An Engineering Guide to Lunar Geotechnical Properties

John Connolly
NASA – Johnson Space Center
2101 E. NASA Parkway
Houston, TX 77058
john.connolly@nasa.gov

W. David Carrier
Argila Enterprises, Inc.
Lakeland, FL 33813
wdcarrier@verizon.net

Abstract— **The renewed interest in returning human and robotic explorers to the lunar surface has identified a need for a renewed understanding of lunar geotechnical properties related to landing, exploration, excavation, and construction activities on the lunar surface. This paper summarizes measurements conducted during US and Russian/Soviet landed missions as well as experiments performed on returned samples to establish fundamental geotechnical properties such as particle size distribution, particle shape, bulk density, shear strength, cohesion and bearing strength. While many of these properties are well known, how they vary with increased lunar soil depth is less understood, and those properties that vary significantly as a function of depth are explored in additional detail. Selected examples discuss mechanical excavation forces, rocket exhaust erosion forces, and the preparation of launch/landing pad surfaces, with the goal of a better understanding of lunar soil geotechnical properties that apply to large-scale exploration of the lunar surface and dictate the design of future exploration systems.**

TABLE OF CONTENTS

1. INTRODUCTION

Lunar geotechnical investigations were important measurements undertaken by the Apollo astronauts, and US and Russian landed robotic missions. Prior to the return of this data, basic lunar surface properties such as soil bearing capacity were nothing more than engineering estimates with wide uncertainty bands. In fact, the uncertainty in just this one property resulted in the design of early landing gear and footpads to accommodate an inefficiently large range of landing conditions. Once the Apollo and Luna missions concluded, the geotechnical data was reduced and compiled into useful products such as the Lunar Sourcebook [1].

Today we are witnessing a revived interest in lunar exploration that now includes new commercial and international players, and new motivations for sending human crews to the lunar surface. With the newest generation of lunar engineers and explorers looking to the Moon, it is timely to review what is known about lunar geotechnics, and what has been learned over the past 50 years. Section 2 of this paper summarizes lunar soil properties measured by those US and Russian landed missions, and includes discussions of particle size distribution, particle shape, bulk density, shear strength, and bearing strength, and importantly emphasizes critical properties that vary with depth. With this renewed understanding, Section 3 explores practical applications of these geotechnical properties, using excavation and lander exhaust-surface interaction as practical examples.

Section 4 offers an insightful view of lunar geotechnical field observations, leading to a summary of observations in Section 5.

2. LUNAR SOIL GEOTECHNICAL PROPERTIES

Particle Size Distribution

In general, lunar soil (regolith) is a well-graded/poorly sorted, silty sand to sandy silt that corresponds to the Unified Soil Classification System categories "SW-SM" to "ML". The median particle size is 40 to 130 μm, with an average of 70 μm, so approximately half of the soil by weight is finer than the human eye can resolve and roughly 10% to 20% of the soil is finer than 20μm [2]. Particle size distribution of lunar soil is also amazingly consistent on the Moon to a depth of at least several meters or more, so the particle size distribution shown in Figure 1 can be applied to depths of several meters, which would incorporate the depths of most human exploration activities. The consistency of the lunar soil particle distribution makes it possible to easily calculate the probabilities of encountering larger particles, such as rocks, when excavating or drilling to moderate depths.

Particle Shape

The gross shape of lunar soil particles varies from spherical to extremely angular, and examples of various soil particles from Apollo 11 are shown in Figure 2. The average elongation of a soil particle is approximately 1.35. One distinguishing feature of lunar soil particles are their extremely irregular, often reentrant surfaces - on average, a

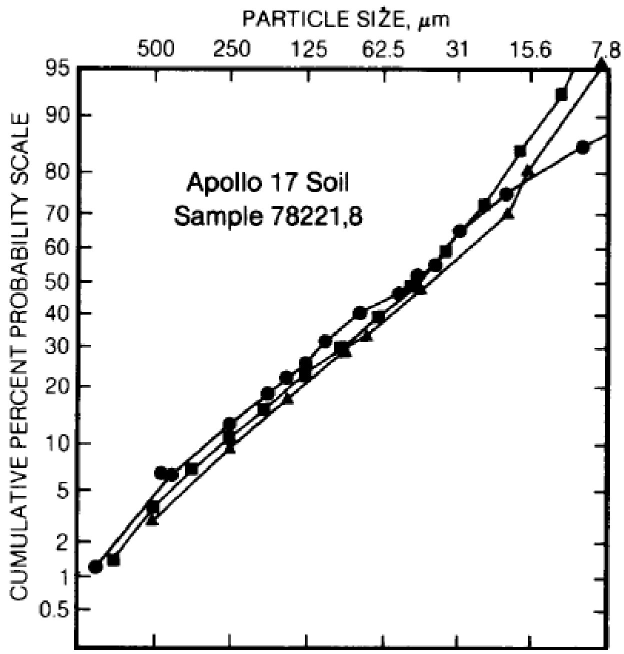

Figure 1. Particle size distribution is almost exactly log-normal. Reference: Lunar Sourcebook, p477[1].

