Measuring the Shear Stress of In-situ Soils on Planetary Surfaces. R.C. Anderson[1], G. Peters[1], and G. Meirion-Griffith[1], 1Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA, Robert.C.Anderson@jpl.nasa.gov.

Introduction: Major advances in robotics have demonstrated successful deployment of scientific payloads for robotic field geology. These payloads include instruments to identify the mineralogy and elemental chemistry of in-situ soils. However, these measurements do not tell the entire story. Mechanical properties (i.e., geotechnical studies) proved essential to support hardware development for human presence, especially on the Moon; however, instruments for geotechnical properties have been underrepresented since the conclusion of Apollo and have been largely absent from our explorations of other worlds beyond the Moon.

One physical property that needs to be studied on any planetary surface is shear strength of the surface materials. Shear strength is a term used in soil mechanics to describe the magnitude of the shear stress that a soil can maintain. The shear resistance of soil is a result of friction and interlocking of particles, and cementation or other adhesive or cohesion bonding at particle contacts (including chemical or electrostatic-based attractions). Due to interlocking of grains, particulate material may expand or contract in volume as it is subject to shear strains [1]. For terrestrial soil investigations, shear strength testing is performed to determine load bearing capability and internal shear under various loadings and is required for all geotechnical engineering stability, design and performance analyses, such as determining the stability of slopes or cuts, finding the bearing capacity for foundations, and calculating the pressure exerted by a soil [2]. The specific knowledge of shear strength is an essential component in: 1) in the design of landing and mobility systems (e.g. the evaluation of bearing capacity of the soil is dependent on the shear strength); and 2) the analysis of the stability of the slope(s), crucial for mobility and other exploratory activities; and, with respect to increasing knowledge of basic planetary sciences to 3) the understanding aeolian bedform activity [3] on planetary surfaces (e.g. Titan, Mars, etc.); and 4) understanding how mass wasting and meteoritic impact effect the terrains on small bodies.

Planetary rovers are frequently required to operate on loose, granular material in the form of ripples or dunes. Mobility on such media, ubiquitous across Mars' surface, is often limited not by the vehicle's actuators but by the strength of the terrain and its ability to support locomotion. Bearing and shear strength measurements, both provide the minimum set by which predictions of mobility performance can be made. Shear vane strength measurements, when taken under a range of normal loads, may readily be used to determine two key parameters of the Mohr-Coulomb failure criterion: internal friction angle and cohesion. The shear failure criterion may then be applied to the geometry of the wheel-soil contact patch and provide the basis by which estimates of available traction can be made. Traction, or drawbar pull, is the determining factor in terrain trafficability and is a reliable measure by which go- no-go path planning assessments can be made. In the absence of *in situ* shear strength measurements, predictions of rover mobility performance are reduced either to anecdotal or posteriori analyses, both of which increase the risk of becoming entrenched (e.g. MER Purgatory, MSL Hidden Valley), or to the cautious avoidance of sand at the expense of mission time and scientific objectives.

Classical Vane Shear Testing (VST): During terrestrial soil investigations shear strength testing is used to determine load-bearing capability and internal shear under various loadings for soils. These tests are often performed on sampled soils collected in the field (disturbed) and brought back to a lab, which is not possible for planetary exploration. For terrestrial soils, the pocket shear vane tester provides geologists a quick and efficient method for determining shear strength of in-situ cohesive soils. The test involves pushing a four-bladed vane into soil and slowly rotating it (usually 0.1 degree per second) while measuring the resisting torque.

The shear strength is calculated by equating the torque to the moments corresponding to the total shear strength over the sides and the ends of the cylindrical shear failure surface (4): Torque = Ts + Te where Ts = moment of shear resistance force on the side of the cylindrical failure surface; Te = moment of shear resistance force at the two ends of the cylindrical failure surface. Replacing the above equation with the test parameters, and solving for the shear strength, we obtain: $Cu=T / [\pi d2 (h/2 + d/6)]$ where: Cu=Shear strength of the soil; T=Maximum torque at failure; h=height of the vane; d=diameter of the vane. Generally, the pocket VST requires several measurements due to the testing inaccuracies with humans placing and holding the instrument into the soil. The much steadier platform of a rover and robotic arm is expected to provide much better stability. The vane shear testing method is mostly used for testing undrained clayey material, it has rarely been considered for loose drained material normally found on planetary surfaces such as the Moon and Mars. In a study by Rahmatian and Metzger [5], a VST was used to examine its applicability for loose, granular, lunar soil analogs. Their study concluded that the VST provided good data for loose, granular soils. VST also had the advantage over other tested instruments by being very simple to use, and could be easily adapted for use by a robotic lunar lander, in which the motors and stress sensors in the robotic arm (rather than fixed weights in a basket) can control the normal stress.

