Dynamic Cone Penetration Test in Vacuum

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Enabling long-term human presence in deep space

Outline

- Introduction
- Previous work
- Methods
- Results
- Analysis
- Discussion
- Summary and Conclusions
- Future work

Introduction

- Context
  - Geotechnical investigation ➢ Ground improvement ➢ Construction
  - Infrastructure
    - Landing and launch pads
    - Roads
    - Lunar base
  - Exploration and ISRU
- Potential geotechnical investigation methods on the Moon
  - Cone penetration
  - Vane shear
  - Plate load
  - Seismic
  - Ground penetrating radar
  - Boot imprints, trenches, boulder rolls, etc.

Introduction

- Context
  - Geotechnical investigation ➢ Ground improvement ➢ Construction
  - Infrastructure
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    - Lunar base
  - Space in-situ resource utilisation
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- Lunar environment
  - Regolith
  - Extreme temperatures
  - Radiation
  - Vacuum
  - Each location is unique
- Lunar analogue environment
  - Lunar regolith simulant
  - Homogeneous density
  - Earth’s gravity
  - Lower vacuum

Introduction – Cone penetration

- Purpose
  - Stratigraphy and soil identification
  - Geotechnical investigation – density, stress, strength, etc.
  - Quality control
- Cone penetration test (CPT) - static
- Dynamic cone penetration test (DCPT) – dynamic
- Significant difference - reaction force

Cone penetrometer Rimik CP300

Introduction – Cone penetration

- Purpose
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- Cone penetration test (CPT) - static
- Dynamic cone penetration test (DCPT) – dynamic
- Significant difference - reaction force
- Penetration resistance
  - Hammering energy and momentum
  - Cone shape and size
  - Relative density
  - Depth
  - Internal friction and cohesion
  - Boundary effects
- Penetration history in space
  - Apollo 1969-1972
  - Lunokhod 1969-1973
  - Philae lander on Rosetta 2014
  - HP3 (Mole) on InSight 2018-2022

Lunar Self-Recording Penetrometer test by Apollo 16 astronaut, NASA

Previous work

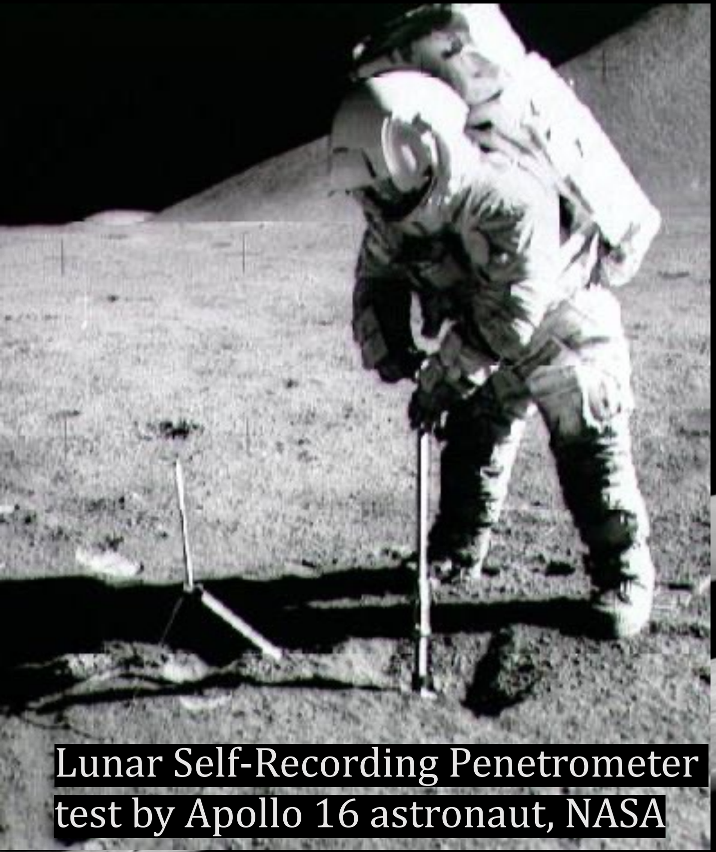
Filling regolith

- Extraterrestrial Environmental Simulation (EXTERRES) laboratory at the Adelaide University
- Regolith pit with 8 tonnes of engineering grade lunar highlands regolith simulant (LHS-1E)
- 1 m^3 regolith compaction chamber
- First large scale DCPT in regolith simulants

Compaction

Previous work cont.

