DYNAMIC CONE PENETRATION TEST IN VACUUM. K. Šļumba[1,*], K. Farries[1], J. L. Ayre[1], A. A. Wang[1], H. Wang[1], B. T. Scott[1], and M. B. Jaksa[1]. [1]Adelaide University, Andy Thomas Centre for Space Resources, SA 5000, Australia, [*]karlis.slumba@adelaide.edu.au

Introduction: Many more steps need to be taken before a permanent human presence can be established on the Moon. Major challenges include, but are not limited to, lunar resource utilisation and lunar construction. Although there is a wealth of knowledge about the lunar environment in general, it can safely be assumed that each site is unique. Therefore, each site needs to be investigated before any construction or resource utilisation tasks can be performed. Static cone penetrometers are very useful, but the main disadvantage is the reactive force. A heavy weight needs to be loaded on the probe to push it into the ground. Therefore, other solutions for penetration are being researched, for example, pneumatic probes [1,2] and vibrating probes [3,4].

In previous research, a miniaturised dynamic cone penetrometer (Mini-DCP) was tested in a regolith simulant in a laboratory environment [5]. The Mini-DCP results in different densities were correlated with the standard cone penetrometer and nuclear density gauge, with testing in vacuum being a logical next step.

Methods: Dynamic cone penetration tests were performed both in a laboratory environment and in a vacuum.

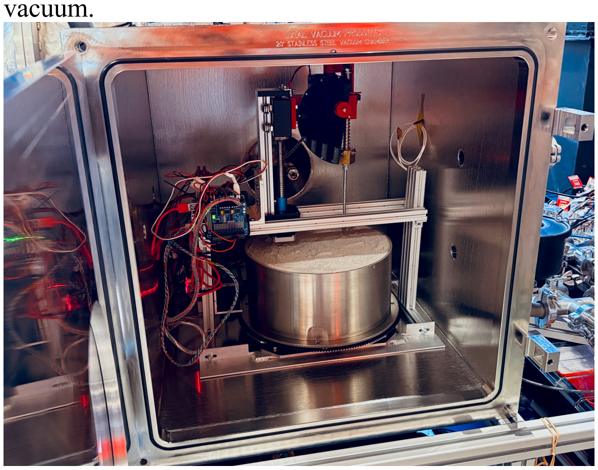

Figure 1. Vac-DCP inside regolith vacuum chamber.

A vacuum-compatible dynamic cone penetrometer (Vac-DCP) was manufactured in-house at Adelaide University. The Vac-DCP was created to suit the size of the 500 x 500 x 500 mm regolith thermal vacuum chamber (RTVac) (Figure 1). The Vac-DCP hammering mechanism works by rotating a cam that lifts a hammer and compresses a spring. When released, the hammer is accelerated by the spring and impacts an anvil, which transfers momentum to a cone, causing it to penetrate into the regolith. The cycle is then repeated. The cone depth is recorded after each strike.

The sampling container was created from stainless steel; 266 mm in diameter and 125 mm depth. The container size was selected to fit in the RTVac. Tests were initiated when the cone tip was at 20 mm depth and ceased when the cone tip was at 100 mm depth, still 25 mm from the container floor. The widest part of the cone, which is 12.7 mm in diameter (30° apex angle), was at the surface at the beginning of the test and at 80 mm depth at the end. Four tests were performed in a single sample to minimise boundary effects. No boundary effects were observed from the sides, from the bottom of the container, or from previous tests. Preliminary testing was performed in a smaller container, where boundary effects were obvious.

All tests were performed in lunar highlands regolith simulant LHS-1 [6]. LHS-1 is known to accumulate very little atmospheric water (especially in dry climates); nevertheless, it was oven-dried at 200°C for at least 16 hours before most of the tests. For the few tests where it was not freshly oven-dried, the measured water content was approximately 0.1%. No difference in results was observed between the freshly dried LHS-1 and LHS-1 with 0.1% water content.

To ensure sample homogeneity, samples were prepared following a strict compaction procedure, whereby samples were prepared in five 25 mm thick layers. Each layer was compacted using a hammer adapted from the Proctor test. The density of each sample was measured from the volume and mass.

Due to the large size of the regolith container, vacuum pumping was slow. The vacuum level achieved in the tests was between 2.6e-5 and 3.0e-4 mbar. When a new sample was prepared, the vacuum was pumped for at least 20 hours, the tests were performed on the next day, and then the next sample was prepared.

Results: In total, 12 samples were prepared for vacuum testing at various densities ranging between 1674 and 1893 kg/m^3 (relative densities between 45 and 82%). 41 successful Vac-DCP penetration tests were performed. 18 samples were prepared for atmospheric testing at densities between 1674 and 1888 kg/m^3 (relative densities between 45 and 81%). 63 successful Vac-DCP penetration tests were performed in atmosphere.

Cumulative hammer strikes with penetrated depth were recorded. Figure 2 shows that 6 hammer strikes were necessary to penetrate 80 mm of LHS-1 at 1686 kg/m^3 density, but approximately 30 hammer strikes were necessary to penetrate the same depth into the simulant with a density of 1867 kg/m^3.

