near side and conventional highland regolith, making it a typical research object for landing impact and geotechnical characterization studies.

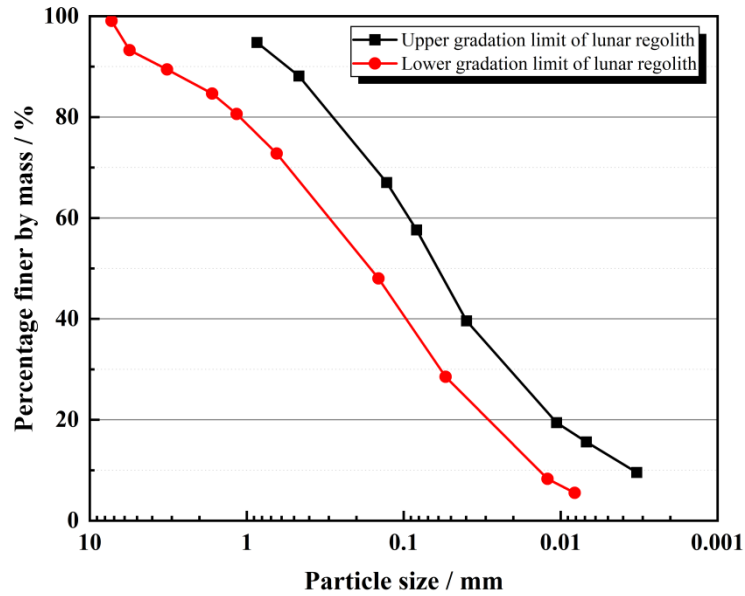


Fig. 1 Target particle size distribution of the lunar soil simulant (LSS)

Table 1. Physical and mechanical parameters of the lunar soil simulant (LSS)

Parameter	Value range
Dry density ρ (g/cm ³)	0.90-1.60
Void ratio e	0.90-1.30
Cohesion c (kPa)	0.03-2.1
Compression index C_{c+}	0.01-0.3
Internal friction angle φ	35-47
Bearing capacity f (kPa)	7-36
Water content ω (%)	< 2

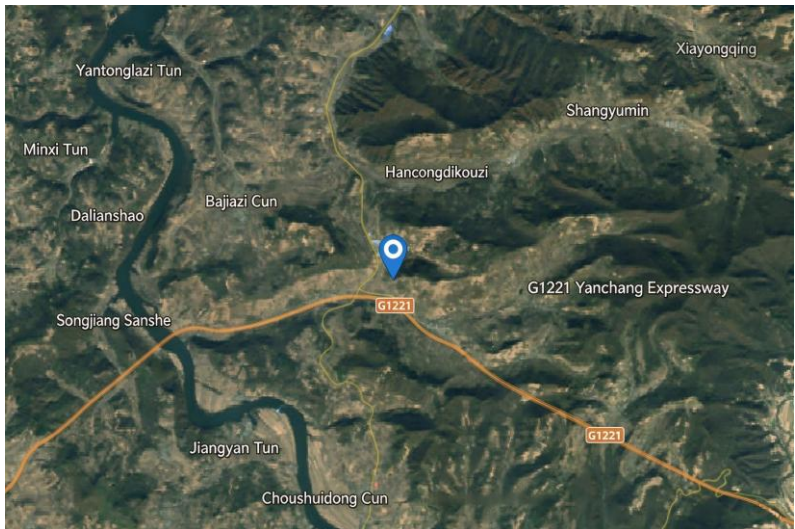
2.2 Lunar Soil Simulant Preparation

2.2.1 Raw Materials and Characterization

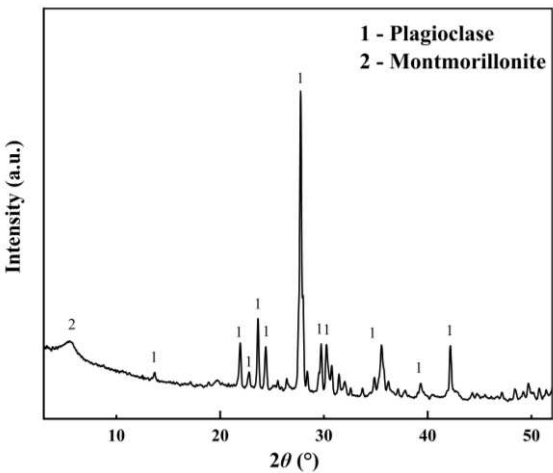
Changbai Mountain volcanic ash was selected as the primary raw material for lunar soil simulant (LSS) preparation in this study. The raw volcanic ash was commercially sourced from Henan Xiaoyushu Engineering Technology Co., Ltd., and was originally extracted from volcanic ash deposits on the northern slope of Changbai Mountain, Jilin Province, China. All mining and commercial procedures of the material were conducted with official permits from local authorities.

The mineral assemblage of Changbai Mountain volcanic ash is dominated by olivine, pyroxene and feldspar, making it one of the most widely used natural

162 feedstocks for lunar soil simulant development. The mineral composition of the raw
 163 volcanic ash was characterized via X-ray diffraction (XRD). The geographic source
 164 location and XRD analysis results are presented in Figure 2. Specifically, Figure 2(a)
 165 shows the source location of the volcanic ash in the Changbai Mountain area, and
 166 Figure 2(b) displays the XRD pattern of the raw material. As indicated by the XRD
 167 result, plagioclase is the dominant mineral phase in the volcanic ash, which is consistent
 168 with the mineralogical features of commonly used lunar soil simulants and natural lunar
 169 regolith.



(a) Geographic location of the volcanic ash source area



(b) X-ray diffraction (XRD) pattern of the raw volcanic ash

Fig. 2 Source location and mineral phase characterization of raw Changbai Mountain volcanic ash

2.2.2 Preparation technology and procedures

The detailed preparation process of the LSS is illustrated in Fig3. First, the primary raw material volcanic ash was subjected to primary crushing using a crusher, followed by thorough grinding in a ball mill. Subsequently, the ground material was dried in an oven at 105°C for 24 hours to remove free water. After drying, the powder sample was sieved using a vibratory sieve shaker into seven particle size fractions: 0-0.075 mm, 0.075-0.1 mm, 0.1-0.25 mm, 0.25-0.5 mm, 0.5-1 mm, 1-2 mm, and >2 mm.

Each fraction was then blended according to mass proportions with reference to the target particle size distribution curve of lunar soil to obtain mixed samples meeting the target gradation requirements. Direct shear tests and uniaxial compression tests were conducted on the blended samples to determine their basic mechanical parameters. The samples that simultaneously satisfied all mechanical property specifications were selected as the final LSS product. These qualified samples were re-dried in an oven at 105°C for 12 hours and then hermetically sealed for storage, completing the entire LSS preparation process.

