UPDATING LUNAR SUBSURFACE GEOTECHNICAL PROPERTIES BASED UPON NONLINEAR WINKLER MODELING OF APOLLO AND LUNOKHOD MEASUREMENTS. J.F. Connolly[1] and W.D. Carrier[2], [1]NASA Johnson Space Center, Houston, Texas (john.connolly@nasa.gov), [2]Argila Enterprises, Inc., Lakeland, Florida (wdcarrier@verizon.net).

Introduction: Returning human and robotic explorers to the lunar surface has identified a need for a renewed understanding of lunar geotechnical properties related to landing on and exploring the lunar surface. We review fundamental lunar geotechnical properties such as bulk density, cohesion, friction angle and shear strength, and apply new data derived from Apollo and Lunokhod geotechnical measurements to update the understanding of lunar regolith behavior. The analysis derives a new, nonlinear relationship of lunar geotechnical properties as a function of depth.

Modeling Lunar Regolith as a Function of Depth: Lunar soil density quickly increases with depth. On average, the bulk density of lunar regolith is approximately 1.30 g/cm^3 at the surface, and increases asymptotically to 1.92 g/cm^3 below a depth of 100 cm. The lunar surface can be thought of as an 10-15 cm upper layer of loosely consolidated regolith that has been gardened by micrometeorite flux, covering a dense and consolidated lower layer that has been tightly packed by the same micrometeorite flux over lunar geological time. Like bulk density, other geophysical properties, such as shear strength, change with depth.

Lunar soil behavior has generally been modeled as a linear Winkler soil [1], and data presented in chapter 9 of the Lunar Sourcebook [2, Figs. 9.26, 9.28-30] reflects this linear modeling. The corresponding soil parameter is the "modulus of subgrade reaction" which is analogous to a soil spring constant, thus the symbol is k and units of stress / length (Pa / mm). On the Moon we use the Winkler model to analyze footpad-soil interaction during landing, deployment of scientific instruments, and wheel-soil interaction of a roving vehicle.

Bootprint statistics were collected during each of the Apollo missions. Knowing the approximate force imposed by an astronaut standing on one foot on the Moon, as well as the dimensions of the bootprint, we knew the approximate stress: 7,000 Pa. In effect, each bootprint was a "plate-load test" of the soil that allowed us to calculate the modulus of subgrade reaction:

$k = q / d$ where:
q = applied stress of boot (Pa)
d = depth of bootprint (mm)

776 Apollo bootprints were analyzed and the average modulus, k was determined to be 920 Pa/mm with an average bootprint depth of 7000 Pa / 920 Pa/mm = 7.6 mm. Furthermore, it was found that the modulus distribution was approximately log-normal [2,Fig 9.37].

Roughly in parallel with the Apollo Program, the Russian Lunokhod 1 and 2 robotic roving vehicles were conducting approximately 1000 cone penetrometer measurements during their respective traverses. The device measured the force required to push the cone into the lunar surface to a depth of 44 mm, and this data was summarized in the Lunar Sourcebook [2, Fig 9.7(a)][3][4].

The average force recorded by the Lunokhod was 66 N, so the average q = 33,600 Pa and hence, the average k was 3 x 33,600 / 44 = 2,300 Pa/mm. This is much greater than the k= 920 Pa/mm from the bootprint data, and though the Lunokhod data was roughly log-normal as was the bootprint data, the deeper penetrometer data was all shifted to higher values of k.

Combining the Apollo data (bootprints/fixed load with variable depth) and Lunokhod penetrometer tests (fixed depth/variable load) led to the development of a non-linear Winkler model in which the resistance, q, increases faster with depth, d. Thus,

Bootprint: $k = q / d^n$
Cone: $k = q (n+1) (n+2) / 2 d^n$

where n is the non-linear exponent

By iteration, we found that the average k for both sets of data match for n = 1.86. That is, the resistance increases almost with the square of the depth. Thus, the average modulus is:

Bootprint: $k = 7000 / 7.6^{1.86} = 163$ Pa/mm$^{1.86}$
Cone: $k = 33{,}600 (2.86) (3.86) / 2 \times 44^{1.86} = 163$ Pa/mm$^{1.86}$

Though the average k matches at n = 1.86, the spread of each set of data is different: the standard deviation of the bootprint data is greater than for the Lunokhod data. Thus, a plot of the log-probability relationship shows a steeper Bootprint line due to the greater standard deviation, with the two lines crossing at 50% probability: k = 163 Pa/mm$^{1.86}$. The recommended non-linear Winkler model is therefore a combination of the two datasets:

The average log k for all three lines is 2.21 and the standard deviations are:

Bootprint: σ =0.657
Cone: σ =0.194
Combined: σ =0.485

Updating Lunar Regolith Shear Strength Model: Lunar soil shear strength is an essential property governing the forces required to core, drill, excavate or penetrate below the lunar surface. The shear strength of a granular soil (τ) is typically defined in terms of the classic Mohr-Coulomb relationship which combines cohesion (c) and friction angle (ϕ) - normal stress (σ) components. Figure 1 summarizes the new non-linear Winkler model for these components [5].

Soil Cohesion— The irregular, interlocking regolith particle shapes account for much of the cohesive behavior of the lunar soil, and accounts for the Astronaut's bootprints appearing so crisp. Like many lunar soil properties, cohesion will increase with depth, related to the increase in soil density. As a significant component of overall soil shear strength, cohesion quickly increases beyond 3 kPa at depths below 50 cm.

Friction Angle and Normal Stress— The second component of soil shear strength is 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 1 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 1. The sum of cohesion and frictional shear stress yields an understanding of how lunar soil shear strength behaves with increasing depth, and follows the understanding of bulk density versus depth – a thin layer of unconsolidated surface material transitioning to layers of soil with increasing density and shear strength.

Exploration and Science: The above analysis represents a revised understanding of lunar soil geotechnical properties which are essential to the understanding of lunar core sampling, excavation, lander engine plume-surface interaction, and lunar construction that will be pertain to all future missions to the Moon. One geotechnical truth is that lunar surface properties change with depth, and an understanding of how these properties change, sometimes non-linearly, is essential to an understanding of the lunar surface and near subsurface.

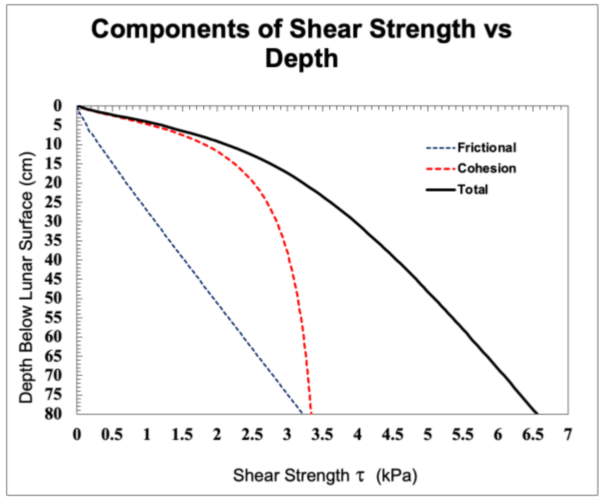

Figure 1. Total lunar soil shear strength as a function of depth for the top 80 cm of regolith.

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