- CPT and DCPT
- **12.7, 20.0,** 27.5, 37.0 mm cone diameters
- Variable hammering energy



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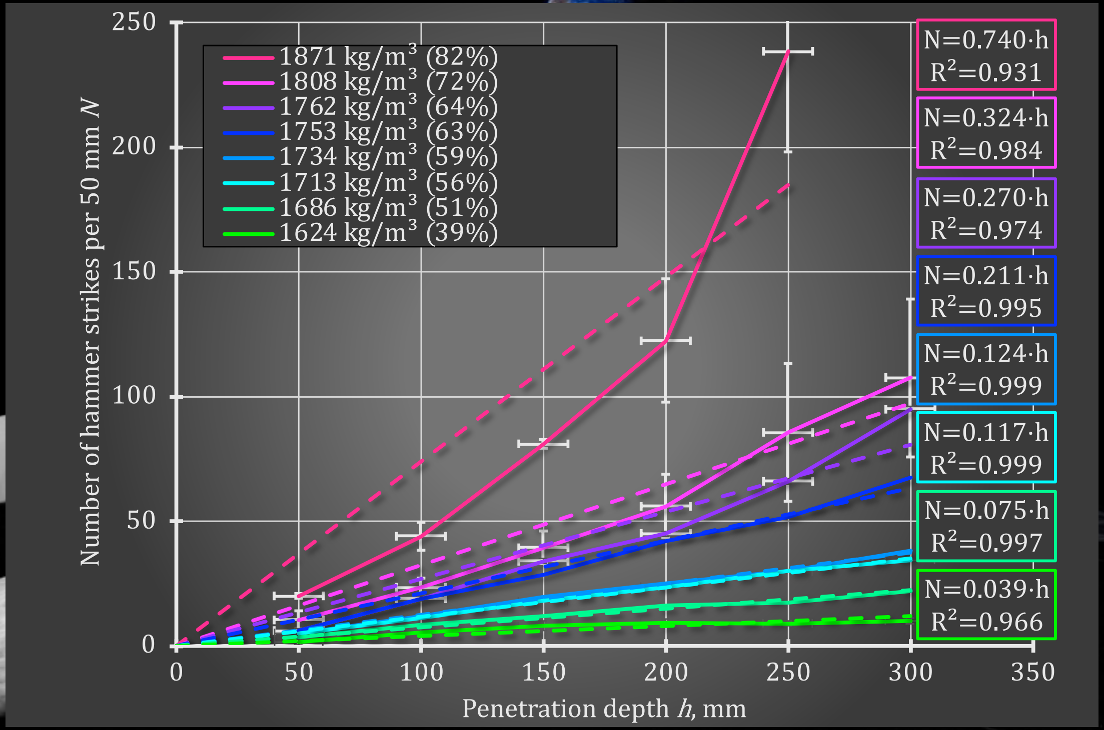
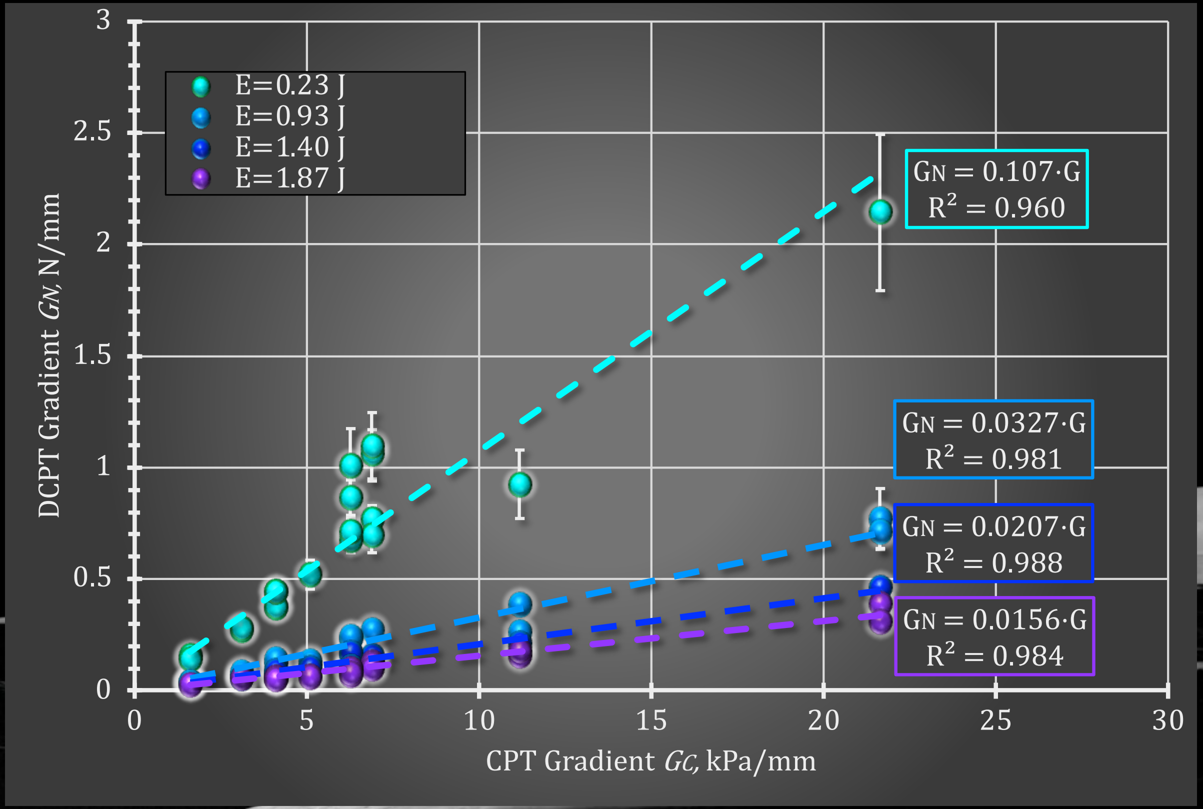