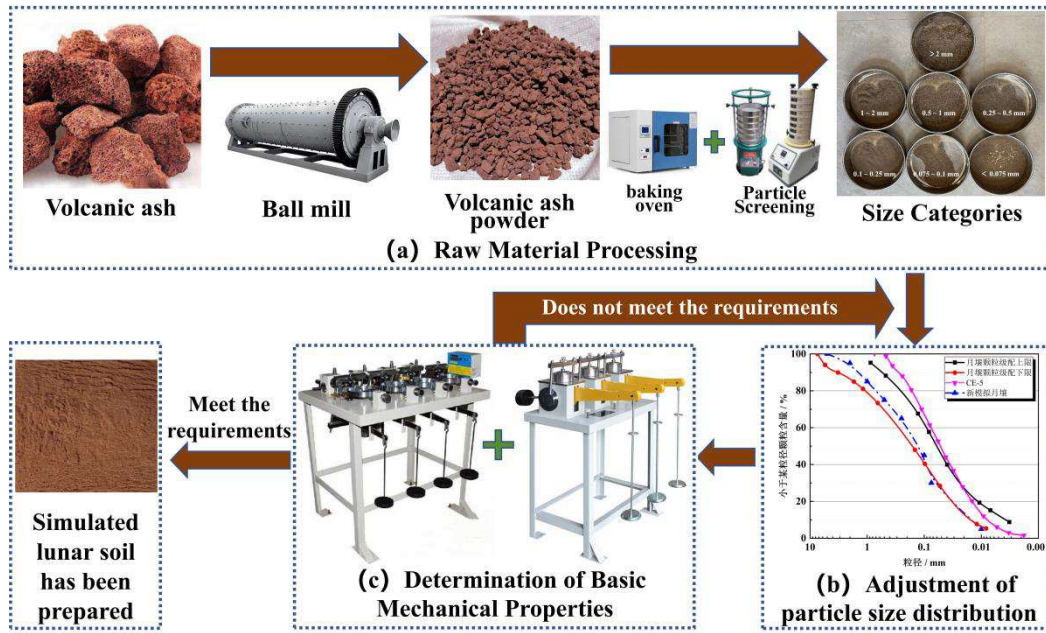


Fig. 3 Preparation flow chart of volcanic ash-based lunar soil simulant

2.3 Mechanical property

2.3.1 Dry density

Dry density is the most fundamental physical and mechanical index of lunar soil simulants, which directly determines its packing state and engineering mechanical behavior. The dry densities of both the initial LSS and post-impact LSS were determined using the ring knife method. The ring knife used in the tests had an inner diameter of 61.8 mm, a height of 20 mm, and a volume $V = 60 \text{ cm}^3$ with an accuracy of $\pm 0.1 \text{ cm}^3$. An electronic balance with a precision of 0.01 g was employed, which meets the accuracy requirements for dry density testing of cohesionless soils. For initial LSS specimens, the prepared LSS was uniformly loaded into the ring knife in layers. Three parallel specimens were prepared for each test group to eliminate random errors. The ring knives containing specimens were dried in an oven at $105^\circ\text{C} \pm 5^\circ\text{C}$ to constant mass. After cooling to room temperature, the total mass of the ring knife and dry soil

m_l was weighed. The dry soil mass m_s was obtained by subtracting the mass of the empty ring knife m_0 from m_l , i.e., $m_s = m_l - m_0$. The dry density ρ was calculated according to Equation (1):

$$\rho = \frac{m_s}{V} \quad (1)$$

Where : ρ = dry density of the lunar soil simulant (LSS) (g/cm^3) ; m_s = mass of dry soil inside the ring knife (g), calculated as $m_s = m_l - m_0$; m_l =total mass of the ring knife and dry soil (g) ; m_0 = mass of the empty ring knife (g) ; V = volume of the ring knife (cm^3).

2.3.2 Direct Shear Test

Direct shear test is the most commonly used method for determining the shear strength parameters of soils. Quick shear tests were conducted in this study using a ZJ-2 strain-controlled direct shear apparatus in accordance with the Standard for Soil Test Methods (GB/T 50123-2019). The shear box used had an inner diameter of 61.8 mm, a height of 20 mm, and a shear surface area of 30 cm^2 . The calibration coefficient of the dynamometer (C) was 1.5 kPa per 0.01 mm deflection, and the shear rate was controlled at 0.8 mm/min, which complies with the specification requirements for quick shear tests on cohesionless soils. For initial LSS specimens, the simulant was uniformly loaded into the shear box with a controlled initial dry density of $0.983 \text{ g}/\text{cm}^3$. Four parallel specimens were prepared for each test group, and four levels of normal pressure were applied: 50 kPa, 100 kPa, 150 kPa, and 200 kPa. Shearing was initiated immediately after the application of normal pressure. The test was terminated when the shear displacement reached 6 mm, or continued to 10 mm after the shear stress exhibited a

peak value. The dynamometer reading (R) corresponding to every 0.1 mm of shear displacement was recorded. The shear strength was calculated according to Equation (2):

$$\tau_f = \frac{C \cdot R}{A} \quad (2)$$

Where: τ_f = shear strength (kPa); C = calibration coefficient of the dynamometer (kPa/0.01 mm), with a value of 1.5 kPa/0.01 mm ; R = dynamometer reading (0.01 mm) ; A = shear surface area (cm²). The cohesion (c) and internal friction angle φ were calculated according to the Mohr-Coulomb shear strength criterion, based on the linear relationship between the shear strength of the soil and the normal stress. Direct shear tests on the post-impact LSS were conducted using identical test procedures, loading levels, and shear rates.

2.3.3 Direct Shear Test

Consolidation compression tests are used to determine the compression characteristics of soils under lateral confinement. Standard consolidation tests were conducted in accordance with the Standard for Soil Test Methods (GB/T 50123-2019) using a WG-1 lever-type oedometer apparatus to measure the compression index C_c , swelling index C_s , and preconsolidation pressure (σ_c) of both the initial LSS and post-impact LSS. The consolidation cell used had an inner diameter of 61.8 mm, a height of 20 mm, and a specimen area of $A = 30 \text{ cm}^2$. The displacement gauge had an accuracy of 0.01 mm. For initial LSS specimens, the simulant was uniformly loaded into the consolidation cell with a controlled initial dry density of 0.983 g/cm³. One specimen was prepared for each test group. A stepwise loading method was adopted, with loads

applied sequentially. The stability criterion for each load increment was that the vertical deformation was no more than 0.01 mm per hour. The next load increment was applied after stabilization. After loading to 1600 kPa and stabilization, stepwise unloading was performed to determine the rebound characteristics of the specimen. The total vertical deformation after stabilization under each load increment was recorded. The void ratio e_i under each load increment was calculated according to Equation (3):

$$e_i = e_0 - \frac{\Delta h_i}{h_0} \cdot (1 + e_0) \quad (3)$$

where: e_i = void ratio under the i -th load increment (dimensionless) ; e_0 = initial void ratio ; Δh_i = total vertical deformation under the i -th load increment (mm) ; h_0 = initial height of the specimen (20 mm) ; The e -lg p compression curve was plotted with void ratio e as the ordinate and the common logarithm of effective stress p (lg p) as the abscissa. The compression index C_c defined as the slope of the linear portion of the compression curve, was calculated according to Equation (4):

$$C_c = \frac{e_1 - e_2}{\lg p_2 - \lg p_1} \quad (4)$$

Where: e_1, e_2 = void ratios at any two points on the linear portion of the e -lg p compression curve; p_1, p_2 = corresponding effective stresses at these two points (kPa).

