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Particle Interface Mechanics Explains Cone Penetration Behavior in Lunar Regolith Simulants Under Load Conditions

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Abstract.

The renewed global interest in lunar exploration necessitates a comprehensive understanding of extraterrestrial soil mechanics, particularly concerning the interaction between geotechnical investigation tools and lunar regolith. Cone penetration testing represents a highly reliable method for in-situ soil characterization; however, the unique physical properties of lunar regolith, characterized by high angularity, broad particle size distribution, and an absence of atmospheric moisture, severely complicate the particle-interface mechanics during penetration. This paper presents an extensive investigation into the microscopic and macroscopic mechanical behaviors at the interface between cone penetration tools and lunar regolith simulants. Utilizing meticulously prepared terrestrial simulants, a series of comprehensive penetration experiments were conducted to evaluate the effects of relative density, tool surface roughness, and penetration rate on tip resistance and sleeve friction. The study focuses on the localized particle kinematics, including rotation, displacement, and crushing at the tool interface. By analyzing the formation of shear bands and the evolution of the compacted soil core ahead of the penetrometer tip, this research delineates the distinct friction mechanisms governing extraterrestrial soil-tool interactions. The findings indicate that particle interlocking and localized dilation significantly augment penetration resistance, deviating substantially from standard terrestrial empirical correlations. These insights are critical for the optimization of future lunar rovers, landers, and automated geotechnical survey equipment intended for in-situ resource utilization and infrastructure development on the lunar surface.

Keywords: *Lunar Regolith, Cone Penetration Testing, Interface Mechanics, Granular Dynamics*

INTRODUCTION

1.1 Background Of Lunar Geotechnical Engineering

The progression of humanity into an interplanetary species is fundamentally dependent on our ability to establish sustainable outposts on extraterrestrial bodies, beginning with Earth's moon. As international space agencies and private aerospace entities accelerate their timelines for lunar surface operations, the discipline of lunar geotechnical engineering has emerged as a paramount

field of study. Unlike the brief exploratory missions of the Apollo era, future lunar missions are explicitly designed for long-term habitation, continuous scientific operation, and in-situ resource utilization. This paradigm shift requires the construction of robust infrastructure, including landing pads, habitat foundations, unpaved roadways, and radiation shielding structures. To design and construct these facilities safely and efficiently, engineers must possess highly accurate and spatially continuous data regarding the mechanical properties of the lunar surface. The topmost layer of the moon is covered by regolith, a fragmental and unconsolidated rock material formed over billions of years through continuous micrometeoroid impacts, solar wind irradiation, and severe thermal cycling. This genesis process results in a granular material that is fundamentally different from terrestrial soils. The particles are extremely angular, often possessing jagged edges and interlocking shapes, and exist in a high-vacuum, low-gravity environment devoid of organic matter and pore water. Consequently, the mechanical behavior of lunar regolith is characterized by unusually high friction angles, extreme compressibility at low densities, and significant dilative behavior under shear stress [1]. Understanding how engineering tools interact with this unique material at the particulate level is essential for the success of future robotic and human missions.

1.2 Cone Penetration Testing In Extraterrestrial Environments

Among the various techniques available for geotechnical site characterization, the cone penetration test is widely regarded as one of the most effective, continuous, and reliable methods. Originating in terrestrial civil engineering, the test involves pushing an instrumented cone into the ground at a controlled rate while continuously recording the resistance at the tip and the friction along the cylindrical sleeve behind the tip. When applied to lunar exploration, cone penetration testing offers the distinct advantage of providing continuous stratigraphic profiles without the need to recover, transport, or preserve physical soil samples, which is a highly complex and energy-intensive process in a vacuum. However, the interpretation of cone penetration data relies heavily on empirical correlations developed from decades of terrestrial testing in standard sands and clays. These traditional correlations cannot be directly extrapolated to lunar regolith due to the profound differences in particle morphology and environmental conditions [2]. When a cone penetrometer is advanced into lunar regolith, the severe angularity of the particles leads to intense mechanical interlocking. As the tool pushes downward, the soil particles must dilate and slide past one another and along the metallic surface of the penetrometer. This action creates a complex zone of particle-interface mechanics governed by micro-scale friction, localized crushing of fragile asperities, and the continuous formation and destruction of force chains within the granular matrix [3]. Therefore, to accurately derive macroscopic soil parameters such as relative density, shear strength, and bearing capacity from lunar penetration data, a rigorous investigation of the micro-mechanical interactions at the tool-soil interface is strictly necessary [4].

