Effect of Vacuum on Force Response of an Ultrasonic Penetrator. E. Rezich[1], Jonathan Davis[2], and G. Aucutt[3], [1] NASA Glenn Research Center, Materials and Structures Division, 21000 Brookpark Road, Cleveland, OH 44135; email: erin.t.rezich@nasa.gov, [2] NASA Glenn Research Center, Propulsion Division, 21000 Brookpark Road, Cleveland, OH 44135; email: jonathan.k.davis@nasa.gov, [3] New Mexico State University, Department of Civil Engineering, 1780 E University Ave, Las Cruces, NM 88003; email: gma55@nmsu.edu

Introduction: The Apollo astronauts encountered higher than expected resistances when interacting with the lunar soil via the Apollo Lunar Surface Drill (ALSD) and the trenching tool [1]. Reducing the force required to move tools or other mechanical components through regolith will impact many steps of the resource extraction process. Force reduction has been achieved in soil materials by imparting vibration to tooling interfaces such as a vibratory farming cultivator [2], a percussive scoop [3], and ultrasonically resonant penetrators [4]. Vibration-assisted tools in granular media reduce interaction forces by fluidizing a volume around the tool, allowing the tool to progress through a dynamic (fluid) medium instead of a static (solid) medium. This work seeks to quantify ultrasonic vibration's effect on the force response of a penetrator in lunar soil simulant in vacuum sufficient to be within the molecular flow regime of any disturbed gases.

Methods: A custom vacuum chamber setup, CUBEvac, was designed and built to facilitate penetration testing in a high vacuum environment, for comparison to penetration behavior in ambient terrestrial environment. A two-stage pumping system (Agilent Triscroll 600 roughing pump, Agilent VHS-6 oil diffusion pump) reached chamber pressures of about 5×10^{-6} Torr with regolith simulant in place. Figure 1 is a schematic of the heart of the assembly (note the penetration drive mechanisms above the chamber feedthrough and the regolith simulant sample in the bottom are not shown). The penetration actuation stack was comprised of a stepper motor driving a lead screw to move the ultrasonic probe vertically inside the chamber. Motion was coordinated with an Arduino Uno.

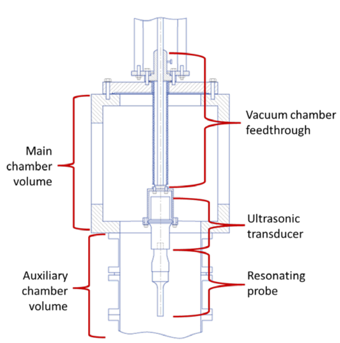

Figure 1. **Schematic front view of the ultrasonic probe inside the CUBEvac chamber.**

GRC-3 lunar simulant was used for this set of experiments. Samples were prepared in a four-liter stainless steel, cylindrical pot with an internal diameter of approximately 15.56 cm (6.125 in) and a depth of 19.37 cm (7 5/8 in) for testing. The soil was baked out prior to compaction preparation as a measure to reduce soil moisture which interfered with pump down capacity. The soil was not baked again if it was removed from the vacuum chamber, prepped, and immediately returned to the vacuum chamber for pump down. The soil was compacted using a 60 Hz vibration table with a surcharge of 34 kg place on top of the soil in the container. Prepared soil samples weighed approximately 6.5 kg (bulk density 1.895-1.934 g/cm^3).

Two probe end effectors were tested: A cone penetrometer (static only) with a nominal diameter of 12.7 mm (0.5 in) and a nominal height of 28.6 mm (1.125 in); and a vibrating cylindrical probe measuring 12.7 mm in diameter and 50.8 mm in effective length from the tip (Figure 2). The cylindrical probe vibrated resonantly at 20 kHz with an amplitude 23 µm. The cone penetration tests were conducted to assess potential soil behavior differences in vacuum. The cylinder probe tests were conducted as the primary subject of this investigation to assess force response in vacuum.

Figure 2. Resonant vibratory cylinder probe (Sonics and Materials), 1.27 cm (0.5 in) diameter and 5.08 cm (2 in) from tip to beginning of fillet curve.

For each test, a regolith simulant sample was loaded and compacted in the chamber, which was then evacuated for roughly 18 hours to reach the lowest possible pressure (approximately 5×10^{-6} Torr for most tests). The probe was then moved to about 10 mm above the soil surface before being pushed to a depth of 50 mm for the cylinder probe tests and to a depth of 100 mm for the cone penetrometer tests, both at a speed of 2 mm/s.

