Testing of a Rover-Mounted Instrumented Percussive Cone Penetrometer in Icy Layered Lunar Regolith Simulant. B. D. Wiegand[1], M. C. Guadagno[2], and P. J. van Susante[3]. [1,2,3]Dept. of Mechanical Engineering-Engineering Mechanics, Michigan Technological University 1800 Townsend Drive, Houghton, MI 49931 (contact: pjvansus@mtu.edu).

Introduction: Current cone penetrometer devices for terrestrial use rely on a decades old database of bearing capacity correlations to determine in-situ properties [1]. Penetrometers for immediate lunar applications will not have access to such a database, thus an ideal solution would be able to determine geotechnical properties directly. To achieve this, the geotechnical team at the Planetary Surface Technology Development Lab (PSTDL) has developed a new iteration of the Instrumented Percussive Cone Penetrometer (IPCP) that will measure additional parameters that can then be used to deduce geotechnical properties of the observed regolith in-situ.

Methods: A percussive action was chosen for the penetrometer due to the energy saving benefits and the greatly reduced downforces observed by a system on the lunar surface [2]. The current IPCP prototype includes a custom made shockproof force transducer mounted at the top of the penetrometer rod, and another force transducer inside of the cone tip at the bottom of the rod. The top transducer allows for the measurement of the total force necessary for penetration, while the bottom transducer enables the measurement of the normal force observed on the cone. An addition of a displacement transducer allows for the measurement of penetration depth and rate. The cone tip geometry is similar to the ASTM D6951 standard, but does not immediately taper behind the head to fit sensors for other experiments [3] [4]. Transducer voltages are acquired via a National Instruments DAQ hardware and software with sampling rates between 51.2 kHz and 3MHz.

The I-PCP sensor suite was field tested to validate functionality in a setting more realistic than a lab environment . A modified version of the z-stage used for the Regolith and Ice Drill for Exploration of New Terrains (TRIDENT) drilling system from Honeybee robotics was used as the motion stage for the I-PCP instrument suite. TRIDENT uses a percussive hammer drilling system interfacing with a vertical motion stage to percussively drill into the terrain below [5]. The system was retrofitted to only percuss for penetrometer testing. Additional DAQs were added to accommodate the thermal profiling aspect of the LuSTR 2020 project associated with identifying volatiles and volatile quantities [6]. The modified TRIDENT drill stage was mounted to the PSTDL's field rover, known as the Heavy Onboard Platform for Lunar ISRU and Terrain Excavation (HOPLITE), for field testing (Figure 1).

Figure 1: Modified TRIDENT z-stage integrated with HOPLITE rover chassis.

The geotechnical properties of friction angle and cohesion are found from IPCP tests by understanding the failure induced on the regolith by the penetrometer cone, observing the shear and normal forces involved, then calculating results using empirically found correlations. Learning how the regolith is failed by the penetrometer cone is crucial for inferring how the data gathered can be interpreted. Observational tests have been conducted to understand the effect of penetrometers on particle displacement through layered mediums [7]. Normal stress is calculated by dividing the cone's force transducer readings by the interacting area. Shear force (and then stress) is calculated by finding the complementive vector between the cone normal force and penetration force. The estimated stresses can then be used with the Mohr-Coulumb failure criteria to determine external friction angle and adhesion [8]. Modified direct shear tests will be used to build a correlation to translate external friction angle and adhesion into internal friction angle and cohesion [9] [10].

Penetrometer tests are conducted in MTU-LHT-1A lunar regolith simulant with varying compaction densities between 1.3 g/cm^3 to 1.78 g/cm^3. To conduct icy regolith tests, shaved ice is mixed into regolith at percentages between 1% and 10% by weight. Test beds are prepared in a 1x1x1.25 m bin by adding regolith mixtures and compacting to a desired density with a vibratory compactor. Field testing will be done in a 1.5x1.25x6 m trench that will be prepared with layers of dry and icy lunar simulant at various concentrations and densities. The field testing was to be conducted in the winter of 2023, however due to unnaturally warm weather the testing has been postponed till the next winter.

Results: Testing with the IPCP has been conducted for dry and icy regolith in ambient and climate controlled testing facilities and an example of calculated friction angle is shown in Figure 2. Regolith samples were compacted to a bulk density of 1.5 g/cc. Figure 2 shows the internal peak friction angle results from four different tests with different regolith and granulated ice mixtures and a lowpass filter applied. Dry regolith exhibits a lower variance than other mixtures. It is hypothesized that this is due to the dry regolith having less layering effects than the icy mixtures. The 5% refrozen test was done in a mixture that started with granular ice, was thawed, and then frozen again. The friction angle for the 5% refrozen test consistently has a higher friction angle than that of the granular 5%. Cohesion was calculated for the dry test and was found to be 3116 Pa.

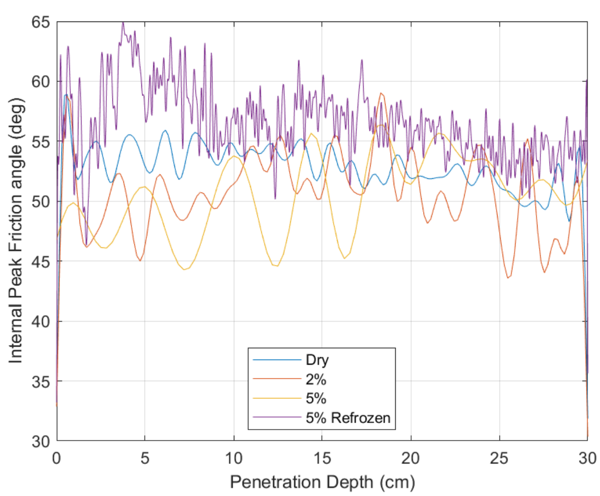

Figure 2: Peak friction angle as a function of depth, recorded for various tests

Discussion: Presented here are preliminary results and further testing and evidence is needed. From external triaxial testing, dry MTU-LHT-1A was found to have a friction angle of 53 degrees and cohesion of 1640 Pa at 1.5 g/cc. From this information, it can be concluded that initial findings for friction angle are promising, and the cohesion values are roughly double.

Conclusion: An IPCP has been manufactured and tested and is capable of determining geotechnical properties in-situ. Initial results show the estimation of internal friction angle is similar to expected values and cohesion is larger by a factor of two. The PSTDL now has access to a Geocomp ShearTrac-2 direct shear test machine that it plans to use to verify IPCP data. Additional plans include the manufacturing of a vacuum rated cryo-cooled direct shear test machine for testing icy and dry regolith samples in MTU's dusty thermal vacuum chamber.

Acknowledgements

This research was supported by NASA's LuSTR 2020 research grant funding 80NSSC21K0769

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