LUNAR PYROCLASTIC SOIL MECHANICS AND TRAFFICABILITY IN THE SCHRÖDINGER BASIN.
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Introduction: Mechanical properties of soils on the Moon may affect the maneuverability and power consumption of lunar exploration vehicles. Different geologic units and their physical properties, such as cohesion, may affect local slope stability and, thus, trafficability. The Schrödinger basin, located on the lunar farside, has emerged as a target of interest for several robotic and human exploration mission concept studies [1-6]. One of the reasons the site is interesting is because it contains a notable volcanic vent, centered at 75°S, 139.4°E, that is surrounded by a blanket of pyroclastic material extending approximately 14 km radially [7]. That pyroclastic material may have important *in situ* resource potential, as it is a source of volatiles and because it provides good feedstock for construction. It is not yet clear, however, if that material will pose a problem for rovers sent to explore it. Here we try to resolve that issue.

Methodology: Physical properties of lunar soils have previously been measured through photographic observations of astronaut footprints, boulder tracks, and Lunar Roving Vehicle (LRV) tracks from the Apollo missions [8-13]. Surficial porosity, cohesion, and friction angles have also been calculated and determined to be relatively constant throughout the upper few centimeters of regolith [11]. The regolith of the Surveyor III site has, for example, observed cohesion values between 7.0×10^2 and 1.2×10^4 dynes/cm^2 and bearing capacities between 4.0×10^5 and 6.0×10^5 dynes/cm^2 and were reliably traversed by Apollo 12 crew [13].

Schrödinger's pyroclastic unit, however, contains unidentified soil parameters, as no detailed investigation into lunar pyroclastic mechanics has been made. To determine the trafficability across pyroclastic material, we began with an assessment of the Apollo 17 landing site, where pyroclastic material was observed, collected, and analyzed upon return to Earth. Qualitatively, that pyroclastic material was determined to be unusually compact, with higher cohesion than the surrounding material, based on how it fragmented in the field [12]. We augmented those observations by measuring boulder track parameters in new Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) images. Those parameters were, thus, used to calculate soil properties. That process was repeated

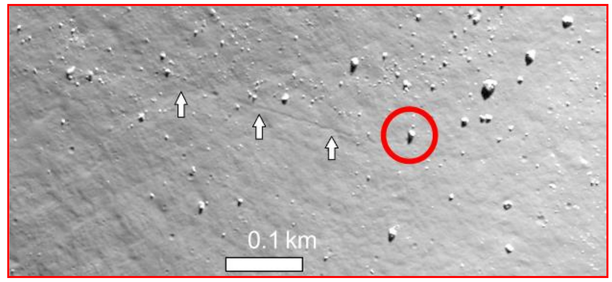

Figure 1: *NAC image M1105047071R within the Schrödinger pyroclastic vent showing a measured boulder along with its associated track (from ArcGIS 10.1™).*

for boulder tracks in the pyroclastic unit at Schrödinger (Fig. 1) and other, nearby geologic units within the basin. Those three sets of measurements and calculations provide a means of assessing the relative soil parameters between normal regolith and pyroclastic material (both in Schrödinger and the Taurus-Littrow Valley of Apollo 17) and between a known site (Apollo 17) and the proposed mission site of Schrödinger.

Determining Bearing Capacity: The key parameter in our assessment is the bearing capacity. For assessing lunar surface conditions, this has traditionally been calculated using the Terzaghi equation for circular footings [14]. To further evaluate that finding, we used the surficial properties of an upper core sample [12] and several LROC-NAC images of boulder tracks within the pyroclastic unit. The Terzaghi equation is given by

$$Q = 1.3\, N_c\, C + \rho\, g\, N_q\, D_f + 0.6\, \rho\, g\, N_\gamma\, R_f \qquad (1)$$

where Nc, Nq, and Nγ are dimensionless numbers for soil shear conditions based on the internal friction angle, which, for this study, is nominally taken to be 30°, based on analyses of Moore [13]. We also consider a friction angle of 35°, because it is the suggested value for the upper 15 cm of general regolith [9-12]. Cohesion (C) is taken to be 10^3 dynes/cm^2, gravity (g) as 163 cm/s^2, and soil density (ρ) is assigned values of 2.0 to 2.9 g/cm^2 based on values in an Apollo 17 core tube sample containing orange glass [10,12,13], and 1.35 g/cm^2 for all other observations [13]. In this analysis, the depth of footing (Df) and radius of footing (Rf)

Table 1.

Boulder	*Soil Density (g/cm²)*	*Geologic Unit[15]*	*Lat (°)*	*Long (°)*	*Boulder Radius (cm)*	*Bearing Capacity (dynes/cm²)*
1	2.00	Pyroclastic (Ep)	-75.156	140.118	297.5	2.60×10^6
	2.29					2.80×10^6
2	2.00		-75.163	140.131	259.0	2.59×10^6
	2.29					2.80×10^6
3	2.00		-75.309	139.173	544.5	5.20×10^6
	2.29					5.62×10^6
4	1.35	Basin Wall Material (Iw)	-79.654	129.295	439.9	1.96×10^6
5			-79.66	129.121	348.0	2.55×10^6
6			-79.676	129.425	486.4	2.60×10^6
7		Peak Ring Material (pNpr)	-75.391	142.203	484.9	2.06×10^6
8			-75.359	142.201	375.4	1.72×10^6
9			-75.354	142.231	424.4	2.28×10^6
10		Apollo 17 Taurus-Littrow	19.921	31.134	389.9	1.07×10^6
11			19.924	31.154	390.9	1.17×10^6
12			19.871	31.146	381.4	1.25×10^6

correspond to the observed boulder and track widths [13].

Results and Discussion: A bearing capacity for the Taurus-Littrow Valley, with soil parameters analogous to Moore [13], was found to be an average of 1.16×10^6 dynes/cm^2, which is comparable to (and within 25% of) the 9.28×10^5 dynes/cm^2 previously calculated for general lunar surface capacities [13], indicating the relative accuracy of the remote sensing technique. The bearing capacity (Q) of Schrödinger's pyroclastic material with an internal friction angle of 30° and soil density of 2 g/cm^2 was calculated to be an average of 3.46×10^6 dynes/cm^2 (Table 1). The results show that Schrödinger's pyroclastic unit has a higher cohesion and bearing capacity for added mass relative to the well-treaded soils from the Apollo 17 region. Additionally, it verifies that the trafficability of the pyroclastic deposit is potentially sufficient, if not preferable, for a lunar exploration vehicle traverse.

However, several assumptions in this analysis have been made, which are: (1) the observed boulders are spherical, (2) the cohesion is 10^3 dynes/cm^2, (3) the internal friction values are limited between 30 and 35°, (4) the soil density from Apollo 17 Shorty Crater station 4 orange glass is representative of surficial vent material, and (5) that the local slope is negligible. Additionally, meter-scale variability in soil properties for Schrödinger's pyroclastic unit is likely, and through the use of a static bearing equation, remains an unknown factor. Therefore, additional investigations into pyroclastic soil mechanics are recommended to further correlate boulder track results and trafficability.

Conclusions: By observing lunar boulder tracks in different geologic units, we calculated the soil bearing capacity for Schrödinger basin's pyroclastic unit and found it to be greater than those in the well-traversed Taurus-Littrow Valley region of Apollo 17. The results demonstrate that the pyroclastic unit is sufficiently trafficable for lunar vehicular activity. However, due to the calculation assumptions, further investigations are needed to better evaluate mechanical properties of soils from remote sensing platforms.

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