For post-impact LSS, consolidation compression tests were conducted on samples collected from different regions and different depths using identical loading regimes and test procedures. Comparative e -lg p curves before and after impact were plotted to analyze the influence law of impact on the compression index C_c and to reveal the mechanism by which impact history affects the compression characteristics of lunar soil.

2.4 Lander Impact Simulation Test

2.4.1 Test Apparatus and Test Bed Preparation

The core test apparatus for the lander impact test consists of a drop-weight impact loading system, a four-legged lander model, and a lunar soil simulant (LSS) test bed. The LSS test bed was constructed according to the design scheme in reference [34], as shown in Figure 4.

The test bed had overall dimensions of 10 m $\times$ 10 m $\times$ 1 m and was placed at the center of a level and compacted foundation site to eliminate boundary effects. It adopted a 45° inclined composite retaining structure with alternating wooden formwork and hybrid wooden-rigid supports. The formwork had a height of 1.5 m, and polyethylene film was fully laid on the inner surface and bottom to prevent LSS leakage and moisture ingress, as well as to reduce side friction resistance.

The test bed was filled in four layers with a thickness of 25 cm per layer. The dry density of each layer was controlled at 0.98 g/cm³ through vibratory compaction. After each layer was completed, four specimens were randomly collected to verify the dry density (deviation $\leq \pm 0.02$ g/cm³). The top surface was carefully leveled after all layers were installed.

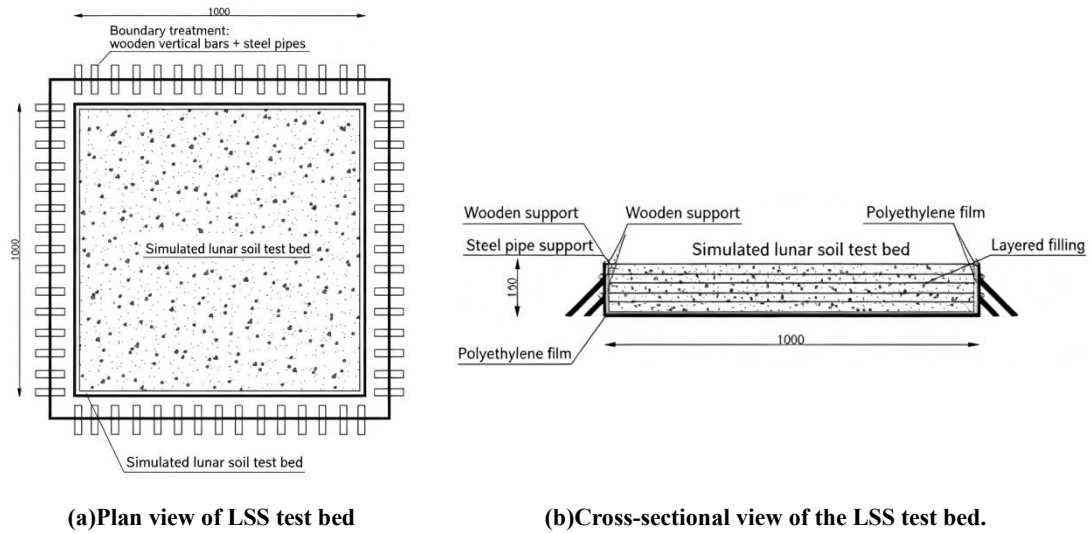


Figure 4. Schematic diagram of lunar soil simulant test bed[36].

2.4.2 Test Condition Design

This study aims to investigate the influence of different landing slopes on the evolution law of lunar soil mechanical properties after landing impact. Based on the actual topographic slope distribution characteristics of the South Pole-Aitken (SPA) basin on the far side of the Moon, four typical landing slope conditions were set: 0° , 4° , 8° , and 12° . A four-legged lander model was used in the tests, and the landing terminal velocity was controlled at 2.5 m/s by the drop-weight loading system, which is consistent with the actual terminal velocity of Chang'e series lunar soft landers. Three parallel tests were repeated for each slope condition to eliminate random errors, and an unimpacted blank control group was set up for comparative analysis.

2.4.3 Post-Impact Sample Collection Method

Sample collection was performed immediately after the completion of each impact test. Considering the significant differences in impact sequence and energy distribution of the four-legged lander at different slopes, independent sampling was conducted separately from the impact zones of each of the four footpads. The schematic diagram

of landing point distribution is shown in Figure 5. For 0° horizontal landing, the impact conditions of the four footpads were basically consistent, and parallel samples were collected from the impact zones of 2 randomly selected footpads. For 4° , 8° , and 12° inclined landing, samples were collected sequentially from the impact zones of each footpad numbered according to their positions: No.1 at the uphill end, No.2 at the left-middle, No.3 at the right-middle, and No.4 at the downhill end, to analyze the influence of different landing positions on the mechanical properties of LSS.

The sampling depth was 0 – 5 cm, covering the main disturbance range of landing impact. Undisturbed specimens were collected using the standard ring knife method, and 3 parallel specimens were collected at each depth in each zone for dry density, direct shear, and consolidation compression tests, respectively. All specimens were sealed immediately with plastic wrap after collection to prevent moisture evaporation and particle scattering, ensuring that the initial state of the specimens was consistent with their post-impact state.

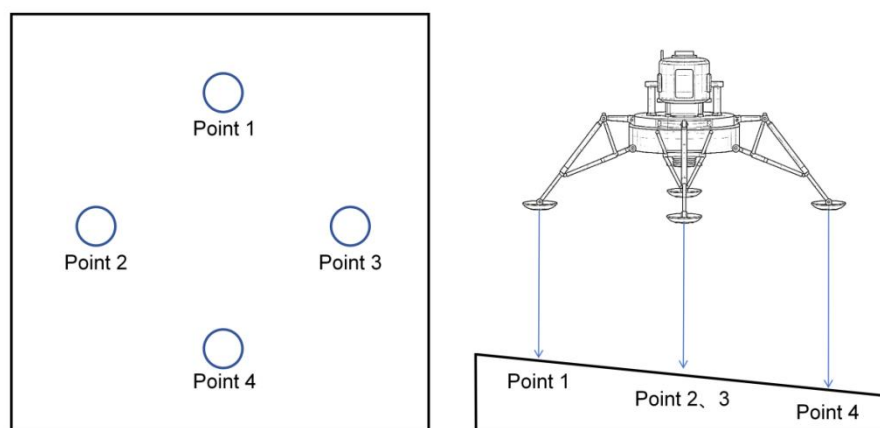


Fig. 5 Schematic diagram of landing point distribution

3 Discussion

Comparative Analysis of Performance between LSS and Lunar Regolith

To verify the consistency of particle composition between the volcanic ash-based LSS prepared in this study and natural lunar regolith, its particle size distribution curve was determined by the sieving method and compared with the in-situ measured gradation of Chang'e-5 (CE-5) lunar soil and the internationally accepted upper and lower limits of lunar soil gradation, as shown in Figure 6. As can be seen from the figure, the particle size distribution curve of the newly developed LSS lies entirely within the upper and lower limits of lunar soil gradation, and shows a high degree of agreement with the gradation variation trend of CE-5 lunar soil. In the coarse particle fraction, the coarse particle content of the newly developed LSS is higher than that of CE-5 lunar soil, but still within the allowable range of the upper limit of lunar soil gradation. In the fine particle fraction (particle size < 0.1 mm), the gradation curves of the two are almost coincident, with a difference in fine particle content of less than 5%.

