Shear Strength of Lunar Regolith under Vacuum and Low Gravity

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Series Preamble

SpaceGeotech Brief Tech Series — Adaptations of Classical Soil Mechanics for Lunar Conditions

This document is part of the *SpaceGeotech Brief Tech Series*, a sequence of technical briefs dedicated to adapting the foundations of terrestrial soil mechanics for lunar regolith conditions. The series builds upon canonical works in geotechnical engineering (Terzaghi, Peck, Lambe & Whitman, Bowles, Das, Holtz & Kovacs) and integrates findings from Apollo soil mechanics experiments, NASA technical memoranda, and current Artemis-era mission planning.

The objective is not to propose standards or guidelines, but to provide rigorous adaptations of established soil mechanics equations for lunar conditions. These adaptations aim to create a structured technical reference that academics, engineers, and mission planners can critique, refine, and build upon.

Each Brief Tech presents:

- An adapted formulation of a classical soil mechanics equation for lunar regolith.
- Theoretical justification and newly defined lunar parameters.
- Figures and charts to illustrate applicability.
- Worked engineering examples tied to realistic mission scenarios (e.g., SpaceX Starship HLS, Blue Origin-Blue Moon).

Disclaimer

SpaceGeotech issues this Brief Tech as part of the *SpaceGeotech Brief Tech Series — Adaptations of Classical Soil Mechanics for Lunar Conditions*.

The material presented herein is intended for educational and professional development purposes. It reflects the author's interpretation of classical soil mechanics theory extended to lunar regolith conditions.

These Brief Techs are provisional technical references. They are not peer-reviewed standards, design codes, or specifications, and must not substitute for:

- In-situ reconnaissance or field investigation,
- Mission-specific testing and validation,
- Regulatory or contractual requirements.

All formulations and examples are subject to refinement and critique by the academic and professional community as new lunar data becomes available. Readers are encouraged to treat these documents as part of an evolving technical dialogue in lunar geomechanics.

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1. Introduction

The classical framework of soil mechanics, established by Terzaghi and developed further by Peck, Lambe, Whitman, Bowles, and others, has provided the foundation for terrestrial geotechnical engineering. Within this framework, the shear strength of soils is typically expressed through the Mohr–Coulomb relation, in which cohesion 'c', the friction angle ϕ, and the effective stress principle define the envelope of soil resistance. On Earth, this formulation has enabled reliable analysis of foundation bearing capacity, slope stability, retaining walls, and trafficability problems for nearly a century.

When transported to the lunar environment, however, several of these assumptions break down. The Moon lacks pore water and an atmosphere; gravity is approximately one-sixth of that on Earth; and the near-surface regolith exists in a vacuum subject to intense thermal cycling, solar radiation, and electrostatic charging. As a result, the conventional concept of "effective stress" becomes irrelevant, and cohesion must be reinterpreted as an *apparent cohesion* arising from a combination of van der Waals forces, electrostatic adhesion, thermal effects, and, potentially, localized sintering of grains.

Apollo mission experiments confirmed that lunar soil displays unusual shear behaviour under low overburden. Footpad penetration tests, astronaut trenching, and laboratory vacuum shear box experiments on returned samples revealed shear resistance that could not be explained by frictional strength alone. These observations strongly suggest that cohesion in lunar soils is not negligible, even at very low confining stresses.

For these reasons, a direct transfer of terrestrial equations to lunar conditions is inadequate. A new formulation is required, one that preserves the familiar structure of Mohr–Coulomb while introducing parameters capable of capturing the unique physical environment of the Moon. This Brief Tech proposes such a reformulation and demonstrates its application through both theoretical derivation and worked examples involving present-day lander concepts such as the SpaceX Starship HLS and Blue Origin's Blue Moon.

2. Reformulated Shear Strength Law

The classical Mohr–Coulomb criterion has been the cornerstone of terrestrial soil mechanics since Terzaghi first applied it systematically in the 1930s. In this framework, shear strength is expressed as a linear function of normal stress, with parameters cohesion (c) and friction angle (ϕ) derived from controlled laboratory testing. On Earth, the effective stress principle underpins this law: pore pressures reduce the interparticle stress that provides resistance, and the balance between effective stress, cohesion, and friction governs stability.