2. Literature Review

2.1 Characteristics Of Lunar Regolith And Simulants

The foundational knowledge of lunar soil mechanics is primarily derived from the analysis of samples returned by the Apollo and Luna missions during the late twentieth century. These invaluable samples revealed that lunar regolith is predominantly composed of basaltic and anorthositic rock fragments, mineral grains, and unique impact-generated glassy agglutinates. The presence of agglutinates, which are complex aggregates of smaller particles bonded together by impact-melted glass, significantly contributes to the high internal friction and interlocking capabilities of the soil [5]. Because actual lunar samples are exceedingly rare and reserved for highly specialized scientific research, the global engineering community relies on the development and utilization of lunar regolith simulants for large-scale geotechnical testing. Early simulants, such as the Minnesota Lunar Simulant, provided basic bulk density and mineralogical approximations [6]. Subsequent generations of simulants, including the widely used Johnson

Space Center Number One series, were engineered to more accurately replicate the particle size distribution, specific gravity, and general geomechanical behavior of lunar mare regions [7]. More recently, advanced simulants have been developed in various countries to simulate specific regions of the moon, such as the polar highlands where water ice is anticipated to exist. These modern simulants are subjected to extensive crushing, milling, and sometimes plasma treatment processes to recreate the characteristic jaggedness and glassy textures of genuine lunar particles [8]. While no simulant is perfect, they remain the most viable medium for terrestrial laboratory experiments concerning machine-soil interactions [9]. Researchers have continuously noted that the mechanical response of these simulants is highly sensitive to their initial packing state, requiring meticulous preparation techniques to achieve repeatable test conditions [10].

2.2 Mechanics Of Soil-Tool Interaction

The study of soil-tool interaction is a mature field within agricultural and earthmoving engineering, yet its application to extraterrestrial environments requires a significant reevaluation of established theories. Classical analytical models often treat the soil as a continuous, homogenous macroscopic continuum, utilizing plasticity theories to predict failure mechanisms and resultant forces [11]. While continuum approaches are computationally efficient and sufficient for large-scale terrestrial earthmoving estimations, they fundamentally fail to capture the discrete, discontinuous nature of granular flow around penetrating objects in highly angular media. When a penetration tool moves through lunar regolith simulants, the interaction is not a smooth, continuous plastic flow. Instead, it is characterized by the discrete rearrangement of particles, the formation of transient load-bearing arches, and the localization of shear strains into very narrow bands [12]. As the cone tip advances, it compresses the soil immediately beneath it, forming a hardened, quasi-static core of interlocking particles that effectively alters the geometric shape of the penetrating tip. This phenomenon, often referred to as a false tip or dead zone, significantly increases the required penetration force. Furthermore, the material that is displaced laterally by the advancing tip must slide along the cylindrical sleeve of the tool. The mechanics of this sliding interface are governed by the relative roughness of the tool surface compared to the median particle size of the soil, as well as the normal stress exerted by the surrounding soil matrix [13]. High friction at this interface can lead to a condition where the failure surface shifts from the boundary between the metal and the soil to a boundary entirely within the soil itself, creating a shear band of rotating and translating particles parallel to the tool surface [14].

2.3 Gaps In Particle-Level Interface Mechanics

Despite decades of research into cone penetration testing, significant knowledge gaps remain concerning the micro-mechanical behavior of highly angular, crushable granular materials at the interface of penetrating tools. Most experimental studies historically relied on post-test visual inspections or bulk force measurements, which provide only a macroscopic view of the interaction [15]. The internal kinematics of the particles during the continuous penetration process were largely treated as a black box. With the advent of advanced computational techniques such as the Discrete Element Method, researchers began to simulate the individual trajectories and contact forces of thousands of particles during penetration [16]. However, these numerical simulations often employ simplified particle shapes, such as spheres or simple clumps, to reduce computational overhead. This simplification inherently underestimates the degree of interlocking and rotational resistance that occurs with true lunar regolith [17]. Furthermore, experimental validation of these micro-scale phenomena in physical laboratories has been hindered by the opacity of granular materials. While techniques like X-ray computed tomography and transparent synthetic soils have been applied to terrestrial sands to visualize internal deformations, their application to actual lunar simulants remains limited due to the specific optical and physical properties of the basaltic materials used [18]. Consequently, there is a pressing need for comprehensive experimental

investigations that utilize highly realistic lunar simulants and precisely instrumented penetration tools to systematically study the interface mechanics, particle crushing, and friction mobilization under conditions that closely mimic the extraterrestrial operational environment.