Particle size distribution is a key factor determining the physical and mechanical properties of granular materials, and directly affects their compaction characteristics, shear strength, and compression properties. The LSS prepared in this study exhibits excellent matching with CE-5 lunar soil in terms of particle composition and meets the requirements of internationally accepted lunar soil gradation standards. This indicates that it can effectively reproduce the particle contact characteristics and mechanical response laws of natural lunar regolith, laying a solid foundation for the validity and engineering applicability of subsequent landing impact test results.

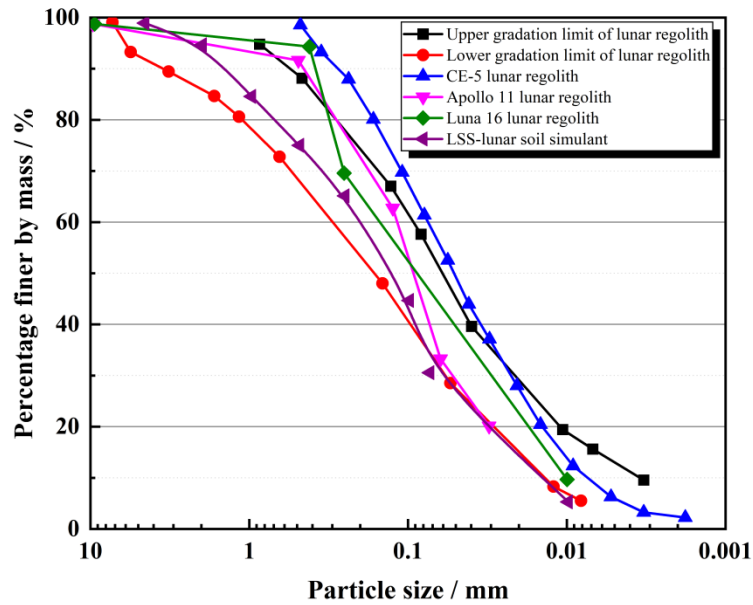


Fig. 6 Particle size distribution comparison of LSS, CE-5 lunar soil and standard limits

Figure 7 shows the shear curves of the newly developed LSS. As can be seen from the figure, the shear curves of the newly developed LSS exhibit typical strain-hardening characteristics, consistent with the shear failure law of loose cohesionless soils. In the initial shear stage (0 – 2 mm), the shear stress increases rapidly and linearly with displacement. At this stage, elastic deformation and initial contact adjustment mainly occur between particles, and the shear stiffness increases significantly with increasing normal stress. In the middle shear stage (2 – 4 mm), the growth rate of shear stress slows down. Particles begin to undergo significant rearrangement and sliding, the interlocking effect between angular particles gradually strengthens, and the shear surface is gradually formed. In the late shear stage (4 – 6 mm), the shear stress reaches a peak value and remains stable. The interlocking effect between particles reaches an equilibrium state, and no obvious strain-softening phenomenon is observed. The higher the normal stress, the greater the peak shear strength, and the shear displacement required to reach the peak value increases slightly. This is because the contact stress

and interlocking resistance between particles are stronger under high normal stress, and a larger displacement is required to destroy the stable structure between particles.

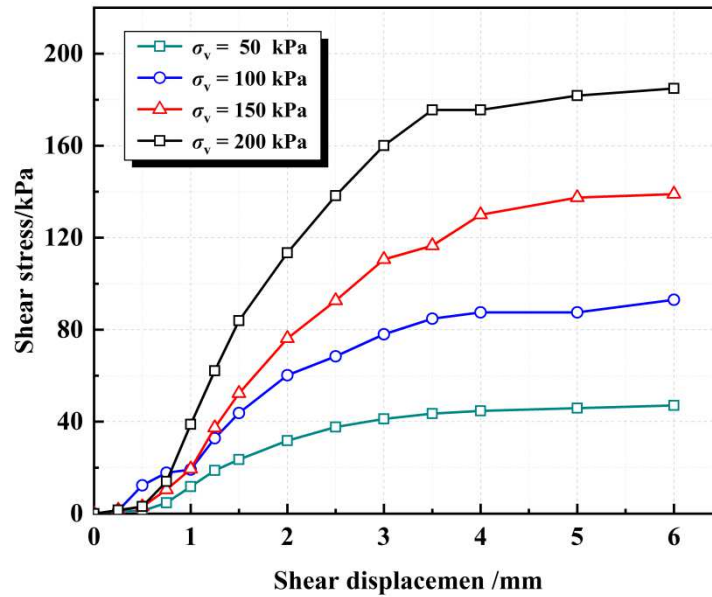


Fig. 7 Shear curves of the newly developed lunar soil simulant

To verify the engineering applicability of the volcanic ash-based LSS prepared in this study, its basic mechanical parameters were compared with the measured values of Apollo series lunar regolith and Chang'e-5 (CE-5) lunar regolith, and the results are presented in Table 2. As shown in Table 2, all mechanical parameters of the newly developed LSS exhibit good consistency with natural lunar regolith. The dry density ranges from 0.90 to 1.60 g/cm³, covering the measured ranges of both Apollo series lunar regolith and CE-5 lunar regolith, which can simulate the lunar soil states at different depths and with different compaction degrees on the lunar surface. The void ratio ranges from 0.90 to 1.30, which is consistent with the void characteristics of Apollo 11 lunar regolith (0.67–1.21) and Apollo 14 lunar regolith (0.87–2.37), and can reproduce the porous structural characteristics of natural lunar regolith. The cohesion ranges from 0.03 to 2.1 kPa, which is close to the measured values of Apollo series

lunar regolith (0.34 – 1.40 kPa), and accurately reflects the low cohesion nature of lunar soil as a cohesionless granular material. The internal friction angle ranges from 39° to 47°, covering the range of Apollo series lunar regolith and slightly higher than some Apollo lunar regolith samples. This is mainly because volcanic ash particles are more angular and have rougher surfaces, resulting in stronger interlocking effects between particles. This difference is within the allowable range for engineering applications. The compression index ranges from 0.01 to 0.3, which can well simulate the compression deformation characteristics of lunar soil under impact loading.

Overall, the volcanic ash-based LSS prepared in this study has a high degree of similarity with natural lunar regolith in terms of physical and mechanical properties. It can accurately reproduce the shear failure and compression deformation laws of lunar regolith, and meets the requirements of landing impact geotechnical tests for simulant materials.

