Replicating the Geotechnical Properties of Lunar Highland Regolith Stratigraphy Using High-Fidelity LHS-1 Simulant

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Background: Planned robotic (e.g., VIPER) and human (e.g., Artemis) missions will begin the process of establishing infrastructure for a long-term presence on the Moon, as NASA has plans [1] to achieve this at highland [2] landing sites at the lunar south pole. The logistical requirements for a sustained presence on the lunar surface necessitate a thorough understanding of the geotechnical properties of lunar regolith. Lunar regolith samples brought back from Apollo missions are too scientifically precious for large-scale engineering tests, thus the need to use regolith simulants for Earth-based engineering studies (e.g., vehicle trafficability). Previous trafficability studies typically focused on vehicle/wheel development and testing; not on how regolith properties evolved due to prolonged interaction with the vehicle. Apollo 17 astronauts undertook three EVAs and spent only ~22 hours outside the LM on the surface. Future lunar activities will demand much longer visits. These future endeavors will require a firm understanding of the density profile of the near-surface regolith, which will be fundamental for infrastructure development (e.g., launch/landing pad), and other mission logistics, such as vehicle mobility and ISRU activities.

Introduction: Shortly after the Apollo 11 mission, technicians at NASA JSC had astronaut Buzz Aldrin walk on a simulated lunar surface test track (sand ~15 cm deep) with 5/6 of his weight supported in a special marionette rig. When asked how the test track compared to walking on the actual lunar surface, Aldrin replied that the test track sand was *too yielding*, while walking on the Moon he noticed that although the lunar regolith was *soft at the surface*, there was a *firmer stratum underneath* [3]. This straightforward observation emphasizes the overall objective of this study. That is, to understand how regolith will react to extended lunar surface activities, it will be critical to replicate the geotechnical properties of the regolith column for large-scale testing in engineering test beds (i.e., pack simulant in layers of specific densities, rather than just dumping it into the test bed). Here, we use Exolith Lab's LHS-1 Lunar Highlands Simulant (hereafter LHS-1; https://exolithsimulants.com) to replicate the geotechnical characteristics of the highlands regolith column, as measured *in situ* with cone penetrometer testing (CPT) during the Apollo 16 mission.

Geotechnical Properties of LHS-1: LHS-1 was designed to optimize simulant fidelity relative to the typical mineralogy and particle size distributions (PSD) of returned Apollo highland regolith samples. The geotechnical properties (e.g., PSD, specific gravity, minimum (ρ_{min}), uncompressed bulk (ρ), maximum (ρ_{max}), and relative densities (ρ_R), in addition to shear strength) of both undried (ambient storage) and dried LHS-1 are reported by [4]. Briefly, the PSD of LHS-1 is similar to that of Apollo highlands regolith for particle sizes <~60 μm. The average specific gravity of dry LHS-1 is 3.11, in excellent agreement with the recommended value of 3.1 for general scientific and engineering analyses of lunar regolith [3]. Densities of dry LHS-1 were found to be ρ_{min} = 1.24 g/cm^3, ρ_{max} = 1.95 g/cm^3, with an uncompressed bulk density of ρ = 1.58 g/cm^3 (ρ_R = 59.3%). Shear strength parameters of cohesion and angle of internal friction for dry LHS-1 were found to be 0.299±0.018 kPa and 31.7±2.4°, respectively. In summary, the above values are in good agreement with the range of values found for lunar regolith from Apollo 11-15 [3] and for highland regolith from Apollo 16 [5]. The relationship between bulk density and relative density for dry LHS-1 is illustrated in Figure 1.