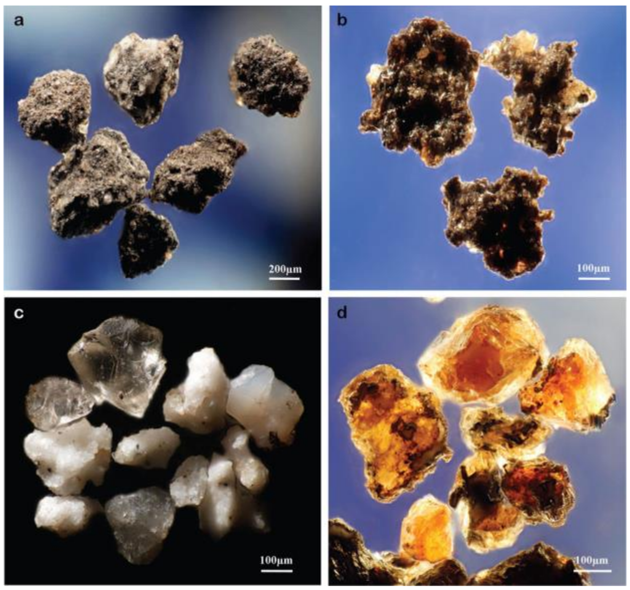

Figure 2. Apollo 11 Lunar regolith particle morphologies (Kiely, C. and Greenberg G, A New Look at Lunar Soil Collected from the Sea of tranquility during the Apollo 11 Mission, Microscopy and Microanalysis, Cambridge Press, November 2010 [3]

typical lunar soil particle has nearly eight times as much surface area as an equivalent-sized sphere, and interlocking of soil particles contributes to overall soil cohesion. This irregular, contorted shape means the individual soil particles are somewhat fragile, compared to terrestrial ground-up basalt simulants. However, as depth increases, the irregularly shaped particles become more tightly packed together, and soil cohesive and shear strength increases with depth.

Bulk Density

Lunar soil quickly gets more dense with depth. On average, the bulk density of lunar regolith is approximately 1.30 g/cm at the surface, increases rapidly to 1.52 g/cm at a depth of 10 cm, then more gradually to 1.83 g/cm at a depth of 100 cm. Below 100 cm, the density asymptotically approaches a value of 1.92 g/cm3. Density versus depth can be expressed by the following hyperbolic relationship:

$$r = 1.92\ (z + 12.2) / (z + 18) \qquad (1)$$

where z = depth in lunar surface (cm)

The lunar surface can be thought of in two general regions: a loosely consolidated top layer (labeled "fluffy" top layer in Figure 3) in which the micrometeorite flux has gardened and loosened the top 10 to 15 cm; and a dense and consolidated lower layer that has been tightly packed by the same micrometeorite flux over lunar geological time (shown as "dense subsurface" in Figure 3). This division of soil characteristics is important in understanding how bulk density changes with depth, AND how many other soil characteristics change with depth. Later sections of this paper will discuss the relationship of regolith depth to such other properties such as cohesion and shear strength. Another consequence of the high density is that the soil volume will increase or "swell" when excavated and excavated soil volume could not be practically placed completely back into the original excavated "hole".

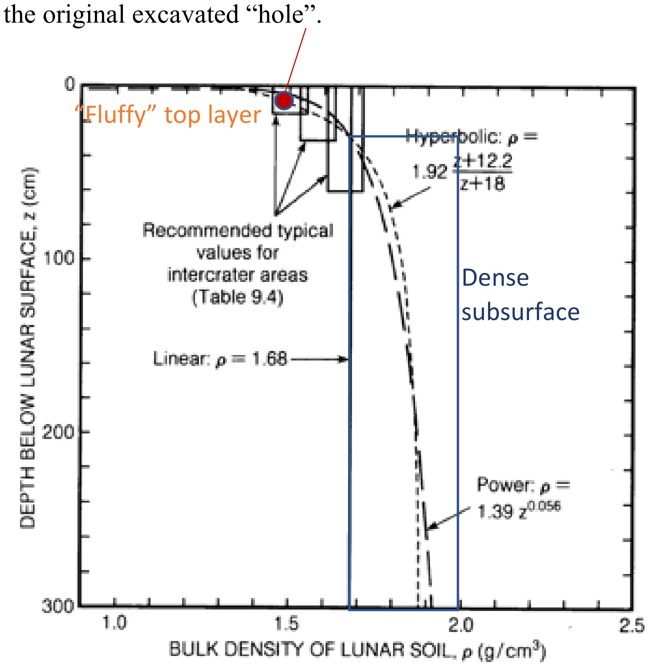

Figure 3. Lunar regolith bulk density. Source: Lunar Sourcebook, p. 494 [1].

