Review of The Moon SourceBook Geotechnical Parameters

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Executive Summary

This review is grounded entirely in the in-situ measurements compiled in Chapter 9 – *Physical Properties of the Lunar Surface* of the **Lunar Sourcebook** (Heiken et al., 1991), including Apollo and Lunokhod data. The proposed L1–L5 zoning framework does not imply uniformity; it explicitly incorporates the full documented variability of density, compressibility, and shear parameters across sites. The zoning is a structured translation of the measured range into conservative, design-ready strata for engineering application under uncertainty, enabling contractors and mission planners to apply Apollo-era knowledge directly in modern design scenarios.

This work presents a forensic, data-driven re-examination of the Lunar Sourcebook, isolating and re-plotting each relevant dataset and interpreting them within a consistent geotechnical framework. The Sourcebook data remain the foundation; modern interpretations (including Chang'e-5 and selected terrestrial analogues) are used only for comparison, verification, or to explain divergences.

The L1–L5 framework (de Moraes, 2025) integrates Apollo-era observations into a pragmatic zoning system, classifying regolith by depth, density, compressibility, and shear strength. This approach enables site-specific Apollo measurements, originally published as discrete datasets, to be generalized into design guidance for preliminary and conceptual-level engineering.

Key property groups reassessed include:

- Bearing capacity (static/dynamic) linked to L1–L5 stratigraphy.
- Settlement behavior recalculated from compressibility indices and density profiles.
- Slope stability reframed with zoned shear strength.
- Cone penetration resistance correlated with L1–L5 density and shear parameters.
- Shear strength envelopes redrawn from Apollo/Lunokhod points with transparent caveats.
- Seismic properties interpreted for load transmission, anchoring, and vibration-sensitive systems.

The resulting diagrams, tables, and nomographs are intended as **provisional guidance tools**. They are not substitutes for in-situ investigation but serve as a structured baseline for mission planners and contractors preparing for landing pads, ISRU plants, habitats, and related infrastructure.

This review reinforces that Apollo data remain the most authoritative baseline. However, variability, sample disturbance, and cohesion/friction uncertainty require that any engineering translation be transparent about its limits. Accordingly, all provisional charts herein include **explicit caveats on data origin, applicability, and validation needs.**

Disclaimer

1. **Density Profiles and Variability**
   All interpretations are based on Apollo and Lunokhod in-situ datasets as compiled in the Lunar Sourcebook (Heiken et al., 1991, Ch. 9). While several Apollo measurements show relative densities approaching ~90% Dr at ~0.3 m, the Sourcebook also documents significant variability, including loose layers in drive tubes, SRP records, and slope deposits. The L1–L5 zoning framework structures this variability into design categories, with conservative margins for site-specific uncertainty. It is not a contradiction of Apollo data, but an engineering abstraction for practical use.
2. **Speculative extrapolations at depth**
   Parameters below ~1 m are inferred from indirect density–compressibility relations rather than direct measurements. These values are useful for preliminary design but should be regarded as provisional until future missions validate them.
3. **Risk of oversimplification through zoning**
   The L1–L5 framework is not a claim of rigid stratification but a structured method of managing uncertainty. Like zonation systems in terrestrial geotechnics, it translates scattered measurements into usable layers without erasing natural variability.
4. **Seismic properties**
   P-wave velocities and Q values are faithfully reported from Apollo measurements. Their inclusion here emphasizes engineering implications (impact loading, vibration response, structural resonance) rather than simply repeating descriptive data.

1. Introduction

This review is based entirely on *Chapter 9 – Physical Properties of the Lunar Surface* from the *Lunar Sourcebook* (Heiken et al., 1991), which remains the most authoritative compilation of in-situ measurements from Apollo and Lunokhod missions. The objective is not to question or replace those datasets, but to extract, reorganize, and interpret the information in a form that is directly usable for engineering design, construction planning, and operational decision-making in future lunar missions.

The proposed L1–L5 zoning framework is an engineering translation of the Apollo/Lunokhod record. It uses the measured density, compressibility, shear strength, and related parameters exactly as presented in the *Lunar Sourcebook*, but restructures them into discrete, design-ready strata. This approach reflects the full documented variability in the Apollo record, including high-density surface cases (e.g., ~90% relative density at ~0.3 m) and looser, block-free or disturbed zones with lower density that increase rapidly with depth.

Unlike averaged density–depth charts, which can suggest a misleading uniformity, the L1–L5 zoning preserves spatial and stratigraphic variability while still providing a consistent basis for settlement prediction, bearing capacity, and constructability assessments. This makes it suitable for preliminary engineering under uncertainty, where site-specific testing is not yet available.

By presenting the Apollo/Lunokhod data in this structured way, the framework aims to bridge the gap between historical scientific reporting and the practical requirements of designers, contractors, and mission planners. It is not a new dataset; it is a method to apply the best available in-situ data within realistic project constraints, acknowledging that local conditions can depart from global averages and that engineering must be prepared to manage that variability from the outset.

2. Particle Size Distribution

The particle size distribution (PSD) of lunar regolith is one of the most consistently documented physical properties from Apollo core tubes, drive tube samples, and Lunokhod rover scoop analyses. Chapter 9 of *The Lunar Sourcebook* compiles these results, showing that lunar regolith is predominantly composed of particles in the silt-to-fine-sand range (0.02–0.2 mm), with a tail extending into both finer (<0.01 mm) dust and coarser (>1 mm) fragments.

