Provisional Slope Stability and Berm Design in Lunar Regolith

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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 provisional 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

This document presents the author's independent technical viewpoints under the SpaceGeotech.org platform. The content is **provisional** and intended solely for educational and professional development purposes in the emerging field of extraterrestrial civil engineering.

All frameworks, equations, and values herein are adaptations of terrestrial geotechnical principles to lunar conditions. They are not definitive laws and must not be used as substitutes for in-situ site investigation, mission-specific validation, or detailed engineering design.

Figures and parameters are derived from Apollo mission data, later orbital datasets, and terrestrial analogs. They remain subject to revision as further lunar ground-truth data becomes available through Artemis, Chang'e, and other missions.

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1. Introduction

Slope stability is a central problem in geotechnical engineering, controlling the design of natural cuttings, embankments, berms, and excavations. On Earth, the subject is supported by decades of empirical data, laboratory testing, and analytical frameworks ranging from Taylor's stability charts to advanced limit equilibrium and numerical methods. These tools rely on well-characterized soil and rock mechanics, including the role of effective stress, pore water pressures, and the long-term effects of weathering.

On the Moon, the problem must be reframed. The lunar surface is composed of unconsolidated regolith, overlying fractured megaregolith and bedrock. The regolith behaves as a dry, cohesionless soil in terrestrial terms, but Apollo investigations demonstrated measurable *apparent cohesion*, high friction angles, and the ability of shallow cuts to stand vertically. Trenching performed by astronauts revealed that walls of ~0.3 m could remain stable without support, but deeper trenches quickly collapsed. Similarly, dumped regolith piles formed slopes with angles of repose between 30° and 50°, depending on particle size and compaction.

Modern observations from the Lunar Reconnaissance Orbiter (LRO) extend this picture. Numerous landslides have been identified within crater walls, some associated with new impact craters, others linked to seismic shaking from shallow "moonquakes." At the south pole, a key target for Artemis missions, lobate scarps caused by lunar contraction intersect steep crater walls, creating regions highly susceptible to slope failure. Recent LRO imaging has even documented multiple new slides within a span of years, confirming that lunar slopes are *active systems*, not static landscapes.

These findings confirm two critical points. First, slope stability on the Moon cannot be analyzed by direct application of terrestrial methods. The absence of groundwater, the presence of vacuum and extreme thermal cycles, and the much lower gravitational acceleration all shift the balance of forces. At shallow depth, adhesion dominates stability, a behavior unknown in clean terrestrial sands. At greater scale, frictional resistance governs, but in a stress-dependent manner rather than as a constant. Second, slope failures are not merely theoretical risks. Apollo observations, coupled with modern orbital imaging, provide empirical proof that slope instability is both real and relevant to exploration.

For engineering purposes, slope stability on the Moon must therefore be viewed in two distinct regimes:

1. **Regolith-dominated slopes (L1–L3 layers):** shallow cuts, berms, and excavations where apparent cohesion (c^*), stress-dependent friction $\phi^*(p')$), and cohesive length (ℓc) govern performance.

2. **Rock-dominated slopes (megaregolith and bedrock):** fractured outcrops and crater walls where rock mass classification systems (e.g., GSI, SMR) may be adapted, but only provisionally until real lunar rock slope data are available.

This Brief Tech focuses on the first regime, adapting slope stability methods for regolith slopes and berms. The objectives are to:

- Reformulate the factor of safety equations (infinite slope and circular slip) with lunar-specific parameters,
- Interpret Apollo trenching and LRO slope observations within this framework,
- Provide provisional but applicable guidance for blast berms, excavation slopes, and dumped piles,
- Demonstrate through worked examples how reliance on terrestrial charts could misrepresent lunar behavior.

By retaining the familiar analytical structure of Taylor, Bishop, and Morgenstern, but substituting lunar parameters, the approach preserves continuity with established geotechnical practice while adapting it to a radically different environment. As with other Brief Techs in this series, the framework is provisional: it does not replace in-situ investigation or future standards. But by anchoring its assumptions in Apollo and LRO data, and by presenting its formulations transparently, it provides both applicability for current mission planning and authority within the engineering community.

2. Adapted Framework for Lunar Slopes

The fundamental requirement for slope stability analysis is to compare resisting shear strength against driving shear stress along a potential slip surface. On Earth, this is done using the classical Mohr–Coulomb law with cohesion ccc and a constant friction angle ϕ. For lunar regolith, these assumptions are inadequate. Cohesion must be replaced by *apparent cohesion* c*, the friction angle must be treated as *stress-dependent* ϕ∗(p′), and the concept of a *cohesive length* ℓc must be introduced to capture the shallow adhesion-dominated regime.

The slope-stability method presented here is a **provisional** extension of classical limit-equilibrium analysis to lunar regolith. It incorporates c*, ϕ*(p′), and ℓc, reproducing Apollo trench stability and dumped-pile angles while remaining consistent with Mohr–Coulomb in the appropriate limits. Results are presented with parameter ranges, design values, and sensitivity checks. Within the stated stress window and geometrical bounds (H/ℓc), the approach is reliable for decision-making and ready to be refined as in-situ Artemis data become available.

The adapted shear law is:

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

With stress-dependent friction defined as:

$$\varphi^*(p') = \varphi_{ref} + k_\varphi ln\left(\frac{p'}{p_{ref}}\right)$$

And the cohesive length:

$$l_c = \frac{c^*}{\gamma}, \gamma=\rho g_m$$

Where ρ is bulk density and g_m is lunar gravity.

2.1. Infinite-Slope Formulation

The infinite-slope model is widely used for analyzing shallow translational failures where the failure surface is approximately parallel to the ground surface. On Earth, it is most often applied to surficial slides in cohesionless soils under rainfall or surcharge loading. On the Moon, the absence of pore water simplifies the formulation but also makes shallow adhesion effects far more important.

The adapted lunar infinite-slope factor of safety is:

$$FS_\infty = \frac{c^* + \gamma z \cos^2\beta\, tan\left(\phi^*(\gamma z \cos^2\beta)\right)}{\gamma z \sin\beta \cos\beta}$$

Here, c* accounts for adhesion effects that stabilize shallow cuts, while $\phi*(p')$ varies with confinement, representing the observed rise in friction with stress in Apollo shear data. When slope depth z is smaller than the cohesive length ℓc, adhesion dominates, and near-vertical slopes may stand temporarily. For larger depths, friction governs, and slope stability converges toward angles of 30–40°. This makes the infinite-slope model particularly suited for berms, shallow trenches, and surface spoil piles during early lunar construction.

2.2. Circular Slip (Bishop Simplified)

For deeper excavations or engineered berms, rotational slip surfaces provide the governing failure mechanism. On Earth, Bishop's simplified method remains a standard for circular slip analysis because of its balance between accuracy and computational efficiency.

For lunar conditions, the adapted form becomes:

$$FS = \frac{\sum \left[c^* l_i + W_i \tan\left(\phi^*(\sigma_{n,i})\right)\right] \sec\alpha_i}{\sum W_i \sin\alpha_i}$$

the governing assumptions are unchanged, slices are analyses for equilibrium of forces and moments, but the inputs are redefined: c* replaces cohesion, $\phi*(p')$ replaces constant ϕ, and pore pressure terms are omitted (u=0). This formulation is particularly applicable for