Implementation: To test the possibility of building a robotic arm mounted VST for planetary research, we designed a new instrument (VSS) that incorporates flight like components for testing in planetary simulants. As mentioned previously, one concern with the commercially available hand tester is that under different normal loads the tester may give different readings. Each user can apply a slightly different normal load when pushing into the soil and results in different soil compaction and torque reading. The prototype and testing set-up developed offers a direct method of loading the shear tester consistently, and allows users to analyze the effect of normal load on the torque required to break the soil. The goal of building a prototype is to collect data and demonstrate relationship between normal load and torque needed to break and spin soil.

Initial Results:

- Built a prototype Vane Shear Tester, connected it to an instrumented dummy arm, and got torque data.
- Successfully performed 173 tests in 4 different simulants.
- Was able to differentiate the mechanical properties of the four tested soils.
- Established a relationship between normal forces and torque that will lead to planetary measurements of cohesion and the internal angle of friction.
- Concluded the slope of the torque vs. load before the soil breaks shows that as the load increases, the initial slope (Shear Modulus) increases (Figure 1).

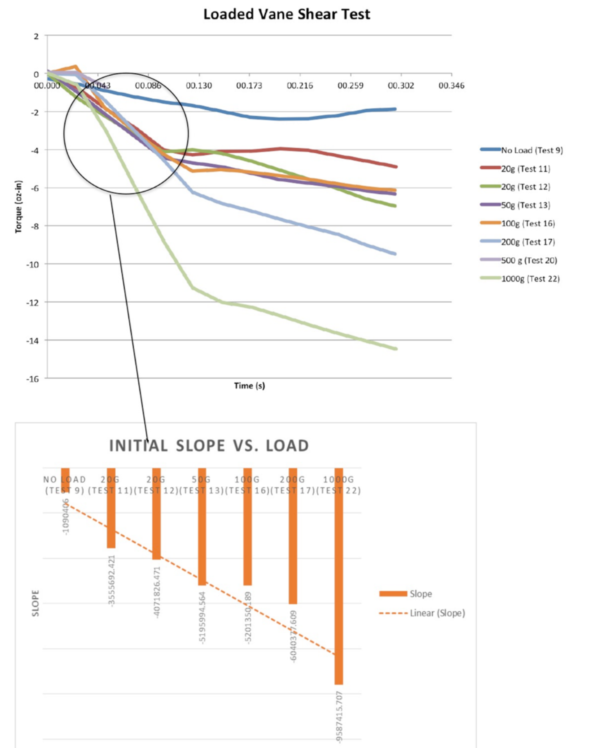

Fig. 1 Plotting the slope of the torque vs. load before the soil breaks shows that as the load increases, the initial slope increases. This finding provides experimental confirmation that normal loads affect the measurement.

Referees: [1] Payne, P. C. J., and E. R. Fountaine, (1952), J. of Soil Science, vol. 3, (1), 136-144. [2] Bardet, J.-P. (1997). Experimental Soil Mechanics. Prentice Hall. ISBN 978-0-13-374935-9. [3] Fenton, L. K., et al., (2010) Summary of the Second International Planetary Dunes Workshop: Planetary Analogs— Integrating Models, Remote Sensing, and Field Data, Alamosa, Colorado, USA, May18–21, 2010, Aeolian Research, 173-178. [4] ASM Handbook, Vol. 8, Mechanical Testing and Evaluation, ASM International, Materials Park, OH 44073-0002, fig. 6(b), page 146; Test Methods, first paragraph only, page 147; fig. 1, page 143; 2 sentences under Flexural Strength Test, page 32. [5] Rahmatian, L. A., and P. T. Metzger (2010), abstract in Earth and Space 2010: Engineering, Science, Construction, and Operations in Challenging Environments, 2010 ASCE.