Porosity and Relative Density

While the bulk density of lunar soil approaches an asymptotic value of 1.92 g/cm^3, the specific gravity of lunar soils range from 2.3 to >3.2, with an average of about 3.1g/cm^3, indicating a significant fraction of porosity in the soil matrix. Even in the regions of high bulk density below 10-15 cm, the porosity of the lunar soil is about 40 to 50%, See Figure 4. This is due to the broad particle size distribution and the irregular particle shapes discussed in earlier sections - because of the shape coefficients of lunar soil particles, the smaller particles do not fit efficiently in the interstices between the larger particles.

Using Apollo density measurements, porosity was plotted as a function of depth (Figure 5), and ranges from 65% at the surface to less than 40% at depth. The Apollo measurements and the model presented in Figure 5 agree well, and these data are also in generally agreement with the 32 to 58% visual

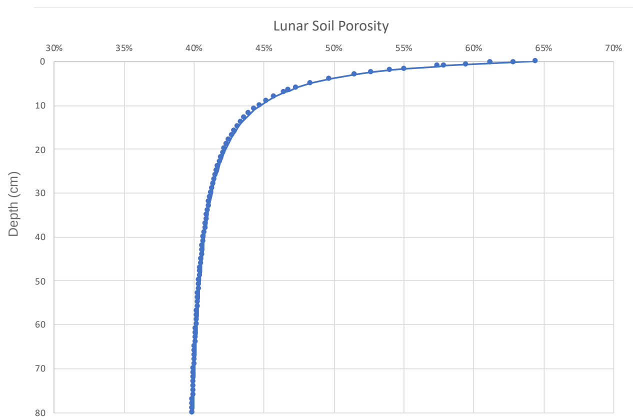

Figure 4. Lunar soil porosity as a function of depth

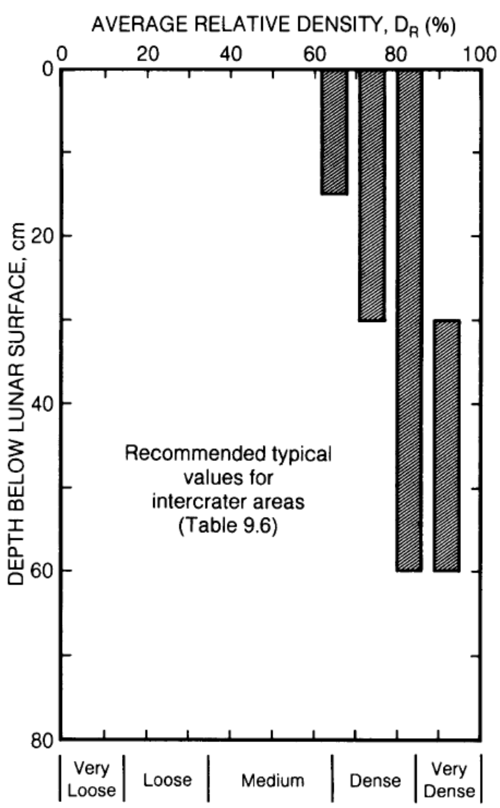

Figure 5. Relative Density of lunar soil. Lunar Sourcebook, p. 501 [1].

Surface regolith porosity estimates at the Apollo landing sites using an analysis of the astronauts' bootprints [3].

Lunar Soil Shear Strength

Lunar soil shear strength is an essential property governing lunar excavation and construction, engine plume interaction with the lunar surface, drilling into the lunar surface, and mining below the surface for volatiles. The shear strength of a granular soil is typically defined in terms of the classic Mohr-Coulomb equation in Figure 6, where τ = shear strength (kPa); σ = normal stress (kPa); c = cohesion (kPa); and ϕ = friction angle. Lunar soil particles are most easily separated at the surface, where density, normal stress and cohesion are at a minimum. The blowing dust seen under the Apollo lunar module landings shows the upper layers of regolith being scoured away by the descent engine's exhaust plume, but the lack of any measurable crater formation under the engines indicates how deeper levels of regolith have increasing shear strength to resist further erosion.

The shear strength consists of two components: a cohesive component that is independent of the applied stress, and a frictional component that is directly proportional to the normal stress (i.e., the stress that is perpendicular to the failure surface). Figure 8 shows how shear strength increases approximately linearly with depth, and how shear strength quickly increases beyond 1 kPa at depths of only 50 cm. Shear strength governs such important engineering properties as ultimate bearing capacity, slope stability, excavatability, drillability and trafficability.