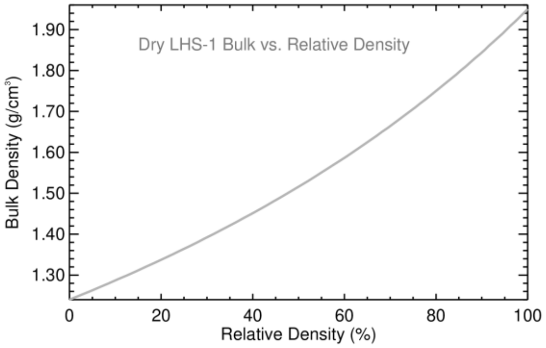

Figure 1. Bulk density versus relative density for LHS-1 [4].

Lunar Regolith Simulant Column Test Bins: To create simulated regolith columns that can replicate the geotechnical characteristics of the near-surface regolith at the Apollo 16 highland landing area, we fabricated rigid test bins (~30 × 30 × 80 cm tall) using clear acrylic Plexiglas, which enables observation of simulated lunar regolith columns in cross section. These bins allow LHS-1 simulant to be packed at specific relative densities (see Fig. 1), which permits separate layers with different densities to be deposited within the test bins.

Cone Penetrometer Measurements: We used a Rimik CP40II cone penetrometer to obtain Cone Index (CI) penetration resistance values (i.e., stress in kPa) versus depth for LHS-1 simulant packed at various densities in the test bins. We used an ASAE standard cone area of 1.3 cm^2 [6], which is the recommended size for hard soils. This cone size is the same as that used for six CPT measurements (3 each at Stations 4 and 10) during the Apollo 16 mission. We measured CI values at 10 mm intervals to nominal depths of ~200–300 mm in order to derive slope parameters (G) for LHS-1 simulant, which is simply the slope of CI values versus depth calculated from individual stress-penetration curves as measured from the surface to 100 mm depth [see 7].

Slope Parameter Derivation for LHS-1: To derive a correlation between CPT data and relative density (ρ_R), we collected CI values of LHS-1 simulant packed at various densities to determine the range of strength of LHS-1 in terms of G [see 8 for GRC-1 simulant G values]. Since absorbed ambient moisture can alter the geotechnical properties of regolith simulants [4], we used LHS-1 simulant that was dried at ~105 °C for ~3 hr and then stored in airtight containers. Specific relative densities were achieved by compacting the simulant using a vibration apparatus and by applying variable surcharge loads to the surface of the soil column. Due to the height of simulant required (20–30 cm) to obtain reliable stress-penetration curves for G determinations, it was difficult to achieve relative densities significantly less than the uncompressed bulk value (ρ_R = 59.3%). A total of 30 CPT measurements (5 G determinations at 6 different ρ_R) were performed on LHS-1 simulant over a range of ρ_R from 52.8 to 85.0% (Fig 2). These data yield an exponential relationship, which was fit using the least squares method. This relationship is described by the equation:

$$G = 0.014e^{0.072\rho_R} \quad \text{(Eq. 1)}$$

which has a correlation coefficient (R^2) value of 0.88. This relationship allows us to obtain information regarding the density profile of simulated regolith columns directly from CPT stress-penetration curves. Slope parameter values for LHS-1 simulant are in good agreement with the range of estimated G values determined from CPT data at Apollo 16 Stations 4 and 10 (Fig. 2).

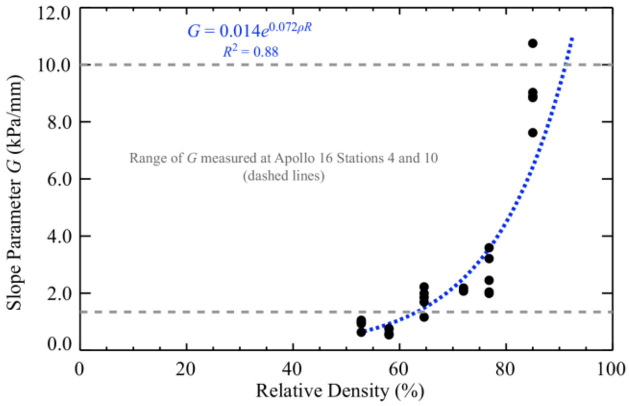

Figure 2. Slope parameter (G) of stress-penetration curves (black circles) versus ρ_R for LHS-1. Range of G values from Apollo 16 Stations 4 and 10 are bracketed by gray dashed lines.

