Outdated Assumptions, Unrealistic Designs: Soil Mechanics Must Be Rewritten for the Moon

Author: Roberto de Moraes

Date: July 2025

Source: www.spacegeotech.org

Disclaimer

The views and analyses presented in this article are solely those of the author and do not reflect the positions, strategies, or opinions of any employer, organization, or affiliated institution. All interpretations and recommendations are provided for academic and engineering discourse only.

Would you trust classical soil mechanics equations to design a foundation on the Moon? Well... that might lead your structure to collapse!

1. Introduction

Lunar infrastructure planning has advanced from conceptual design to mission-phase implementation. Programs such as Artemis and commercially funded surface operations now require geotechnical input at the level of formal engineering. However, classical soil mechanics frameworks, developed under terrestrial conditions of atmospheric pressure, fluid saturation, and Earth gravity, are not valid for lunar applications. The Moon presents a granular medium formed by impact fragmentation, with no pore pressure, no cohesion from moisture, and no biological or chemical weathering. Load response, shear strength, and deformation mechanisms occur under a distinct set of physical conditions that are not addressed by existing design models.

This article defines the specific limitations of terrestrial soil mechanics in lunar environments and presents the foundation of a new discipline: *regolith mechanics*. It examines particle-scale behavior, electrostatic effects, low-gravity stress regimes, and the role of thermal cycling in shaping mechanical properties. It then establishes the critical parameters required for engineering assessment and design, and outlines the minimum requirements for site investigation, performance modeling, and material simulation. The objective is to support the development of codified standards for structural interaction with lunar ground, using data and principles appropriate to its physical reality.

2. Why Classical Soil Mechanics Fails on the Moon

Classical soil mechanics, as codified by Terzaghi, Peck, and others, evolved under assumptions directly tied to Earth's geophysical and hydrogeological environment. These frameworks rely on pore water pressure, effective stress distribution, capillarity, soil plasticity affected by saturation, and confinement by overburden. None of these mechanisms are operational in the vacuum-dominated, waterless, and reduced-stress field of the Moon. As a result, foundational equations, bearing capacity formulations, settlement predictions, and slope stability models derived from terrestrial conditions lose their theoretical validity and practical utility.

Furthermore, terrestrial classification systems such as the Unified Soil Classification System (USCS), which hinge on grain-size distribution and plasticity indices influenced by water content, become meaningless when applied to anhydrous regolith. Laboratory strength tests such as triaxial compression, which presume pore pressure response and failure envelopes governed by drainage conditions, do not correspond to regolith behavior. Even empirical correlations, such as those linking standard penetration test (SPT) blow counts to bearing capacity or modulus, have no calibration basis in a vacuum particulate regime.

Uncritical application of these models introduces design risk. Assumptions of cohesion, dilatancy under saturation, and depth-dependent stiffness all result in overestimated bearing resistance or underestimated deformation. These errors can lead to foundation rotation, differential settlement, bearing failure, or excessive structural drift, especially under dynamic loading or thermal cycles. Without a fundamental reinterpretation of ground mechanics tailored to regolith properties, lunar infrastructure remains technically unsound at the most basic interface: structure to ground.

A particularly problematic case is the continued citation of Terzaghi's bearing capacity equation (see Section 3). This formulation relies on values of cohesion (c), surcharge ($\gamma \cdot D_f$), and width effects (N_γ) that become either zero or severely misrepresented under lunar surface conditions. The $\gamma \cdot B \cdot N_\gamma$ term becomes nearly negligible due to extremely low unit weights, and the cohesion term (c), interpreted on Earth as partly due to capillary suction, has no analogue in dry regolith.

Likewise, the effective stress equation (see Section 4). This equation assumes the existence of pore pressure (u). In the complete absence of fluid, σ' is indistinguishable from σ, making the concept void of practical meaning. Shear strength in regolith must be interpreted through interparticle friction, fabric, and angular locking, not through saturated soil parameters.

Terrestrial classification systems such as the USCS, mentioned above, which depend on plasticity and Atterberg limits, are inapplicable. Laboratory tests, including triaxial shear and consolidation tests based on fluid pressure regulation and drainage conditions, cannot be meaningfully applied to lunar simulants or regolith analogs.

Even empirical correlations used in civil engineering, such as N-values from the Standard Penetration Test (SPT) or modulus correlations from Cone Penetration Test (CPT), have no calibration basis under vacuum and low confining stress. Their continued use in lunar simulations reflects methodological error, not technical progress.

> *In practice, applying terrestrial geotechnical models to lunar environments results in serious design risks: overestimation of bearing capacity, failure to predict settlement, rotation of superstructures, and foundation instability under thermal loading or dynamic excitation. These are not theoretical errors, they are operational hazards.*

This has been evidenced in several lunar scenarios. Apollo trenching efforts, although shallow, revealed unexpected shear boundaries and difficulty in penetration, even in loose regolith. Rover entrapments on Mars and challenges encountered in recent Chang'e and Chandrayaan landings further illustrate the consequences of misinterpreting surface mechanics.

Moreover, the current generation of lunar architecture and infrastructure concepts, ranging from landers and towers to ISRU reactors, frequently present their designs without any mention of regolith interaction or foundation anchoring. The implicit assumption that ground conditions can be ignored or that structures may be placed directly onto unprepared regolith is a systemic oversight.

To recalibrate engineering procedures, future lunar geotechnics must abandon terrestrial presumptions. New laboratory standards are needed that simulate vacuum, electrostatic behavior, and granular rearrangement under appropriate stress states. Triaxial chambers must be redesigned, and material models must incorporate discrete element behavior with no reliance on fluid-phase effects (see Table 2).

Table 2 - Comparison Table: Terrestrial Assumptions vs. Lunar Reality

Terrestrial Soil Mechanics	***Lunar Regolith Reality***
Saturated or moist soils	Completely dry, no pore pressure
Gravity-driven confinement	Minimal confinement, shallow stress field
Elastic-plastic continuum	Discrete angular granular behavior
Time-dependent consolidation	No drainage or time-rate settlement