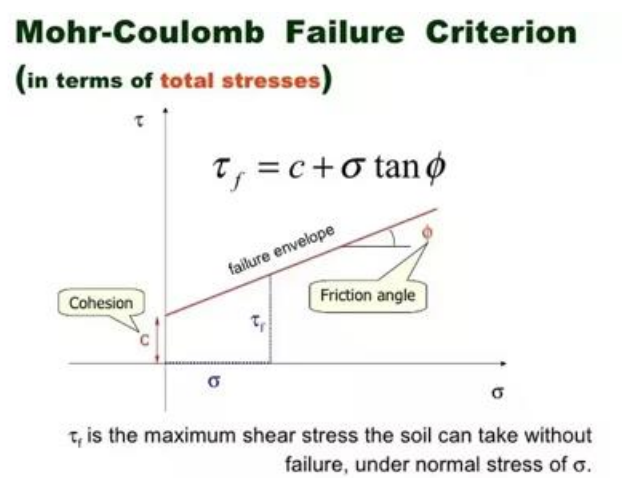

Figure 6. The components of soil shear strength as defined by the Mohr-Coulomb equation

Soil Cohesion— The irregular particle shapes discussed earlier account for much of the cohesive behavior of the lunar soil. Cohesion of the lunar soil is due to the mechanical interlocking of the irregular particles, like Velcro®[1]. It is for

[1] *Trade names and trademarks are used in this report for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration*

this reason that the Astronaut's bootprints appear so crisp and clean, like they were imprinted in "damp beach sand", and even fine, delicate features leave a lasting impression in the lunar soil. The cohesion and the frictional shear strength of the lunar regolith allowed the astronauts to dig trenches in the lunar surface with smooth, nearly vertical walls. Because of the low lunar gravity, trenches with vertical walls can be excavated to a depth of approximately 3 m, and drill core holes will remain open and stable to that same depth. Terrestrial simulants often lack those cohesive properties, and small percentage of water must be added to ground basalt simulant in order to create similar cohesion.

Like many lunar soil properties, cohesion will increase with depth, related to the increase in soil density. Soil cohesion is plotted as a function of depth in Figure 7 below; as a significant component of overall soil shear strength, cohesion quickly increases beyond 3 kPa at depths below 50 cm.

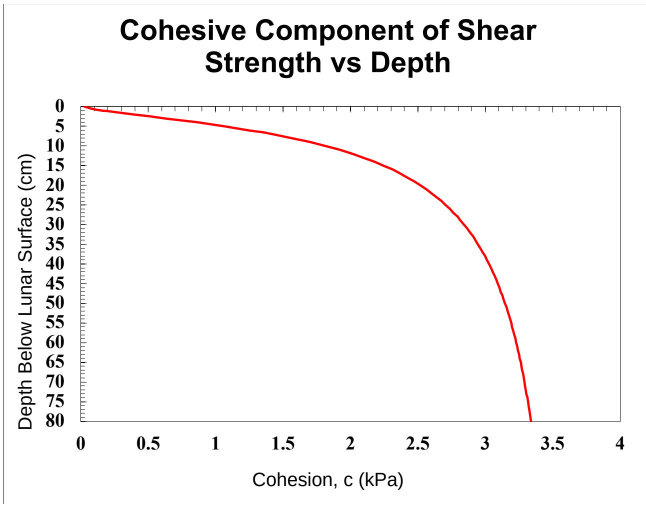

Figure 7. Cohesion vs Depth for Lunar Soil

Friction Angle and Normal Stress— The second component of soil shear strength is the frictional component derived from the internal friction angle ϕ and normal stress σ. Apollo experiments estimated the internal friction angle of the lunar soil to be between 30 and 50 degrees, but did not take into account that friction angle would increase with depth as the relative density increases. Figure 8 incorporates both the increasing normal stress of the soil overburden as well as an asymptotically increasing friction angle that approaches 55 degrees within the first meter of depth – the product is a mostly linear increase of the frictional shear strength with depth.

Total Shear Strength— Combining the cohesive and frictional components of Mohr-Coulomb yields the total shear strength curve shown in Figure 9. The sum of cohesion and frictional shear stress yields an understanding of how lunar soil shear strength behaves with increasing depth, and follows the paradigm set with the initial discussion of density – a thin layer of unconsolidated surface material transitioning to layers of soil with increasing density and shear strength.