Table 2 Comparison of mechanical parameters of LSS and natural lunar regolith

Parameter	Dry density ρ (g/cm ³)	Void ratio e	Cohesion c (kPa)	Internal friction angle φ	Specific gravity of soil	Compression index C_c
Apollo 11	1.59~1.71	0.67~1.21	0.35~1.40	35~45	3.01	-
Apollo 12	1.74~1.98	-	0.36~0.72	35~45	-	0.01~0.11
Apollo 14	1.6~1.75	0.87~2.37	0.34~0.60	35~46	2.90	-
Apollo 15	1.3~1.91	0.71~1.94	-	-	3.24	-
Apollo 16	1.4~1.72	-	-	-	-	-
Apollo 17	1.57~2.29	-	-	53~56	3.20	-
CE-5	1.24	53~56	-	-	3.20	-
LSS	0.90-1.60	0.90-1.30	0.03-2.1	39-47	2.72	0.01-0.3

Effect of Landing Impact on Shear Strength of Lunar Soil Simulant

To investigate the regulation law of landing slope on the spatial distribution of shear strength of LSS after impact by a four-legged lander, direct shear tests were conducted separately on the impact zones of the four landing points under four typical

slope conditions (0° , 4° , 8° , and 12°). The Coulomb shear strength line was fitted using the least squares method to obtain the cohesion and internal friction angle under each working condition, and the results are shown in Figure 8. As shown in Figure 8(a), under the 0° horizontal landing condition, the differences in shear strength parameters among the four landing points were extremely small: the cohesion ranged from 1.14 to 1.24 kPa, and the internal friction angle ranged from 39.69° to 43.23° . This is because the four legs almost simultaneously touched the ground during horizontal landing, the impact energy was uniformly distributed, and the compaction degree and particle arrangement state at each landing point were basically consistent, which verifies the equivalence of the impact effects of the four legs under horizontal landing conditions.

With the increase of landing slope, the differences in shear strength parameters among the four landing points gradually appeared and significantly expanded. As shown in Figure 8(b), under the 4° slope condition, the internal friction angle of landing point 1 at the uphill end decreased to 39.60° , which was the minimum value under this slope; the cohesion of landing point 4 at the downhill end increased to 2.14 kPa, and the internal friction angle increased to 42.32° , both being the maximum values under this slope; the parameters of the middle landing points 2 and 3 were between them, with a difference of less than 0.1° .

As shown in Figure 8(c), under the 8° slope condition, the spatial differences in strength parameters further increased: the internal friction angle of landing point 1 rebounded to 41.49° , but was still the lowest among the four landing points; the cohesion of landing point 4 decreased to 1.40 kPa, and the internal friction angle

remained at a relatively high level of 43.31° ; the internal friction angles of the middle landing points 2 and 3 increased to 42.89° and 43.36° respectively, and the difference with landing point 4 was significantly reduced, indicating that with the increase of slope, the impact compaction effect of the middle footpads also gradually increased.

As shown in Figure 8(d), under the 12° slope condition, the shear strength parameters of each landing point were basically consistent with those under the 8° slope condition, showing a stable spatial distribution law: the internal friction angle of landing point 1 at the uphill end was still the lowest, the cohesion and internal friction angle of landing point 4 at the downhill end were still the highest, and the parameters of the middle landing points 2 and 3 were at a medium level with extremely small differences. This indicates that when the slope exceeds 8° , the spatial distribution pattern of shear strength of the post-impact LSS has been basically stabilized, and further increasing the slope will not significantly change its overall distribution characteristics. The above laws can be explained by the mechanical mechanism of the impact process of the four-legged lander: Landing point 1 at the uphill end touched the ground first. At this time, the lander was not yet stable, and the tangential slip component accounted for a large proportion of the impact energy, resulting in the directional arrangement of particles along the slope surface and weakening the interlocking effect between particles, so the internal friction angle was relatively low. The middle landing points 2 and 3 touched the ground simultaneously afterwards, with relatively balanced energy distribution and moderate vertical compaction and horizontal shear effects, so the shear strength parameters were at a medium level. Landing point 4 at the downhill end touched the

ground last. At this time, the lander was basically stable, and almost all the impact energy acted on the lunar soil in the form of normal components, resulting in the most sufficient compaction effect. The number of contact points and contact stress between particles increased significantly, and the interlocking effect reached the maximum, so both the cohesion and internal friction angle reached their peak values.