Replicating Apollo 16 Regolith Stratigraphic Profiles: *In situ* CPT measurements at Apollo 16 Stations 4 and 10 showed marked differences in the shapes of the penetration-depth versus CI curves [5]. These differences are a direct indication that the regolith density profile varies locally at the Apollo 16 landing area. However, CPT readings from Stations 4 and 10 (1.3 cm^2 cone) display a noticeable similarity in that a firm layer is encountered at ~5–10 cm below the surface, then resistance increases significantly at depths of ~20–40 cm below the surface [3;5]. This increase in resistance indicates a denser, stronger regolith layer at depths of several decimeters below the surface. We created a simulated two-layer stratigraphic profile using LHS-1 simulant packed to relative densities of 72% (0–15 cm depth) and 94% (15–30 cm depth) in a simulant column test bin. Figure 3 shows our laboratory penetration depth versus CI (avg. of 5 curves) compared with those measured *in situ* during Apollo 16. The dense lower layer (ρ_R=94%) in our simulated column is clearly detected at a depth of ~15 cm. Apollo 16 curves show larger stress values than LHS-1 for depths of 5–20 cm, indicating that our upper test layer (ρ_R=72%) could represent a lower limit for regolith density for Apollo 16 sites for these depths. Apollo 16 CPT data below depths of ~20 cm most likely did not record the maximum stress for deep, dense layers (Apollo 16 max. recordable stress ~1650 kPa). Our dense lower test layer (ρ_R=94%) records stress as high as ~5100 kPa (CP40II max. recordable stress ~5600 kPa); clearly ρ_R estimated from Apollo 16 CPT data for deep, dense layers at highland sites represent lower limits.

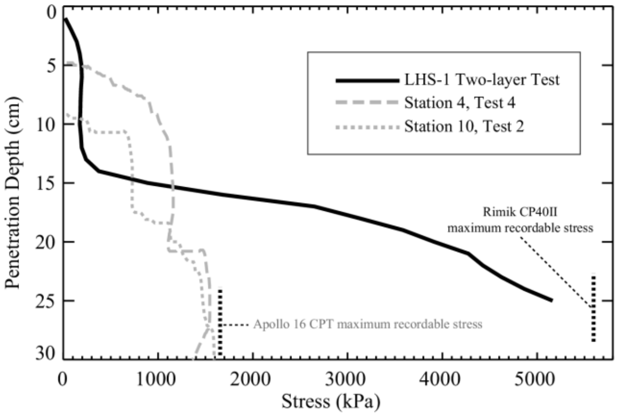

Figure 3. Depth versus CI for a ~30 cm deep simulated two-layer regolith column compared to Apollo 16 CPT data.

Summary: CPT measurements demonstrate a relationship between G of stress-penetration curves and relative density for LHS-1 simulant. Furthermore, LHS-1 can be used to replicate near-surface regolith stratigraphy at the Apollo 16 highland landing site. The ability to recreate the density profile and geotechnical properties of actual lunar regolith is critical to engineer the hardware and infrastructure required to inhabit the lunar environment.

References: [1] NASA (2020) *NASA Pub. 2020-05-2853-HQ.* [2] Lemelin et al. (2021) *PSJ* 2:103, (17 pp). [3] Carrier et al. (1991) *Lunar Sourcebook*, Chap. 9. [4] Long-Fox et al. (2022) *ASCE Earth & Space Proceedings, in review*. [5] Mitchell et al. (1972) *Apollo 16 Prelim Sci. Report*, Chap. 8. [6] ASAE S313.3 (1999) *Soil Cone Penetrometer.* [7] Houston and Namiq (1971) *Journal of Terramechanics* 8, 59-69. [8] Oravec et al. (2010) *Journal of Terramechanics* 47, 361-377.