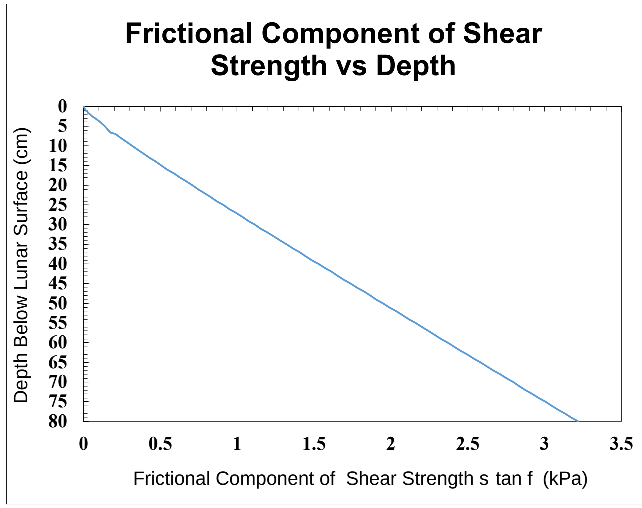

Figure 8. Frictional component of shear strength vs Depth for lunar soil

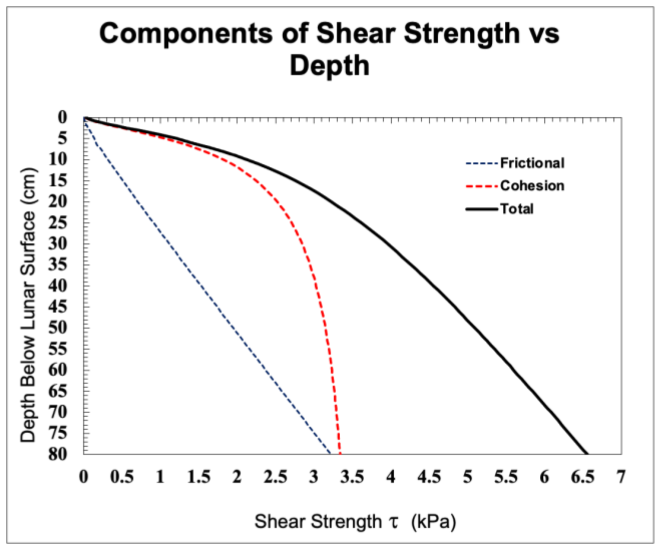

Figure 9. Total lunar soil shear strength as a function of depth

Bearing Capacity

Bearing capacity describes the ability of a soil to support a load such as that of a lander, rover, permanent structure of booted astronaut. Bearing capacity is divided into two categories: ultimate bearing capacity and allowable bearing capacity. Each of these are then subdivided further into static and dynamic quantities.

Ultimate bearing capacity defines the maximum possible load that can be applied without causing gross failure, such as the overturning of a structure. As an example, for a 1-m footing on the lunar surface, the ultimate bearing capacity is approximately 6000 kPa. This is a significant quantity of bearing strength and matches the experience of the Apollo astronauts – Apollo 15-17 crewmembers attempted to hammer thin-walled core tubes into the lunar soil, and found that the practical depth limit was only about 70 cm, with 50 hammer blows typically needed to reach this depth

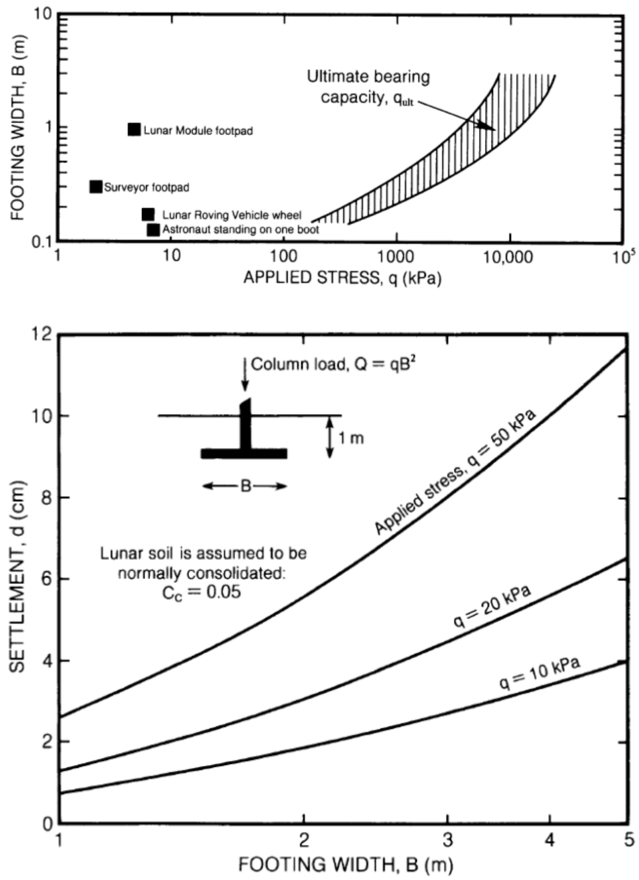

Figure 10. Lunar soil ultimate bearing capacity for a footing (top) and footing settlement depth (bottom), Lunar Sourcebook$_1$, p518, 520 [1].