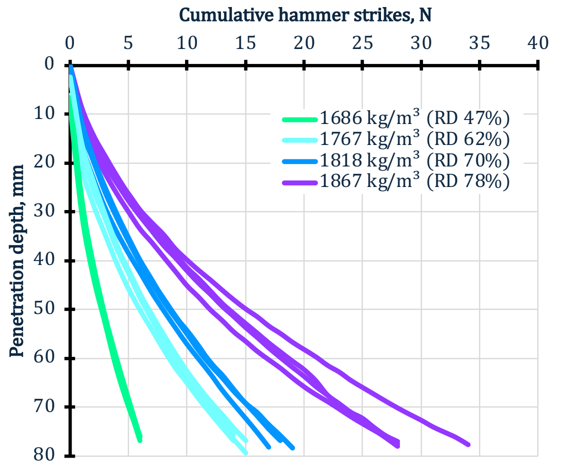

Figure 2. Cumulative hammer strikes with depth in atmosphere. The plot shows four tests at each density; some results are obscured where each test gave indistinguishable results.

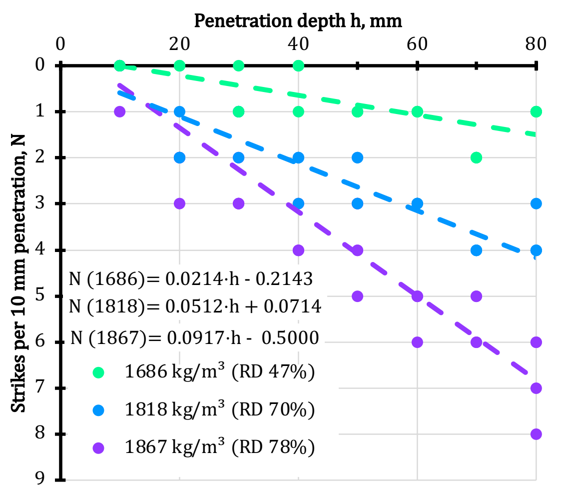

Figure 3. Hammer strikes per 10 mm with depth in atmosphere.

Hammer strikes per 10 mm of penetration are plotted against penetration depth in Figure 3. This plot shows that the number of hammer strikes required to penetrate 10 mm of regolith increases with depth.

The gradient of this increase is called DCP gradient (G) [5]. The DCP gradient can be directly correlated to other parameters, like penetration resistance and density [5]. It is advantageous to use a DCP gradient because then it is not necessary to prepare multiple identical samples, but samples at a range of densities; however, it is crucial to know the density accurately. If all other variables are held constant, then the DCP gradient increases exponentially with density increase. This relationship is shown for vacuum and atmospheric tests in Figure 4. The DCP gradient is higher for tests in vacuum, especially at higher densities.

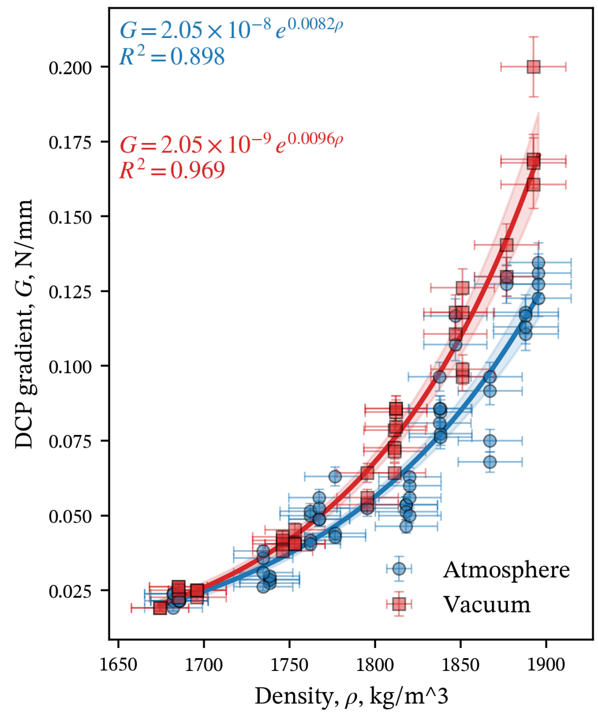

Figure 4. DCP gradient and density.

Discussion and Conclusions: The removal of air from the regolith introduces a number of changes; for example, the capillary forces from liquids and gasses are removed, and volatile molecules are desorbed. The effects of these changes on dynamic cone penetration are difficult to predict. An additional concern is the pump-down speed and its effect on the sample. In this research, care was taken to oven-dry the sample and draw a vacuum slowly to avoid sample disturbance [7]. No visual sample disturbance was observed.

Other research suggests that cone penetration, percussive penetration [8], and vibrating penetration [4] slightly decrease the penetration force in a vacuum. However, this research shows that the DCP gradient in the vacuum is higher, especially at the higher densities. Although there is noise in the results, it was generally **more difficult to penetrate into the regolith with a DCP in vacuum** as compared to in atmosphere. To validate this further, static cone penetration and vane shear tests are being performed using the same setup.

References: [1] Zacny, K. et al. (2025). Planet. Sci. J., 6, 297 [2] Nagihara, S. et al. (2025). Planet. Sci. J., 6, 232 [3] Rezich, E. et al. (2025). Acta Astronaut., 236, 1272–1286 [4] Rezich, E.T. (2025). PhD Thesis Colorado School of Mines [5] Šļumba, K. et al. (2026). Acta Astronaut., 243, 172–188 [6] Long-Fox, J.M. et al. (2023). Adv. Space Res., 71, 5400–5412 [7] Go, G.-H. et al. (2021). Sci. Rep., 11, 1878 [8] Green, A. et al. (2014). J. Terramechanics, 51, 43–52