3. Methodology

3.1 Material Properties And Preparation

To conduct a rigorous experimental investigation of particle-interface mechanics, a high-fidelity lunar regolith simulant was selected as the testing medium. The simulant was engineered to replicate the geotechnical properties of typical lunar mare regions, characterized by a predominantly basaltic composition and a broad, well-graded particle size distribution. The specific gravity of the simulant particles was measured, and a comprehensive sieve and hydrometer analysis was performed to determine the particle size distribution curve. The simulant features a high proportion of fine materials, including silt-sized particles, which are critical for replicating the cohesive-like behavior observed in real lunar soils under high vacuum due to van der Waals forces, although these tests were conducted under atmospheric conditions. The angularity of the particles was quantitatively assessed using dynamic image analysis, confirming a high degree of edge sharpness and morphological irregularity typical of micrometeorite-impacted materials.

Table 1: Physical properties of the selected lunar regolith simulant.

Property	Value	Unit
Specific Gravity	2.92	Dimensionless
Mean Particle Size	0.085	Millimeters
Coefficient of Uniformity	15.4	Dimensionless
Coefficient of Curvature	1.8	Dimensionless
Maximum Dry Density	1.95	Grams per cubic centimeter
Minimum Dry Density	1.45	Grams per cubic centimeter

Achieving uniform and repeatable initial states within the testing chamber is crucial for the reliability of penetration data. The simulant was prepared using a precisely controlled dry pluviation technique. The material was deposited into the testing chamber through a series of diffuser sieves from a calibrated drop height. By systematically altering the drop height and the mass flow rate of the falling particles, the relative density of the soil bed could be accurately controlled. For this experimental program, three distinct relative density states were targeted: a loose state, a medium-dense state, and a very dense state. The dense state was achieved by combining the maximum drop height with high-frequency mechanical vibration applied to the base of the chamber, ensuring maximum particle interlocking and minimizing void spaces prior to penetration.

3.2 Penetration Tool Design And Instrumentation

The central apparatus for this study is a custom-designed miniature cone penetrometer, scaled down to minimize boundary effects within the laboratory testing chamber while maintaining geometric similarity to standard field equipment. The penetrometer consists of a conical tip and a cylindrical friction sleeve, both fabricated from high-strength stainless steel to resist abrasion from the hard basaltic simulant particles. To investigate the effect of tool geometry and surface characteristics on interface mechanics, multiple interchangeable cones and sleeves were manufactured. The apex angle of the cone is a critical parameter that dictates the volume of soil displaced and the predominant direction of particle flow; therefore, cones with different apex angles were utilized.

Table 2: Geometric and surface parameters of the cone penetration tools.

Tool Component	Parameter	Value Range
Cone Tip	Apex Angle	30 to 60 degrees
Cone Tip	Base Diameter	15.0 millimeters

Friction Sleeve	Length	45.0 millimeters
Friction Sleeve	Outer Diameter	15.0 millimeters
Surface Finish	Average Roughness	0.2 to 2.5 micrometers
Internal Sensor	Load Capacity	5.0 kilonewtons

The penetrometer is internally instrumented with high-precision miniature load cells. The design independently isolates the forces acting on the conical tip from those acting on the cylindrical sleeve. The tip load cell measures the vertical axial resistance encountered as the soil is compressed and sheared downward and outward. Simultaneously, the sleeve load cell measures the longitudinal shear force generated by the soil sliding past the cylindrical surface. The surface roughness of the interchangeable sleeves was precisely quantified using white light interferometry, providing an average roughness value. The selection of roughness values ranged from highly polished surfaces to artificially roughened textures, designed to span the spectrum from smooth boundary sliding to complete interface interlocking.