Mini-DCP hammer strikes per 50 mm versus depth

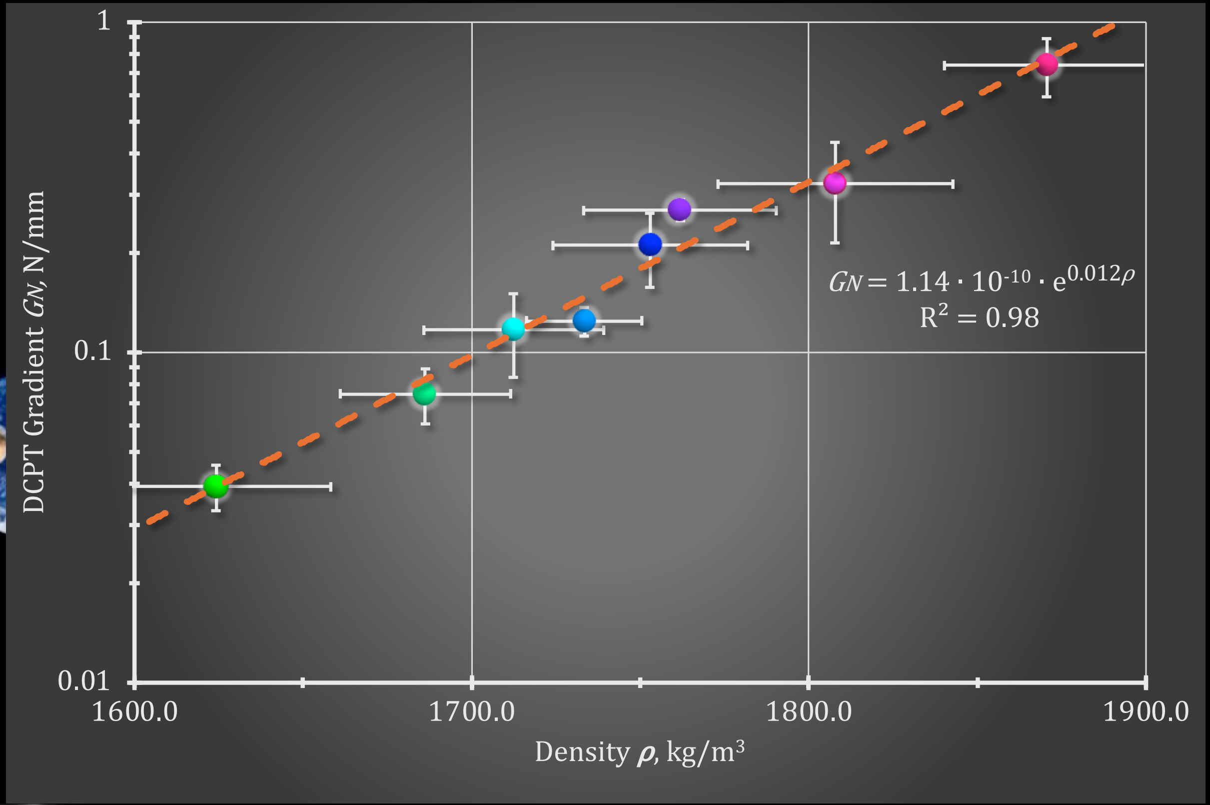
Mini dynamic cone penetrometer (Mini-DCP)