3. APPLIED LUNAR GEOTECHNICAL ENGINEERING

Lunar geotechnical measurements and data are interesting, but their application to future lunar engineering applications now becomes the challenging task for today's engineers. A cross-section of the lunar surface is useful to picture the regolith properties that change with depth, and to visualize mechanisms that will attempt to shear particles from the soil matrix, such as excavation or engine exhaust. Section 2 previously discussed how regolith density and shear strength increase with depth - density increases approximately hyperbolically, and shear strength increases approximately linearly – with the result of soil particles becoming more difficult to "shear away" as depth increases. Figure 11 combines a cross-section of the lunar soil with density and shear strength data to illustrate this dynamic relationship with depth.

Excavation of the lunar soil is a topic that arises frequently when discussing mining lunar regolith for oxygen or volatile extraction, burying habitats for radiation shielding, or creating roadways or landing facilities. The geotechnical data presented above suggests that excavation of the upper, "fluffy" layers of lunar soil, to a depth of 10-15 cm, will be fairly easy, as that upper layer has the lowest density, cohesion and shear strength. Excavating below that depth will require considerably more breakout force to release particles from soil matrix, and this force will increase as the excavation depth increases. The lower lunar gravity plays a small part in the complex relationship of excavation forces [5], but the high excavation forces at depth are primarily attributable to the large shear strength formed by densifying the regolith for millions of years of micrometeoric bombardments. Future lunar excavation equipment must overcome soil shear strength exceeding 2.0 kPa at 1 meter depth and 4 kPa below 2 meters of depth.

In addition to machine excavation, the lunar surface will tend to increasingly resist other fracturing forces as depth increases. Rocket engine plume-surface interaction has been studied since the 1960's, and studies of Apollo lunar module descent propulsion system (DPS) disturbance of the lunar surface under the lander (see Figure 14) has been studied extensively by Immer, et.al. [6]. Lunar landers produce high velocity exhaust gasses that will scour loose lunar regolith and accelerate it away at potentially high velocities. There are likely multiple mechanisms at work as a rocket plume interacts with the soil matrix – shearing via viscous erosion, particle fluidization due to gas diffusion, and others. This complex combination of soil particle release mechanisms is not easily modeled, but Apollo experience and an understanding of lunar soil geotechnics makes some observations possible.

Lander plumes will first remove the unconsolidated top layer of regolith, as seen in the Apollo mission landing videos. Removal of this top layer of soil will result in dust obscuration of the area during landing and ascent, and will transport soil particles at shallow angles, at velocities approaching engine exhaust velocity. As deeper levels of regolith, with higher density, cohesive force and shear strength, are exposed to the engine plume, higher plume viscous shear forces, or other mechanisms, are needed to strip the regolith away from the soil matrix. At the same time the porosity of the lunar soil matrix decreases quickly near the surface, and then asymptotically with depth, so diffusion of gas into the soil will continue at a lesser rate in deeper soil layers. The combination of lunar soil porosity decreasing, as density and cohesion increase with depth, suggests that the forces required for viscous shear and diffusion into soil pores would need to increase in order to excavate lower layers. The interaction of the engine plume with the complex lunar soil matrix remains an intriguing topic for further analysis, and even properly constructing terrestrial regolith simulants that correctly model the change of porosity, density and cohesion as a function of depth in order to test excavation or rocket engine exhaust effects on the surface in terrestrial vacuum chambers becomes immensely challenging.

