Probing the geomechanical properties of the south polar (pen)-umbral regolith

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Introduction

Before the first robotic or human touchdown on the Moon, the physical properties of the lunar surface were of great concern to engineers and scientists, specifically, whether the surface would be able to bear any type of load (Carrier et al., 1991). Later exploration by Luna, Surveyor, Lunokhod, and the Apollo-era astronauts proved that the surface regolith allows for extended wheeled and legged traverses. Moreover, the study of core-tube samples, drill cores, cone penetrometer and other measurements from the six different Apollo landing sites, the five different Surveyor landing sites, and the two extensive Lunokhod traverses indicated that the variability of regolith properties is similar on local and regional scales – indicating that the regolith features similar physical properties across the equatorial mare and highland regions (e.g. Costes et al., 1972).

However, both Lunokhod and the Apollo Lunar Roving Vehicle encountered locally-constrained regions of regolith with poor or insufficient surface strength that resulted in excessive wheel sinkage or even wheel deadlock (Costes et al., 1972). There is some evidence that suggests local strength anomalies could be related to geomorphic features, such as fresh impact craters: For example, Lunokhod 2 encountered excessive wheel sinkage when traversing the toes of crater slopes in the Le Monnier crater area (Florensky et al., 1978). Data from the Lunokhod 1 cone penetrometer appears to support this qualitative observation, but is not entirely conclusive (Mitchell et al., 1972; Carrier et al., 1991). A better understanding of the relation between geomorphic features and the physical properties of the regolith would facilitate planning of safer traverses, but many important questions remain unanswered.

Despite these uncertainties, the regolith in equatorial mare and highland regions is rather well studied (see Carrier et al., 1991). However, there are regions on the Moon that could potentially host regolith with substantially different geomechanical properties, such as temporarily and permanently shadowed regions (PSRs). In these regions, differences in mechanical soil behavior could be caused by differences in regolith composition, relative density, or by the presence of volatiles and ice, for example. Past missions tried to shed light on the physical properties of the regolith in these regions: for example, observations of the LCROSS impact plume and in Diviner data indicate that the uppermost centimeters and meter(s) in PSRs could feature an increased porosity and thus, potentially, reduced surface strength (Schultz et al., 2010; Hayne et al., 2017). More recent studies analyzed boulder tracks in south polar sunlit, penumbral, and umbral regions, but did not observe reduced regolith strength values at ~10 to 30 cm depth and deeper (Bickel and Kring, 2020; Sargeant et al., 2020). The wide range of surface strength estimates demonstrates that our understanding of the properties of the uppermost – and most crucial – part of the surface (the first ~15 cm) in these regions is still very limited and urgently requires ground truth.

All future surface exploration missions, including ISRU efforts, require asset mobility. The Artemis program offers a unique opportunity to address – in situ and via sample return - a series of pressing questions about the nature of the lunar soil around the lunar poles, two top priority regions. The earlier information about polar soil conditions is available, the earlier all subsequent engineering, science, and exploration efforts can benefit.

Science questions

(1) What is the shear strength of the surface in polar (pen)-umbral regions and how does it change as function of depth, geomorphology, and slope angle?

(2) What is the variability of the individual shear strength parameters in polar (pen)-umbral regions?

(3) Do (sub)-surface volatiles influence the geomechanical behavior of the regolith (and how)?

(4) Are there any unforeseen trafficability hazards related to interaction of (sub)-surface volatiles and boots/wheels (e.g. traction during slope descent and ascent, (lack of) ice-related surface roughness, etc.)?

(5) How does the (pen)-umbral regolith respond to frequent traverses around landers and in key passages over time?

Potential objectives for crew

One of the simplest means of sampling the lunar surface is by looking at (stereo)-photographs of lander pad and astronaut boot imprints, as it has been done during the Apollo program (see e.g. Buzz Aldrin's iconic bootprint photo). In combination with (orbital) context imagery and elevation maps, Artemis bootprint (stereo)-photographs could be used to characterize variations of the surface and shallow subsurface, e.g. across the penumbral – umbral transition zone -, addressing many aspects of the science questions listed above with minimal effort.

The geomechanical properties of the subsurface (down to ~50 cm or more) can be characterized using a portable, light-weight cone penetrometer, a tool that has already been used to analyze the regolith during the Apollo and Lunokhod missions. Penetrometer sampling could be frequently performed by the astronauts en route to other sampling sites and would only require a few seconds per measurement. A portable cone penetrometer could be upgraded with a gamma-ray attenuation densiometer to retrieve in-situ regolith bulk density information as function of depth and location.

A more detailed (and deeper) view into the subsurface and the spatial variability of geomechanical properties would be enabled by trench, core tube, and drill core sampling. While drilling or digging a trench require more effort and time, the derived samples would represent a rich source of information for geomechanical analyses and for other science investigations, such as the study of volatile distribution and stratigraphy, in situ and after their return to Earth.

Many of the science questions listed above are directly or indirectly linked to other relevant investigations and go "hand in hand", such as the study of the lateral and vertical distribution of volatiles in and around PSRs by probing and/or drilling. On the one hand this means that many of the science objectives of this paper can be addressed "on the fly", as secondary observations made during traverses or other sampling operations. For example, the monitoring of bootprints/sampling with a penetrometer could be frequently performed during all traverses, without negatively impacting other mission operations or objectives. On the other hand, the overlap with other science questions means that potential sampling targets and strategies would also align, effectively maximizing the science return.

Conclusions

The geomechanical properties of the polar (pen)-umbral regolith are poorly understood and potentially challenging. With our currently limited knowledge, unrestricted mobility of astronauts or robots in these regions is not guaranteed. The Artemis missions present a unique opportunity to close some of the strategic knowledge gaps related to regolith properties and trafficability in lunar polar (pen)-umbral regions. Conveniently, many soil mechanical experiments could be performed in parallel or adjacent to other measurements – in situ or after a return to Earth -, requiring only a minimal amount of extra time and effort. Still, the knowledge gained during early missions could directly benefit all future surface exploration and ISRU efforts in the lunar polar regions – and beyond.

References

Bickel and Kring (2020), Icarus; Carrier et al. (1991), Lunar Sourcebook; Costes et al. (1972), NASA TR R-401; Florensky et al. (1978), LPSC 1978; Hayne et al. (2017), JGR: Planets; Mitchell et al. (1972), LPSC 1972; Schultz et al. (2010), Science 330; Sargeant et al. (2020), JGR: Planets.