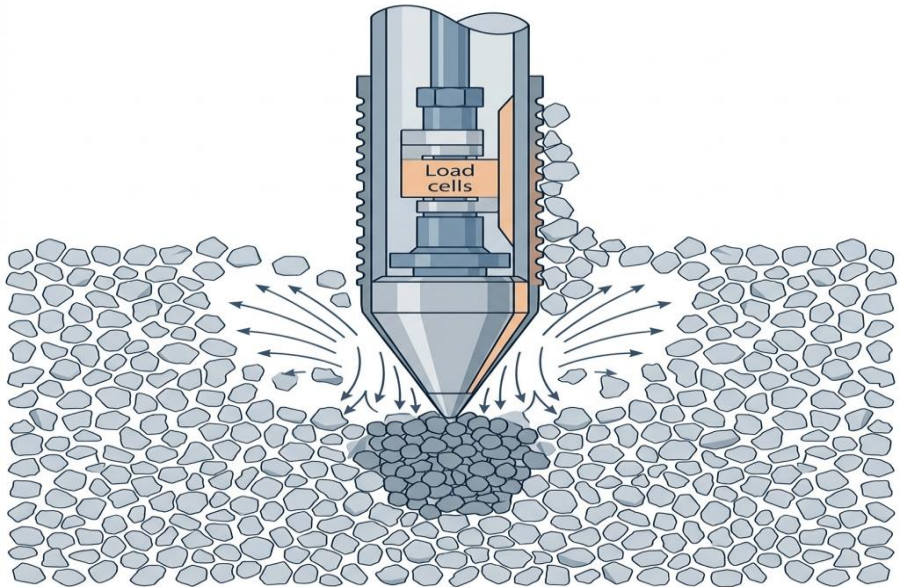


Figure 1: Comprehensive Schematic of Miniature Cone Penetration Tool and Granular Interface Mechanics

3.3 Experimental Setup And Testing Procedure

The penetration tests were conducted within a rigid cylindrical soil calibration chamber designed to withstand high lateral stresses without significant deformation. The internal diameter of the chamber was sized to be sufficiently large compared to the penetrometer diameter, ensuring that boundary effects from the rigid walls did not artificially inflate the measured penetration resistance. The penetrometer was attached to a servo-mechanical linear actuator capable of applying substantial vertical force with strict control over the displacement rate. The actuator system was mounted on a heavy-duty reaction frame to prevent any structural deflection during the tests.

Table 3: Experimental testing matrix detailing controlled variables.

Test Series	Relative Density Target	Penetration Rate	Surface Roughness
Series A	Loose (30 percent)	1.0 millimeters per second	Smooth
Series B	Medium (60 percent)	1.0 millimeters per second	Smooth
Series C	Dense (90 percent)	1.0 millimeters per second	Smooth

Series D	Dense (90 percent)	0.1 millimeters per second	Rough
Series E	Dense (90 percent)	10.0 millimeters per second	Rough
Series F	Loose (30 percent)	1.0 millimeters per second	Rough

For each test iteration, the chamber was filled with the simulant using the specified pluviation method. The surface of the soil bed was carefully leveled. The linear actuator then advanced the penetrometer into the center of the soil bed at a constant rate of penetration. Data from the tip load cell, sleeve load cell, and displacement transducer were continuously recorded by a high-speed data acquisition system at a sampling frequency sufficient to capture the minute fluctuations in force caused by individual particle interlocking and failure events. The penetration continued until a target depth was reached, which was deep enough to ensure that steady-state boundary conditions were established and the influence of the free surface was negligible. Following each test, the simulant was carefully excavated. In tests aimed at studying particle crushing, samples of the soil situated immediately adjacent to the penetration path were collected and subjected to post-test sieve analysis to quantify any changes in the particle size distribution resulting from high-stress fracturing.

4. Results and Discussion

4.1 Analysis Of Penetration Resistance

The continuous measurement of tip resistance and sleeve friction provided a detailed macroscopic record of the energy required to displace the lunar regolith simulant. As the penetrometer advanced from the free surface into the soil bed, an initial transient phase was observed where both tip resistance and sleeve friction increased non-linearly. This initial phase corresponds to the mobilization of shear strength in the shallow soil layers, where the failure mechanism is predominantly governed by the upward displacement of soil toward the unconfined surface. Once the penetrometer reached a critical depth, the failure mechanism transitioned from shallow heaving to deep cavity expansion. At this critical depth, the tip resistance transitioned into a steady-state phase, exhibiting a much more gradual rate of increase directly proportional to the increasing lithostatic pressure of the overlying soil material [19]. The relative density of the initial soil bed proved to be the most dominant factor influencing the magnitude of penetration resistance. In the loose state, the angular particles of the simulant were able to easily rotate and slide into adjacent void spaces, accommodating the volume of the penetrometer through localized densification without transmitting large stress chains outward. Conversely, in the dense state, the initial void ratio was near its minimum, and the particles were highly interlocked. To accommodate the penetrometer, the dense soil was forced to dilate, causing particles to move outward against the confining pressure of the surrounding material. This forced dilation in a highly angular and interlocking medium resulted in an exceptionally high tip resistance, an effect that is substantially more pronounced in lunar simulants than in typical rounded terrestrial silica sands [20]. The extremely sharp edges of the basaltic simulant heavily resist rolling, meaning that deformation must occur through sliding friction or the physical breakage of asperities.