Previous results

- CPT and DCPT **correlated**
- LHS-1E at 1600 – 1900 kg/m^3 densities



DCPT and CPT correlated at constant density and cone



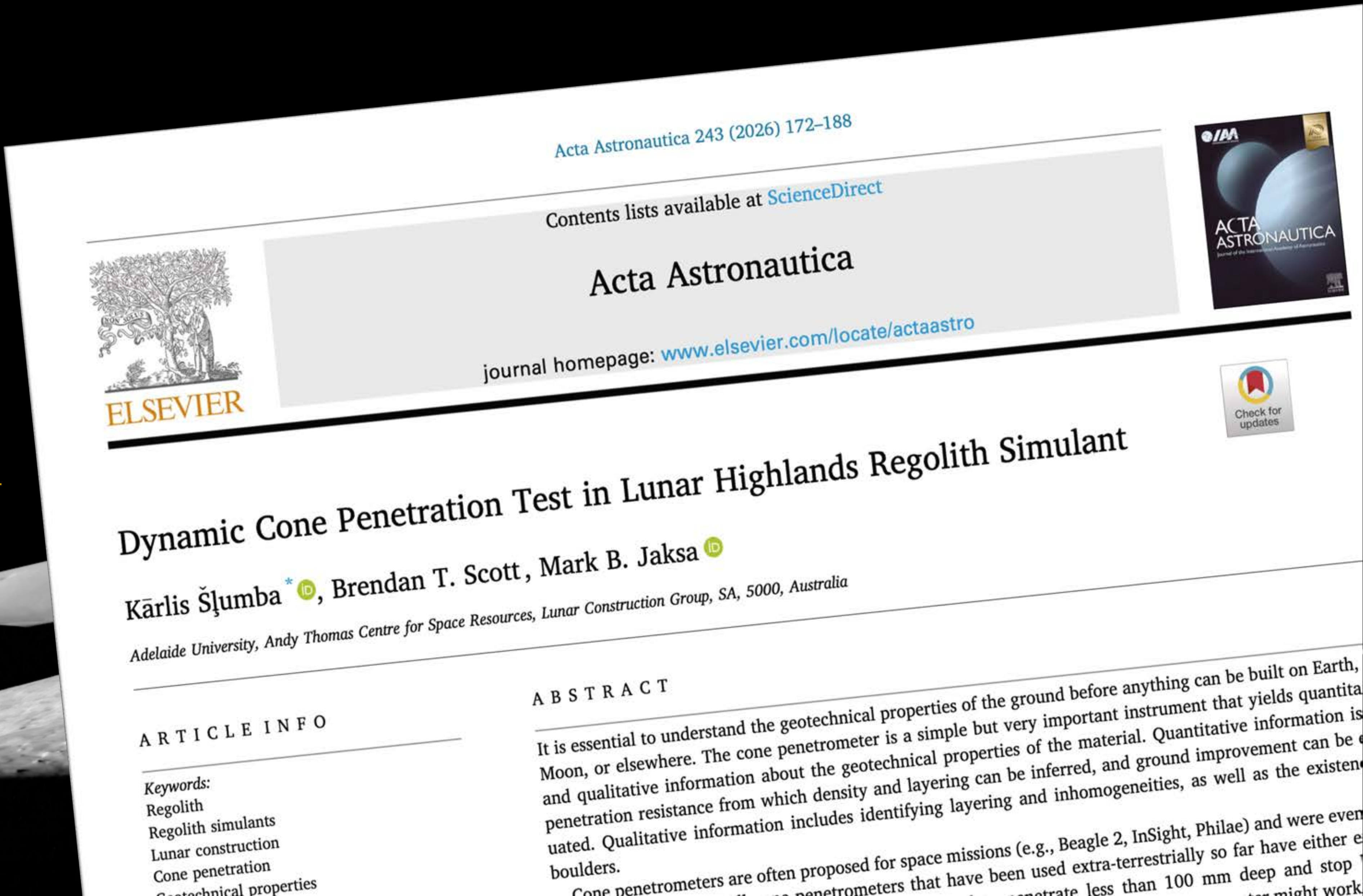
DCPT Gradient and density at constant energy and cone

- Found optimal hammering energies
- DCP might be better for lunar exploration

Previous results published

Adelaide University

Acta Astronautica paper DOI: 10.1016/j.actaastro.2026.01.055


Acta Astronautica 243 (2026) 172–188

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

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Dynamic Cone Penetration Test in Lunar Highlands Regolith Simulant

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A R T I C L E I N F O

Keywords:
Regolith
Regolith simulants
Lunar construction
Cone penetration

A B S T R A C T

It is essential to understand the geotechnical properties of the ground before anything can be built on Earth, Moon, or elsewhere. The cone penetrometer is a simple but very important instrument that yields quantita and qualitative information about the geotechnical properties of the material. Quantitative information is penetration resistance from which density and layering can be inferred, and ground improvement can be e uated. Qualitative information includes identifying layering and inhomogeneities, as well as the existen boulders.