When extended to the Moon, however, several foundational assumptions no longer apply. First, the lunar regolith is dry and exposed to vacuum conditions, eliminating the role of pore water pressure. Second, the unit weight of the regolith is reduced by a factor of six due to the lower gravitational acceleration, meaning that overburden stresses are extremely small compared to terrestrial soils. Third, Apollo experiments and laboratory studies on returned samples have shown that lunar regolith exhibits an apparent cohesion even in the absence of cementation or bonding. This adhesion arises from van der Waals forces, electrostatic charging, thermal cycling effects, and localized sintering.

For these reasons, the shear strength law must be reformulated. The goal is to retain the mathematical clarity and utility of Mohr–Coulomb while redefining its parameters to capture the lunar environment. The governing relation for lunar conditions is therefore expressed as:

$$\tau = c* + \sigma_n tan\left(\varphi * (p')\right)$$

Where:

- c^* is the *apparent cohesion*, representing a lumped parameter that includes van der Waals forces, electrostatic attraction, thermal adhesion, and localized grain sintering.
- $\Phi^*(p')$ is a stress-dependent friction angle. At very low confining pressures, typical of lunar surface layers, the angular particle morphology of regolith can produce scale-sensitive frictional behaviour.
- σ_n is the applied normal stress at the particle contacts. In vacuum and in the absence of pore water, $\sigma'=\sigma$.

2.1. Stress-Dependent Friction

Experimental evidence from Apollo and subsequent simulant testing indicates that the friction angle is not constant across stress levels, but increases gradually with confining pressure. A logarithmic relationship provides a practical means of capturing this dependency:

$$\varphi^*(p') = \varphi\_ref + k\varphi \ ln(p' / p\_ref)$$

Where:

- ϕ_{ref} is the reference friction angle at a defined mean stress p_{ref},
- k_ϕ is a calibration constant derived from vacuum shear or triaxial tests,
- p' is the mean stress, which in direct shear or shallow bearing problems can be approximated as the applied normal stress σ_n.

2.2. Apparent Cohesion as a Dominant Parameter

A second adaptation introduces a characteristic depth scale:

$$\ell_c = c^*/\gamma$$

with

$$\gamma = \rho g_m$$

Where γ is the unit weight of the regolith, the parameter ℓc represents the depth at which the contribution of apparent cohesion equals that of self-weight.

This scale defines the depth at which apparent cohesion and self-weight contribute equally to shear resistance. On the Moon, where unit weights are typically around 2.5–2.7 kN/m^3, even a small c^* of 1 kPa gives $\ell\ c \approx 0.4$ m. In practice, this means adhesion is dominant in the upper regolith layers, precisely the zone where foundations, rover wheels, and excavation berms operate.

Historical Basis

Apollo-era experiments, including direct shear and triaxial tests on returned samples, reported cohesion intercepts of 0.4–1.5 kPa and friction angles in the range 30°–50° (Heiken, Vaniman & French, Lunar Sourcebook, 1991). Penetrometer data indicated surficial resistance consistent with $c^* \approx 1$ kPa, while astronaut trenching revealed stable vertical walls to depths of ~0.3 m, again confirming the presence of adhesion. These observations demonstrate that lunar soils cannot be treated as purely frictional and justify the introduction of an explicit cohesion term.

Contrast with Terrestrial Practice

On Earth, it is common practice to neglect cohesion in clean sands, assuming $c = 0$ without penalty. In the lunar case, however, such an assumption would underestimate shear strength by 30–50% at shallow depths. More critically, because overburden stresses are an order of magnitude smaller, adhesion becomes disproportionately significant. The explicit use of c^* and ℓc is therefore essential for any realistic treatment of lunar soils.

Practical Construction Implication

Consider a small lunar construction pad designed to receive a 20-tonne lander, such as Blue Origin's *Blue Moon Mark 1*. With landing pads of roughly 1.2 m^2 each, the normal stress imposed on the soil is about 50 kPa. Using a modest adhesion (c^*=1.0 kPa) and a reference friction angle of 32°, the available shear resistance is only 30–35 kPa. The applied stress exceeds this by a significant margin, yielding a factor of safety well below unity.