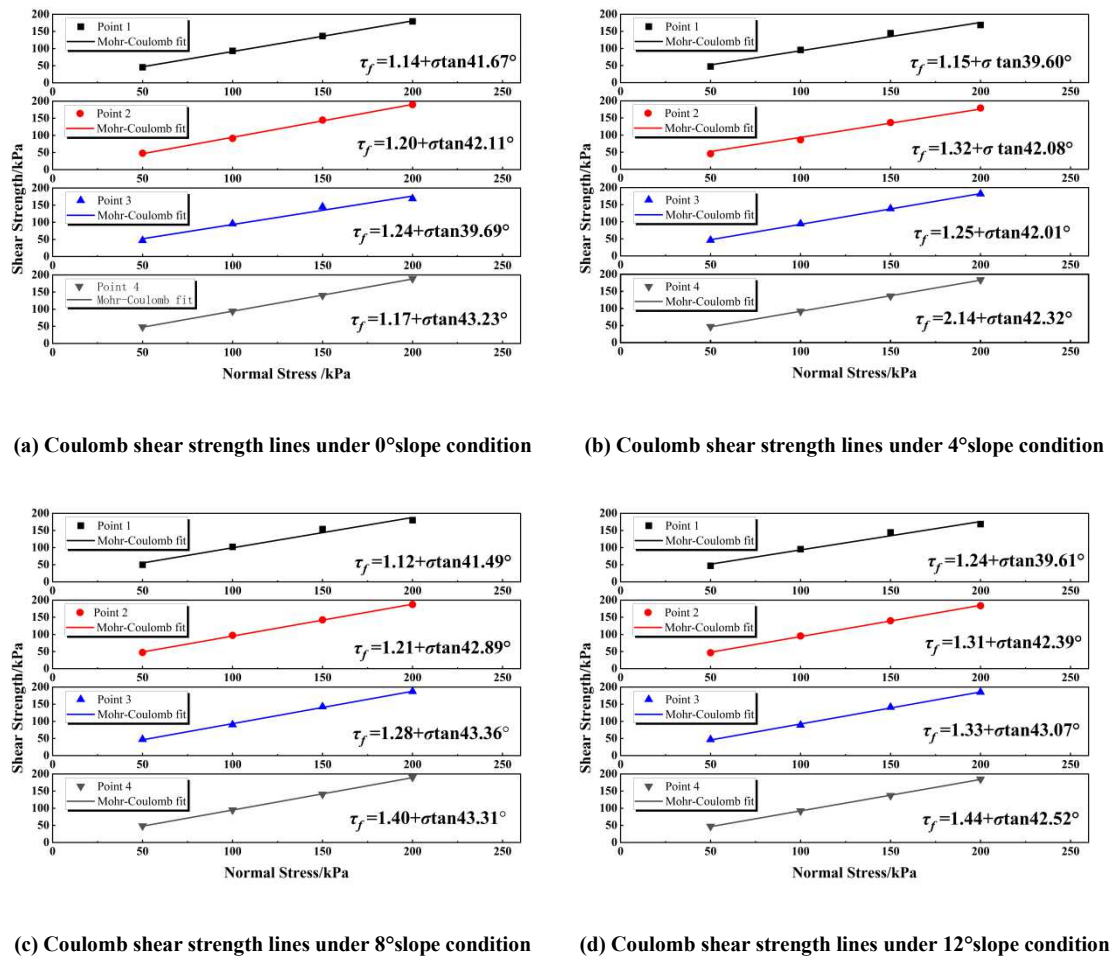


Fig. 8 Shear strength lines of LSS under various slope impact conditions

Overall, the landing slope has a significant influence on the spatial distribution of shear strength of the LSS after impact by a four-legged lander. As the slope increases from 0° to 8°, the differences in strength parameters among the four landing points gradually expand, presenting an obvious spatial distribution characteristic of "uphill weakening and downhill strengthening". This result indicates that there are differences

in the mechanical properties of lunar soil under the footpads at different positions during landing on an inclined lunar surface, which provides important reference for the stability analysis of landers and the design of landing buffer systems.

Figure 9 shows the macroscopic morphology of the impact crater of a single footpad of the lander under the 8° slope condition. The uphill side wall of the impact crater is steep and smooth, with no obvious signs of lunar soil ejection and accumulation. On the downhill side of the footpad (right side of the figure), the crater rim expands outward, forming a crescent-shaped lunar soil accumulation bulge distributed along the crater rim. The height of the bulge is approximately $1/3$ of the maximum depth of the impact crater, forming a smooth transition with the crater bottom. The central area is the direct compaction zone of the footpad, with a flat and dense surface, which is the action area of the normal component of impact energy.

This morphology is a manifestation of the uneven distribution of impact energy during inclined landing. When the footpad lands on an inclined surface, the impact energy is decomposed into a vertical normal component and a tangential component downward along the slope. The normal component forms the main depression of the impact crater. The tangential component causes the footpad to undergo a slight downward slip along the slope at the moment of touchdown, pushing the loose lunar soil in front of the footpad forward and causing shear failure. The extruded lunar soil finally accumulates at the downhill edge of the crater to form the crescent-shaped bulge. This is also in good agreement with the findings of Wang et al. [37].

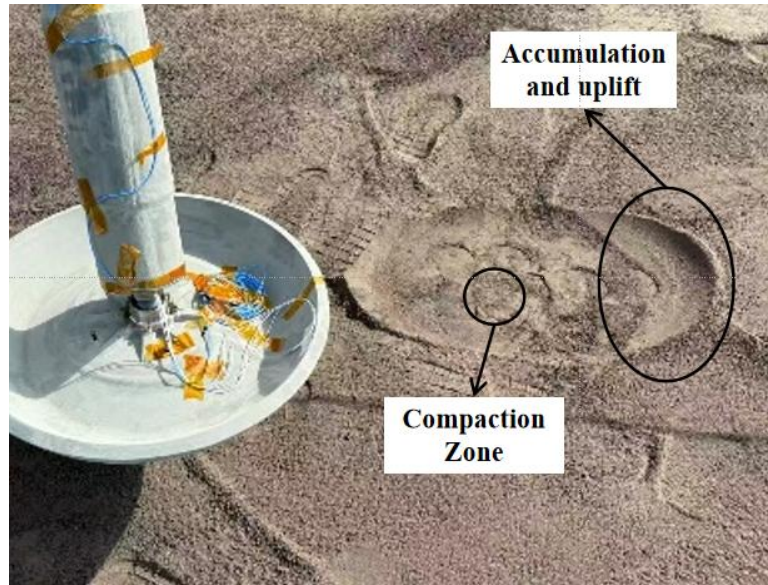


Figure 9 .Macroscopic morphology of the impact crater of the lander footpad

Effect of Landing Impact on Shear Strength of Lunar Soil Simulant

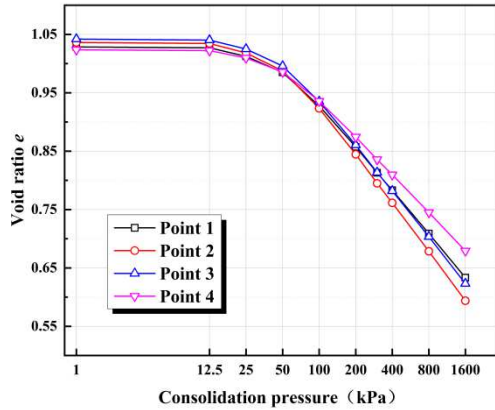
To reveal the influence law of landing impact on the compression deformation characteristics of LSS, standard consolidation tests were conducted separately on the impact zones of the four landing points under four typical slope conditions (0° , 4° , 8° , and 12°). The relationship curves between void ratio e and consolidation pressure p (e - $\lg p$ curves) were obtained, and the results are shown in Figure 10. All curves exhibit typical consolidation characteristics of cohesionless granular material. In the low consolidation pressure range (<50 kPa), the void ratio changes gently with pressure, and particles mainly undergo elastic deformation and slight displacement. When the consolidation pressure exceeds 50 kPa, the void ratio decreases rapidly and linearly with increasing pressure, and particles undergo significant rearrangement and crushing, entering the main compression stage. In the high consolidation pressure range (>800 kPa), the decline rate of void ratio gradually slows down, and the particle structure tends to be stable.

As shown in Figure 10(a), under the 0° horizontal landing condition, the e - $\lg p$ curves of the four landing points almost completely coincide, with an initial void ratio of approximately 1.04 and a final void ratio of approximately 0.63 under a consolidation pressure of 1600 kPa. This indicates that the impact energy of the four legs is uniformly distributed during horizontal landing, and the initial compaction state and compressibility of each landing point are basically consistent, further verifying the equivalence of impact effects under horizontal landing conditions.

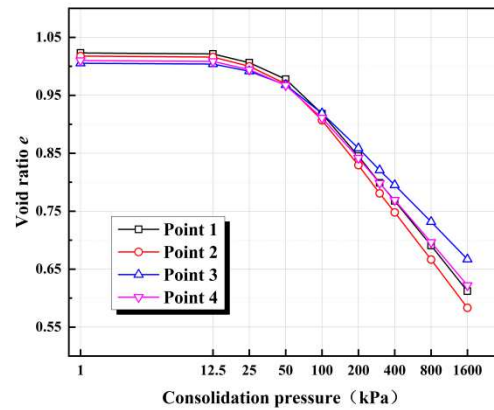
With the increase of landing slope, the consolidation curves of the four landing points gradually separate, and the spatial difference in void ratio significantly expands with increasing slope. As shown in Figure 10(b), under the 4° slope condition, the void ratio of landing point 4 at the downhill end is the lowest in the full pressure range, the void ratio of landing point 1 at the uphill end is the highest, and the curves of middle landing points 2 and 3 almost coincide and lie between them. Under a consolidation pressure of 1600 kPa, the void ratio of landing point 4 is 0.57, which is approximately 0.06 lower than that of landing point 1 (0.63), indicating that the downhill point has a higher initial compaction degree and lower compressibility.