4.2 Particle Kinematics And Localized Failure Mechanisms

The detailed examination of the force-displacement curves revealed frequent, high-frequency oscillations in the measured loads, particularly during tests conducted in the dense state. These micro-fluctuations are indicative of the discrete nature of the granular medium. Each sudden drop in resistance corresponds to the localized collapse of a force chain or the structural failure of an interlocking particle cluster ahead of the advancing tip [21]. This behavior confirms that the soil does not fail uniformly but rather through a series of microscopic avalanches and rearrangements.

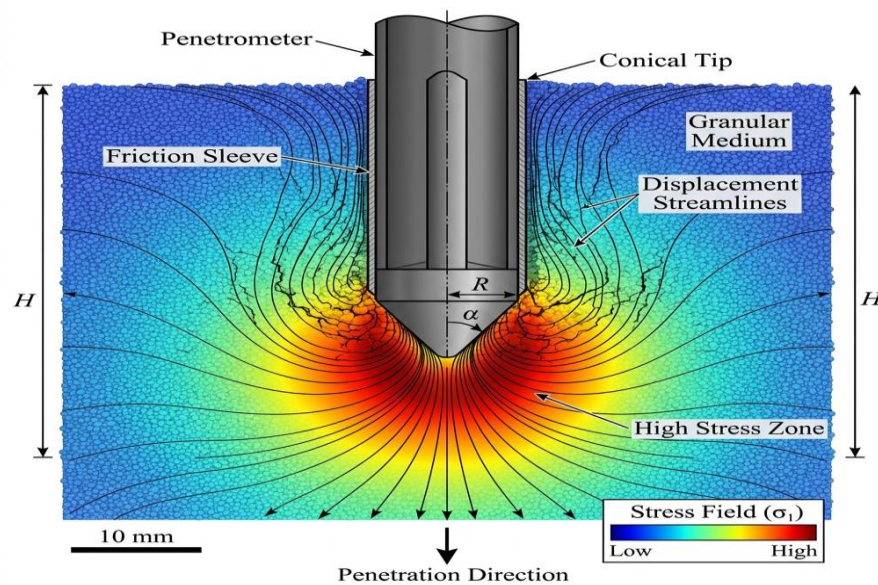


Figure 2: Stress Distribution and Kinematic Displacement Field During Deep Granular Penetration

One of the most critical observations was the formation of a compacted core of soil, often referred to as a dead zone, directly beneath the cone tip. Due to the high friction angle of the simulant, the soil immediately below the tip becomes trapped, moving downward at the same velocity as the penetrometer itself. This trapped mass effectively changes the geometry of the tool from a sharp cone to a blunted, hemispherical shape. The presence of this compacted core means that the actual shear failure surface does not occur at the metal-soil interface of the cone tip, but rather within the soil matrix itself, some distance away from the tool surface. This phenomenon explains why variations in the surface roughness of the conical tip had a negligible effect on the measured tip resistance, as the soil was primarily shearing against other soil particles rather than the metal surface [22]. Furthermore, post-test sieve analysis of the soil recovered from the immediate vicinity of the penetration path revealed a measurable increase in the proportion of fine particles compared to the virgin simulant. This shift in the particle size distribution provides conclusive evidence of particle crushing. The immense stresses generated at the tip of the penetrometer exceed the crushing strength of the individual angular asperities and, in some cases, entire soil grains. The fracturing of these particles consumes a significant amount of input energy, contributing to the high penetration resistance. The generated dust and fine fragments then migrate into the surrounding voids, further altering the local density and frictional characteristics of the shear zone [23].