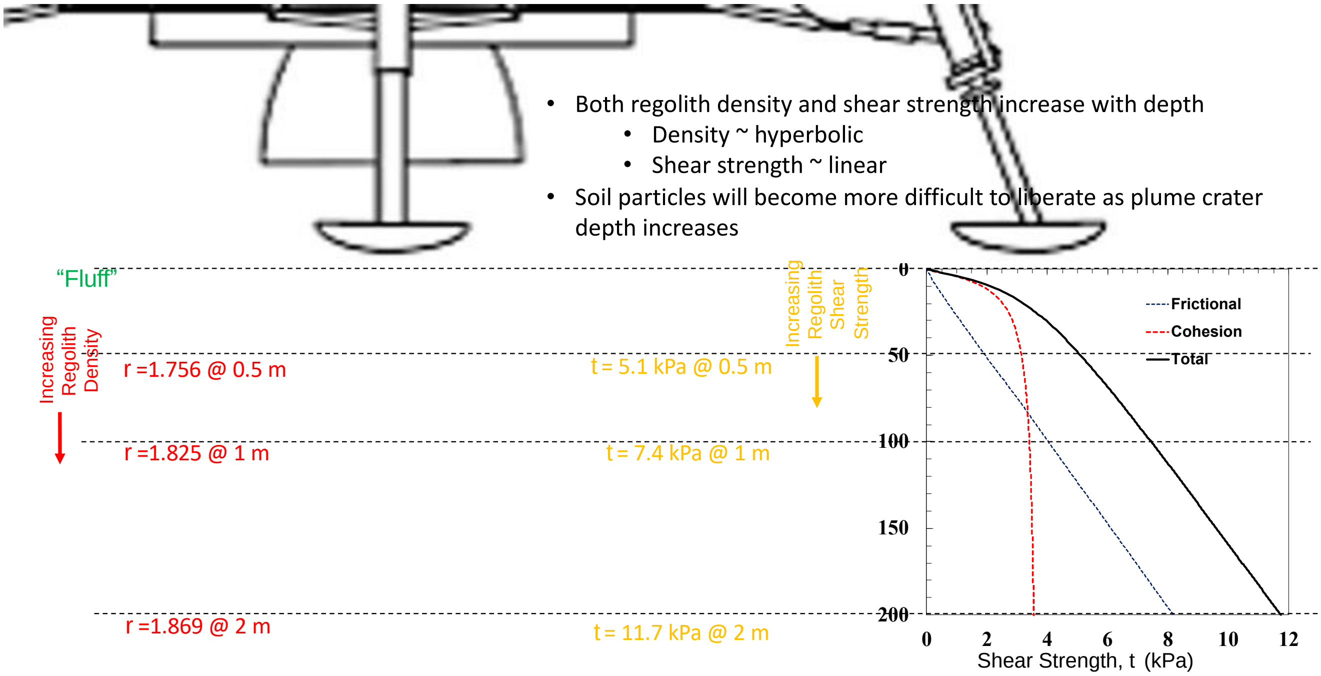

Figure 11. Regolith Density and shear strength plotted vs depth for intercrater areas. Apollo Lunar Module footpads and engine nozzle to approximate scale.

Figure 12. A 1/6-g lunar soil simulant excavation experiment aboard NASA's KC-135 yielded lower excavation forces of compacted lunar regolith simulant required in lunar gravity compared to Earth gravity and concluded that "A complex relationship exists between gravity and excavation forces" [5]

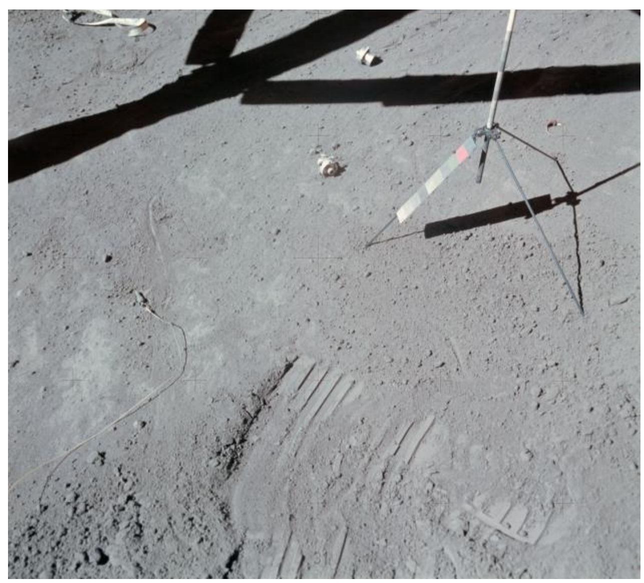

Figure 13. Apollo 15 photograph AS15-088-11884 showing the soil under the lunar module. Note that the upper layer of loose regolith has been mostly removed by the engine plume, exposing a more cohesive (and different color) layer below.

4. Lunar Geotechnical Field Observations

The Apollo 11 lunar module "Eagle" landed on the Sea of Tranquility with the following conditions:

- Vertical velocity: 1.7 ft/sec (-X, down)
- Horizontal velocity: 2.1 ft/sec left (-Y, left)
- Engine throttled to ~26% at landing (~2300lbf thrust)

- Engines shut down with footpads on the surface
- Engine skirt-to surface clearance – 13.5 inches
- Landing Gear struts stroked less than 1 inch
- Local slope 4.5 degrees

The Apollo 11 astronauts photo documented the condition of the lunar module as well as the condition of the lunar surface below the LM. The lunar surface directly below Apollo 11 Descent Propulsion System engine bell was radially eroded with rays emanating outward from the vehicle and engine centerline, but the landing did NOT form any measurable crater. The embedded rock in the lower left of Figure 14 was scoured by the engine plume but remained unmoved. Some small laminations, or "stairsteps" in the soil surface are visible as you move away from nozzle [6].

Note that the groove beginning directly below the engine bell and going to the upper left was caused by the initial contact and subsequent dragging of the lunar contact probe as the LM touched down.