As shown in Figure 10(c), under the 8° slope condition, the spatial difference in void ratio further increases. The initial void ratio shows an obvious gradient distribution: landing point 1 (1.04) > landing point 2 (1.03) > landing point 3 (1.02) > landing point 4 (1.00). Under a consolidation pressure of 1600 kPa, the void ratio of landing point 4 decreases to 0.58, which is approximately 0.06 lower than that of landing point 1 (0.64), and its compression curve has a smaller slope, indicating a higher compression modulus

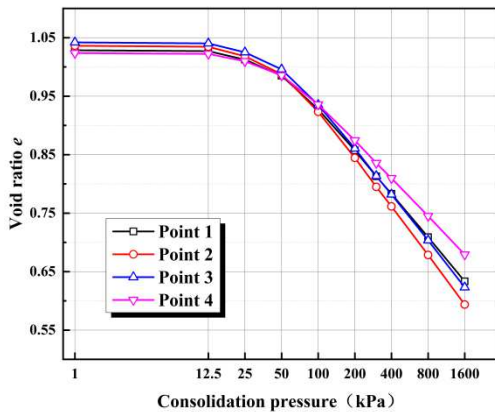
499 and stronger deformation resistance. As shown in Figure 10(d), under the 12° slope
500 condition, the spatial distribution law of void ratio is basically consistent with that under
501 the 8° slope condition, but the difference reaches the maximum. The gradient
502 distribution of initial void ratio is more significant: landing point 1 > landing point 2 >
503 landing point 3 > landing point 4. Under a consolidation pressure of 1600 kPa, the void
504 ratio of landing point 4 decreases to 0.59, which is approximately 0.06 lower than that
505 of landing point 1. This indicates that when the slope exceeds 8°, the spatial distribution
506 pattern of consolidation characteristics of the post-impact LSS has tended to be stable,
507 and further increasing the slope will not significantly change its overall compression
508 deformation law.



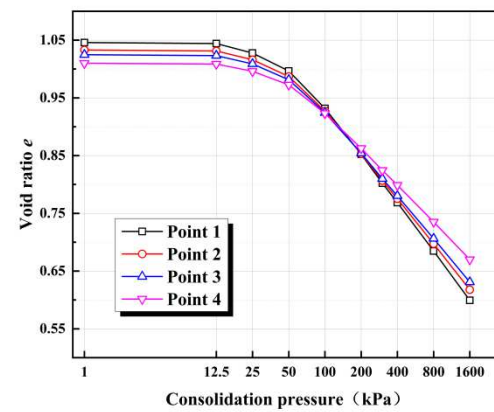
(a) e -lg p curves under 0° slope condition



(b) e -lg p curves under 4° slope condition



(c) e -lg p curves under 8° slope condition



(d) e -lg p curves under 12° slope condition

Fig. 10 Void ratio comparison of LSS under various impact conditions

The spatial differences in the aforementioned consolidation characteristics exhibit a positive correlation with the distribution law of shear strength presented earlier, and both are essentially determined by the spatial differences in impact compaction degree. Landing point 1 at the uphill end touches the ground first, where the tangential slip component dominates the impact energy. Most of the energy is consumed in the horizontal shear rearrangement of particles, resulting in a limited vertical compaction effect. The interparticle pores are well-developed and the particles are arranged disorderly, leading to a higher initial void ratio. Under subsequent loading, particles are more prone to slip and pores are more easily compressed, exhibiting greater compressibility. In contrast, landing point 4 at the downhill end touches the ground last, where particles are strongly squeezed and the pore structure is significantly compressed. This results in the lowest initial void ratio, tighter interparticle contacts, and a stronger ability to resist further compression deformation.

Overall, as the slope increases from 0° to 12° , the void ratio of the post-impact LSS presents a continuous spatial gradient distribution of "high in the uphill and low in the downhill", and this gradient becomes steeper with increasing slope. This distribution law, together with the aforementioned "uphill weakening and downhill strengthening" distribution law of shear strength, reveals the impact energy distribution mechanism on inclined lunar surfaces. These findings not only provide key mechanical parameters for the prediction of differential settlement and the analysis of landing attitude stability of landers, but also offer an important experimental basis for the evaluation of foundation bearing capacity of future long-term lunar surface habitation

bases.

4 Conclusions

A volcanic ash-based lunar soil simulant (LSS) tailored for the far side of the Moon was developed in this study. Its particle size distribution curve generally conforms to the internationally accepted lunar soil gradation standards. Its physical and mechanical parameters cover the measured ranges of natural lunar regolith, with a dry density of $0.90 - 1.60 \text{ g/cm}^3$, cohesion of $0.03 - 2.1 \text{ kPa}$, and internal friction angle of $39^\circ - 47^\circ$. The developed LSS can accurately reproduce the shear failure and compression deformation laws of lunar soil, and meets the material requirements for landing impact geotechnical tests.

The landing slope significantly affects the variation of shear strength of lunar soil after impact by a four-legged lander, presenting an obvious law of "uphill weakening and downhill strengthening". Under 0° horizontal landing, the impact energy of the four legs is uniformly distributed, and the differences in strength parameters among each landing point are extremely small. As the slope increases from 0° to 8° , the internal friction angle at the uphill end is relatively low due to the large proportion of tangential slip component, while the cohesion and internal friction angle at the downhill end reach peak values due to sufficient normal compaction effect, resulting in a gradual expansion of spatial differences in strength parameters.

The compression characteristics of lunar soil after landing impact exhibit a positively correlated distribution law with the shear strength. The void ratio shows a pattern of "high in the uphill and low in the downhill", and the gradient becomes steeper

with increasing slope. The downhill landing point has the lowest initial void ratio and the largest compression modulus, with significantly lower compressibility than the uphill end. This difference is essentially determined by the spatial distribution mechanism of impact energy: most energy at the uphill end is consumed in horizontal shear rearrangement of particles, while energy at the downhill end is mainly used for vertical compaction. This finding provides key deformation parameters for the prediction of differential settlement of landers and the evaluation of foundation bearing capacity of long-term lunar surface habitation bases.