4.3 Interface Friction And Sleeve Interactions

While tip resistance is primarily governed by cavity expansion and soil compressibility, sleeve friction is entirely dependent on the interaction between the cylindrical tool surface and the laterally confined granular medium. The experimental data demonstrated that sleeve friction is highly sensitive to the initial surface roughness of the penetrometer. In tests utilizing a highly polished, smooth sleeve, the measured friction was relatively low, and the failure mechanism was dominated by pure sliding of the soil particles against the metal boundary.

Table 4: Summary of calculated interface friction angles under varying conditions.

Tool Roughness	Soil Density State	Interface Friction Angle	Failure Mechanism
Smooth	Loose	14.5 degrees	Boundary sliding
Smooth	Dense	16.2 degrees	Boundary sliding
Rough	Loose	28.3 degrees	Partial interlocking

Rough	Dense	34.7 degrees	Soil-on-soil shear
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When the rough sleeve was introduced, the behavior changed dramatically. The artificial asperities on the rough sleeve were comparable in size to the mean particle diameter of the simulant. This geometric similarity allowed the angular soil particles to mechanically interlock with the tool surface. As the penetrometer advanced, the interlocked particles were dragged downward, forcing them to shear against the stationary soil particles in the adjacent bulk material. This transition from boundary sliding to internal soil shearing resulted in a massive increase in the measured sleeve friction. The calculated interface friction angle for the rough sleeve in dense soil approached the internal friction angle of the soil itself, confirming that the failure surface had migrated completely into the granular matrix. The penetration rate also exhibited a minor but observable influence on sleeve friction. At higher penetration rates in dense soil, there was a slight reduction in the average sleeve friction. This is hypothesized to be a result of the dynamic fluidization of the boundary layer; the rapid succession of particle impacts and acoustic vibrations generated by the fast-moving tool may temporarily dilate the shear band immediately adjacent to the sleeve, reducing the normal effective stress and consequently lowering the sliding resistance. However, at the slow penetration rates typical of extraterrestrial robotic operations, this dynamic effect is negligible, and maximum interlocking friction must be accounted for in the structural design of the driving mechanisms.

5. Conclusion

5.1 Summary Of Findings

The comprehensive experimental program detailed in this paper provides vital insights into the complex particle-interface mechanics governing the interaction between cone penetration tools and highly angular lunar regolith simulants. The findings unequivocally demonstrate that traditional terrestrial theories of soil-tool interaction, which often rely on continuum mechanics and assume rounded silica sands, are vastly insufficient for predicting the behavior of extraterrestrial soils. The extreme angularity and broad size distribution of the simulant particles lead to severe mechanical interlocking, forcing the granular medium to dilate significantly under shear stress. This forced dilation, particularly in dense packing states, results in exceptionally high tip resistance that cannot be easily mitigated by altering the geometric angle of the penetrating cone. The formation of a rigid, compacted core of soil ahead of the tip effectively transfers the primary failure surface into the surrounding soil bulk, nullifying any potential benefits of a smooth tip surface. Furthermore, the study highlights the critical role of surface roughness in determining the magnitude of sleeve friction. Rough surfaces that allow for particle interlocking shift the sliding interface away from the tool and into the soil matrix, resulting in a mobilization of the soils full internal shear strength and dramatically increasing the required driving force. The physical crushing of particle asperities under high local stresses was also confirmed, indicating that the penetration process fundamentally alters the state and composition of the soil in the immediate vicinity of the tool.

5.2 Future Directions And Implications For Lunar Exploration

The implications of these findings for future lunar exploration are profound. Engineers designing autonomous rovers, sampling drills, and geotechnical survey penetrometers for the Artemis program and beyond must account for these micro-mechanical interlocking and dilation phenomena to prevent tool refusal, excessive power consumption, or structural failure of the deployment mechanisms [24]. To advance this field further, future research must transition from terrestrial laboratory conditions to environments that accurately replicate the reduced gravity and ultra-high vacuum of the lunar surface. Reduced gravity flight experiments or centrifuge testing combined with vacuum chambers are essential to determine how the absence of atmospheric pressure and diminished gravitational confinement alter the dilation behavior and arching mechanisms within the soil. Additionally, the integration of advanced transparent simulants with

three-dimensional optical tracking could finally illuminate the internal kinematics of the shear bands in real-time, providing the definitive data required to refine and validate next-generation discrete element computational models. Ultimately, a deeper, particle-level understanding of extraterrestrial soil mechanics is the bedrock upon which reliable and sustainable lunar infrastructure will be built.

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