Figure 14. Lunar surface directly below the Apollo 11 descent propulsion system (NASA photo AS11-40-5921)

Six and one-half hours after landing on the Moon, Apollo 11 commander Neil Armstrong stood on a footpad at the base of the lunar module. History has recorded his first words as he stepped onto the lunar surface, but immediately before and after his "one small step", he was busy recording geotechnical observations of the lunar surface. His observations, as well as the geotechnical measurements taken by all of the subsequent Apollo crews would form the basis for our engineering understanding of the lunar surface. And so the first geotechnical report from the Moon was heard by 650 million people back on Earth:

"I'm at the foot of the ladder. The LM footpads are only depressed in the surface about 1 or 2 inches, although the surface appears to be very, very fine grained, as you get close to it. It's almost like a powder. (The) ground mass is very fine.

That's one small step for (a) man; one giant leap for mankind.

The surface is fine and powdery. I can kick it up loosely with my toe. It does adhere in fine layers, like powdered charcoal, to the sole and sides of my boots. I only go in a small fraction of an inch, maybe an eighth of an inch, but I can see the footprints of my boots and the treads in the fine, sandy particles".

Figure 15. Apollo 11 bootprint in the soft, cohesive upper layer of lunar soil (NASA photo AS11-40-5877)

5. Concluding Observations

The goal of this paper was to create a common understanding of lunar soil geotechnical properties which are essential to the understanding of excavation, lander engine plume-surface interaction, and lunar construction. All future missions to the Moon will require a level of understanding of lunar soil properties, including an understanding of what is well known and what properties remain more theoretical. Surface geotechnical properties were well measured by the Apollo missions and documented in publications such as the Lunar Sourcebook [1], but the dataset from Apollo was limited. Apollo missions probed no more than a few meters into the lunar surface, and as depth below the lunar surface increases, the understanding of geotechnical properties transition from known, measured values towards best engineering estimates and models. One geotechnical truth is that lunar surface properties change with depth, and an understanding of density, cohesion, shear strength, and porosity of the lunar regolith, as these properties increase with depth, is essential to an understanding of the lunar surface.

References

[1] Heiken, G.H., Vaniman, D.T., and French, B.M. (Eds.), 1991. Lunar Sourcebook : A user's guide to the moon. Cambridge Univ. Press, ISBN 0521334446

https://www.lpi.usra.edu/publications/books/lunar_sourcebook/pdf/Chapter09.pdf

[2] Carrier, W.D.,III, The four things you need to know about the GEOTECHNICAL PROPERTIES OF LUNAR SOIL, September 2005
https://www.lpi.usra.edu/lunar/surface/carrier_lunar_soils.pdf

[3] Microscopy and Microanalysis, Volume 17, Issue 1, February 2011, pp. 34 - 48.

[4] Physical and Mechanical Properties of the Lunar Soil (A Review), E. N. Slyuta, Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, ul. Kosygina 19, Moscow, 119991 Russia. Original Russian Text © E.N. Slyuta, 2014, published in Astronomicheskii Vestnik, 2014, Vol. 48, No. 5, pp. 358–382.

[5] Boles, Walter W., and Connolly, John F., Results of Lunar Excavation Experiments Supporting Lunar Base Construction, Fifth International Conference on Space, ASCE, June 1996

[6] Immer, C.D., Lane, J.E., Metzger, P.T., and Clements, S., 2008. Apollo Video Photogrammetry Estimation of Plume Impingement Effects. In: Proceedings of Earth and Space 2008, 11th Biennial ASCE Aerospace Division International Conference on Engineering, Construction and Operations in Challenging Environments, Long Beach, CA.

BIOGRAPHY

John Connolly *is a member of NASA's Artemis program, planning the return of astronaut explorers to the moon. His 33 year of NASA expertise includes lunar lander design, lunar surface systems, and human Mars mission planning. Connolly has held positions as NASA's Lunar Surface Systems lead, Human Mars Study Team lead, HQ Chief Exploration Scientist, Special Assistant to JSC's Astronaut Office, and Deputy Project Manager and Vehicle Engineering Manager for the Altair Lunar Lander Project. He holds engineering degrees from Penn State and the University of Colorado. Mr. Connolly's NASA career has been devoted to defining future systems that will send human crews beyond Low Earth Orbit, return them to the moon, and lead them to Mars and beyond.*

W. David Carrier *was responsible for the development and performance of lunar soil experiments in support of the Apollo program at the NASA Manned Spacecraft Center in Houston. His activities included astronaut training, design of lunar surface experiments, and laboratory testing of returned lunar soil. He told Neil Armstrong and Buzz Aldrin how deep they were going to sink into the lunar surface. Dr. Carrier was a member of the science support team in Mission Control and a member of the Lunar Sample Preliminary Examination Team in the Lunar Receiving Laboratory during each of the Apollo missions.*

He obtained his bachelor's, master's, and doctorate in civil engineering from the Massachusetts Institute of Technology. He has published many technical papers and lectured extensively. He is one of the co-authors of the Lunar Sourcebook.