CRedit authorship statement

Yi Sui: Writing - Review & Editing, Formal analysis, Data Curation, Conceptualization, Methodology, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used DeepSeek in order to assist with language polishing and grammar checking. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

References

1. Central People's Government of the People's Republic of China. Signature of a joint statement on international lunar research station cooperation between the National Space Administration and the Asia-Pacific Space Cooperation Organization. https://www.gov.cn/lianbo/2023-04/25/content_5753104.htm (2023).
2. Sanders, G. B. & Larson, W. E. Progress made in lunar in situ resource utilization under NASA's exploration technology and development program. *J. Aerosp. Eng.* **26**, 5-17 (2013).
3. Taylor, L. A., Pieters, C. M. & Britt, D. Evaluations of lunar regolith simulants. *Planet. Space Sci.* **126**, 1-7 (2016).
4. Weiblen, P. W. & Gordon, K. Characteristics of a simulant for lunar surface materials. In Second Conference on Lunar Bases and Space Activities of the 21st Century 254 (1988).
5. McKay, D. S., Carter, J. L., Boles, W. W. et al. JSC-1: a new lunar soil simulant. In Engineering, Construction, and Operations in Space IV 857-866 (1994).
6. Ray, C. S., Reis, S. T., Sen, S. et al. JSC-1A lunar soil simulant: characterization, glass formation, and selected glass properties. *J. Non-Cryst. Solids* **356**, 2369-2374 (2010).
7. Stoesser, D. B., Rickman, D. L. & Wilson, S. Preliminary geological findings on the BP-1 simulant (NASA/TM-2010-216444, 2010).
8. He, C., Zeng, X. & Wilkinson, A. Geotechnical properties of GRC-3 lunar simulant. *J. Aerosp. Eng.* **26**, 528-534 (2013).
9. Zeng, X., He, C. & Wilkinson, A. Geotechnical properties of NT-LHT-2M lunar highland simulant. *J. Aerosp. Eng.* **23**, 213-218 (2010).
10. Engelschiøn, V. S. et al. EAC-1A: a novel large-volume lunar regolith simulant. *Sci. Rep.* **10**, 5473 (2020).
11. Zheng, Y., Wang, S., Li, C. et al. The development of CAS-1 lunar soil simulant. In International Lunar Conference (2005).
12. Long, F., Lucas, M., Landsman, Z. et al. Applicability of simulants in developing lunar systems and infrastructure: geotechnical measurements of lunar highlands simulant LHS-1. In Earth and Space 2022 (2023).
13. Li, J., Zou, M., Jia, Y. et al. Stimulation of lunar regolith for vehicle-terramechanics research in laboratory. In Proceedings of the 10th European Conference of the International Society for Terrain-Vehicle Systems (Budapest, 2006)..
14. Sun, X., Zhang, R., Li, X. et al. JLU-H: a novel lunar highland regolith simulant for use in large-scale engineering experiments. *Planet. Space Sci.* **221**, 105562 (2022).
15. Zhang, S., Li, X., Feng, J. et al. Particle size distribution characteristics of CLRS-1 lunar soil simulant processed by a planetary ball mill. *Bull. Mineral. Petrol. Geochem.* **33**, 65-70 (2014) (in Chinese).
16. Li, Y., Liu, J. & Yue, Z. NAO-1: lunar highland soil simulant developed in China. *J. Aerosp. Eng.* **22**, 53-57 (2009).
17. Kumar, P. G. & Jayalekshmi, S. A study on wheel sinkage and rolling resistance with variations in wheel geometry for plain and lugged wheels on TRI-1 soil simulant. In *IOP Conference Series* **330** (2018).

18. He, X., Xiao, L., Huang, J. et al. Lunar regolith simulant CUG-1A. In 41st Annual Lunar and Planetary Science Conference 1183 (Woodlands, 2010).
19. Frew, A., Alshibli, K. A. & Hasan, A. Dynamic compressive strength properties of JSC-1A lunar regolith simulant. *J. Geotech. Geoenviron. Eng.* **137**, 1167-1176 (2011).
20. Patel, R., Park, S. & Frew, A. Evolution of geotechnical properties of lunar regolith simulant under landing impact loading. *Comput. Geotech.* **158**, 105342 (2023).
21. Park, S., Patel, R. & Frew, A. Shear strength evolution of lunar regolith simulant after impact loading. *J. Aerosp. Eng.* **37**, 04023145 (2024).
22. Li, Y., Wang, M. & Zhang, Y. Mechanical degradation of lunar regolith simulant under hypervelocity micro-meteoroid impacts. *Int. J. Impact Eng.* **197**, 104876 (2025).
23. He, H., Liu, B. & Gong, Z. Effect of impact history on shear strength parameters of volcanic ash-based lunar regolith simulants. *Appl. Sci.* **16**, 3327 (2026).
24. Wang, Y., Jiang, W., Wang, L. et al. Research of landing gear technology of human lunar landing. *Spacecr. Recovery Remote Sens.* **3**, 262-267 (2016) (in Chinese).
25. Liang, S., Wang, Y. & Ji, S. Analysis of landing impact process of lunar landing lander based on discrete element method. *Spacecr. Recovery Remote Sens.* **38**, 55-63 (2017) (in Chinese).
26. Jiang, M., Li, L. & Sun, Y. Properties of TJ-1 lunar soil simulant. *J. Aerosp. Eng.* **25**, 463-469 (2012).
27. Xu, G., Li, Y., Pang, R., Chen, Z. & Ren, X. Constitutive model analysis of Chang'e-5 simulated lunar regolith solidified bodies under compression. *Case Stud. Constr. Mater.* **21**, e03704 (2024).
28. Li, Y., Li, J., Zou, W. et al. Discrete element analysis for the effect of particle breakage on mechanical properties of QH-E lunar soil simulant. *Chin. J. Appl. Mech.* **43**, 367-375 (2026) (in Chinese).
29. Xue, L., Zou, M., Li, J. et al. Mechanical performance estimation of lunar soil using wheel-soil interaction parameter and PLSDA. *Acta Aeronaut. Astronaut. Sin.* **36**, 3751-3758 (2015) (in Chinese).
30. Alberquilla, F., Martínez-Frías, J., García-Baonza, V. & Lunar, R. LZS-1, Lanzarote (Canary Island, Spain) lunar (Apollo 14) basaltic soil simulant. *Sci. Rep.* **12**, 16470 (2022).
31. Go, G.-H., Lee, J., Chung, T. et al. Controlling soil disturbance of a lunar regolith simulant bed during depressurization in a vacuum chamber. *Sci. Rep.* **11**, 1878 (2021).
32. Mei, A. et al. KREEP-rich breccia in Chang'E-5 regolith and its implications. *Sci. China Earth Sci.* **66**, 2473-2486 (2023).
33. Chen, B., Li, J., Zhang, R. et al. Study on the pressure-sinkage characteristics of simulated lunar soil. In International Conference on Measurement and Control of Granular Materials (2009).
34. Helfenstein, P. & Veverka, J. Photometric properties of lunar terrains derived from Hapke's equation. *Icarus*. **72**, 342-357 (1987).
35. Qi, S. et al. Strongly cohesive lunar soil identified at the Chang'e-6 landing site. *Nat. Astron.* **10**, 214-223 (2026).
36. Jiang, M., Lv, L., Li, L. et al. Bearing properties of TJ-M1 Mars soil simulant. *Chin. J. Geotech. Eng.* **42**, 1783-1789 (2020).
37. Wang, Y., Wang, L., Wu, S. et al. Investigation of the lunar landing impact characteristics for the lunar regolith base on theory of the discrete element method. *Spacecr. Recovery Remote Sens.* **41**, 21-28 (2020) (in Chinese).