Despite local variability caused by impact gardening, ejecta deposition, and block content, the general PSD profile is remarkably similar across the Apollo sites. Most samples display a broad unimodal distribution with:

- **Fine fraction (<0.02 mm):** 10–20% by weight, consisting of angular glass shards, agglutinates, and mineral fragments.

- **Median particle size:** Typically between 40–80 µm, reflecting comminution from repeated micrometeorite impacts and reworking.
- **Coarse fraction (>1 mm):** 5–10% by weight in typical mare soils, with higher percentages in block-rich or rim deposits.

From an engineering standpoint, this relatively narrow PSD, combined with particle angularity and high surface roughness, produces an interlocking fabric with high frictional resistance and low compressibility once compacted. However, near-surface zones (particularly L1 in the L1–L5 zoning) may exhibit looser packing and higher void ratios despite having the same PSD, due to reduced overburden stress and less compaction energy at the surface.

The L1–L5 framework integrates PSD with depth-dependent density and compressibility data to distinguish between layers where the same particle size distribution exhibits different mechanical behaviors. This distinction is essential for load-bearing predictions, since PSD alone does not capture packing state or structural arrangement.

Particle size distribution is a controlling parameter in the mechanical, thermal, and seismic behavior of any unconsolidated material. In the case of lunar regolith, it influences shear strength, compressibility, and operational factors such as dust generation and equipment fouling. Analyses of Apollo samples confirm that lunar soil is texturally comparable to well-graded silty sand, with grain sizes spanning more than three orders of magnitude but with a marked dominance of the fine fraction.

The most widely adopted descriptive index for particle size is the phi (φ) scale, defined as:

$$\varphi = -\log_2 d$$

Where d is particle diameter in millimeters, this transformation facilitates statistical characterization of the size distribution. Descriptive parameters include mean particle size (M_z), median (M_d), sorting (σ_1), skewness (Sk_1), and kurtosis (K_g), calculated as follows:

Mean:

$$M_z \approx (\varphi_{16} + \varphi_{50} + \varphi_{84}) / 3$$

Median:

$$M_d = \varphi_{50}$$

Sorting:

$$\sigma_1 \approx (\varphi_{84} - \varphi_{16})/4 + (\varphi_{95} - \varphi_5)/6.6$$

Skewness:

$$Sk_1 \approx (\varphi_{16} + \varphi_{84} - 2\varphi_{50}) / [2(\varphi_{84} - \varphi_{16})] + (\varphi_5 + \varphi_{95} - 2\varphi_{50}) / [2(\varphi_{95} - \varphi_5)]$$

Kurtosis:

$$K\_g \approx (\varphi_{95} - \varphi_5) / [2.44(\varphi_{75} - \varphi_{25})]$$

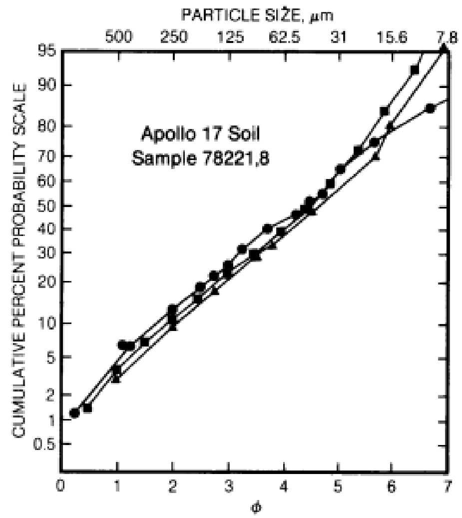

Figure 2.1 *- Shows the cumulative probability plots for Apollo 17 soil sample 78221,8, tested independently by three laboratories. Agreement between curves is close, with divergence mainly in the finest fractions (<10 µm).*

Lunar soil particle-size distributions are remarkably consistent across sampled sites, falling within a narrow and repeatable range (Carrier, 1973). Texturally, the material corresponds to a well-graded silty sand to sandy silt—classified as SW-SM to ML under the Unified Soil Classification System (ASTM D2487, 1987; Lambe and Whitman, 1969). Median particle sizes range from approximately 40 to 130 µm, with an overall mean near 70 µm, indicating that roughly half of the soil mass is finer than the limit of visual resolution to the unaided human eye. Between 10% and 20% of the regolith is finer than 20 µm, forming the fraction most prone to electrostatic charging and adhesion. This fine component readily attaches to any surface, such as spacesuits, tools, optical elements, and mechanical equipment, upon contact. In operational terms, this characteristic imposes a persistent housekeeping burden, as dust infiltration affects seals, moving parts, and visibility.

Within the L1–L5 zoning model, this particle-size profile is most relevant to the L1 disturbed skin, where the abundance of ultra-fines contributes directly to high dust mobility and adhesion hazards. L2 retains much of the same size distribution but with increased compaction, reducing immediate dust release while maintaining the same fine fraction that complicates cleaning and sealing in long-duration surface operations.

2.1. Operational Reinterpretation: L1–L5 Relevance

While the particle size distribution of lunar regolith remains broadly consistent across landing sites, its operational performance varies significantly with depth. The L1–L5 zoning framework incorporates this depth-dependence by coupling the measured PSD with documented density, porosity, and compressibility changes from Apollo core tube and drive tube profiles.