The simulant samples were prepared the same for all tests. Ideally, they would respond consistently to probe penetration under ambient and vacuum conditions. This was evaluated by measuring the resistance of representative prepared simulant beds with a standard cone penetrometer in both environments.

Results and Discussion: The resistance of the simulant samples in the vacuum tests was consistently lower than in the ambient tests as determined by the cone penetration tests. Thus, the ambient and vacuum results cannot be compared directly; work is underway to de-confound and better correlate the data.

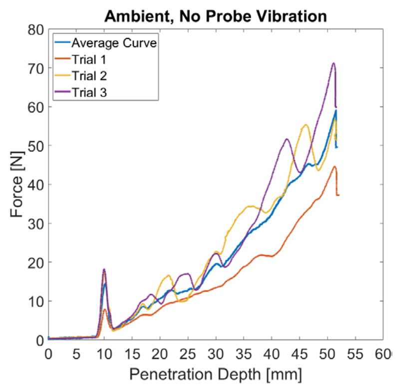

Figure 3. Penetration results using the cylindrical probe in ambient environment with no vibration.

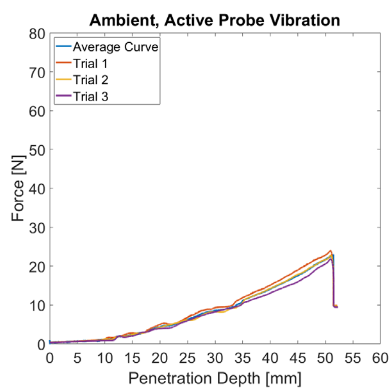

Figure 4. Penetration results using the cylindrical probe in ambient environment with resonant vibration.

Still, Figures 3-6 show that probe penetration forces are lower overall in the vacuum environment. In both environments, resonant vibration of the probe provides two useful effects: It reduces the probe penetration force and smooths the force-depth curve, significantly reducing local maxima. These effects have implications for various potential applications, such as astronaut hand-tools, where benefits (reducing astronaut effort) outweigh the cost of the additional energy required to generate vibration.

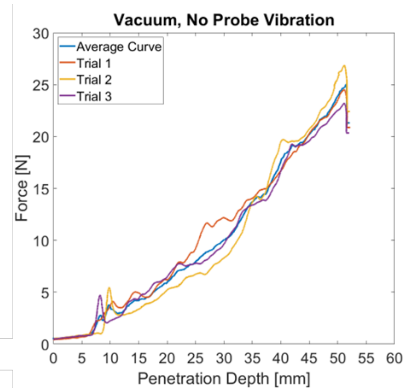

Figure 5. Penetration results using the cylindrical probe in vacuum environment with no vibration.

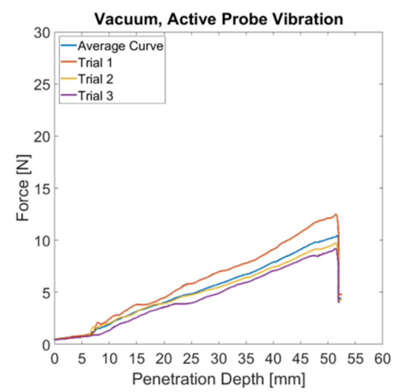

Figure 6. Penetration results using the cylindrical probe in vacuum environment with resonant vibration.

These results demonstrate that resonantly vibrating tools can meaningfully reduce the penetration force required for excavation, probing, and drilling tools in simulated lunar regolith deposits under vacuum levels approaching those that will be experience on the Moon's surface.

Lunar-gravity, ambient environment tests are scheduled soon. The effects of realistic temperatures and temperature gradients and deeper vacuum remain to be tested.

References: [1] Mitchell, J. K., Bromwell, L. G., Carriet III, W. D., & Costes, N. C. (1971). Apollo 14 Preliminary Science Report, Soil Mechanics Experiment. [2] Verma, B. P. (1971). Oscillating Soil tools - A Review. Transactions of the ASAE, 14(6), 1107–1115. [3] Green, A., Zacny, K., Pestana, J., Lieu, D., & Mueller, R. (2013). Investigating the Effects of Percussion on Excavation Forces. Journal of Aerospace Engineering, 26(1), 87–96. https://doi.org/10.1061/(asce)as.1943-5525.0000216. [4] Rezich, E., Harrigan, K., Thomas, F., & Ludwiczak, D. (2021). Ultrasonically Assisted Blade Technologies for Lunar Excavation. Earth and Space 2021.