Cone penetrometers are often proposed for space missions (e.g., Beagle 2, InSight, Philae) and were even

4/June/2026

Methods - DCP

- Standard dynamic cone penetrometer
    - Total mass ~20 kg
    - Non-adjustable
- Mini dynamic cone penetrometer (Mini-DCP)
    - Total mass ~3.5 kg
    - Highly adjustable
    - Manual
- Vacuum dynamic cone penetrometer (Vac-DCP)
    - Robotic

Evolution of dynamic cone penetration

Methods – Vac-DCP

- Manufactured in-house at Adelaide University
- Fits inside 500 x 500 x 500 mm regolith thermal vacuum chamber (RTVac)
- Hammering action
  - Rotating cam lifts the hammer and compresses the spring
  - Hammer is accelerated by the spring and hits the anvil
  - Momentum is transferred to the cone
  - Depth is recorded
- Hammering energy 0.3 J
- Cone diameter 12.7 mm and 30° apex

(Apollo cone)

Vac-DCP inside RTVac.

Methods – Sample

- Stainless steel container 266 mm diameter, 125 mm depth
- Oven-dried Lunar Highlands regolith simulant (LHS-1)
- Compaction in five 25 mm thick layers
- Penetrating until 100 mm depth
- Four tests per sample

Testing order

Stainless steel container with LHS-1

Plate compaction with Proctor hammer

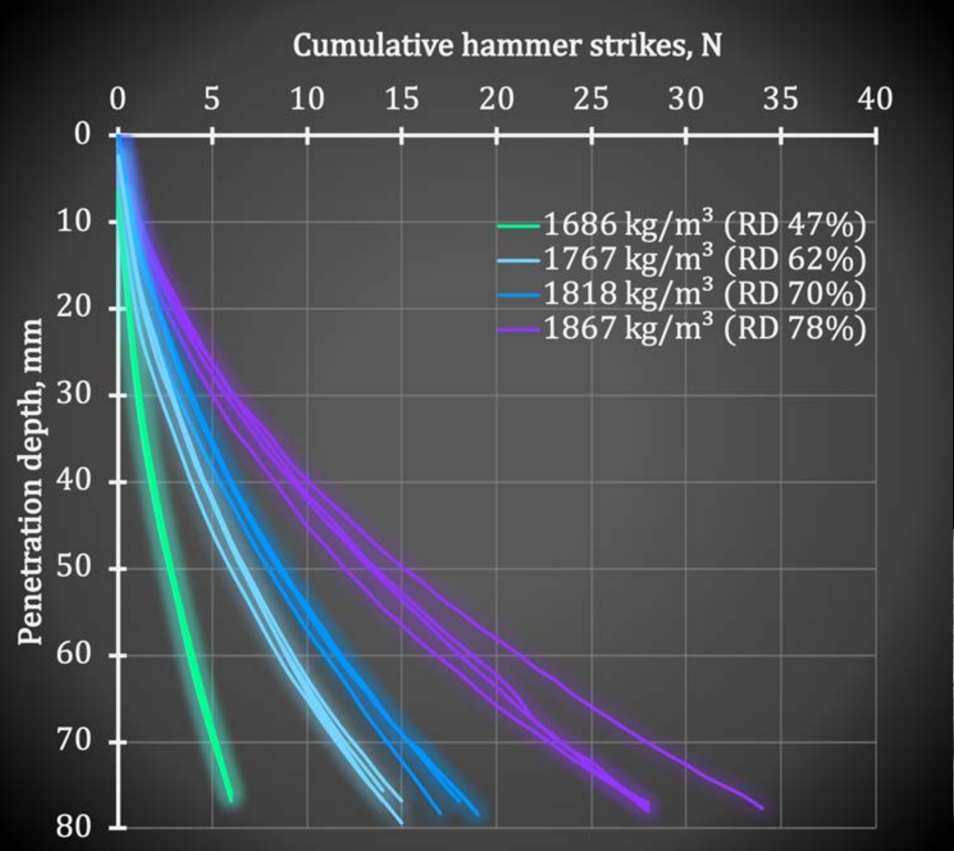
Methods – Vacuum

- High vacuum ($2.6 \cdot 10^{-5}$ to $3.0 \cdot 10^{-4}$ mBar)
- Slow – one test per day
- Avoiding outgassing
- Avoiding contamination
- Avoiding overheating
- No maintenance when under vacuum

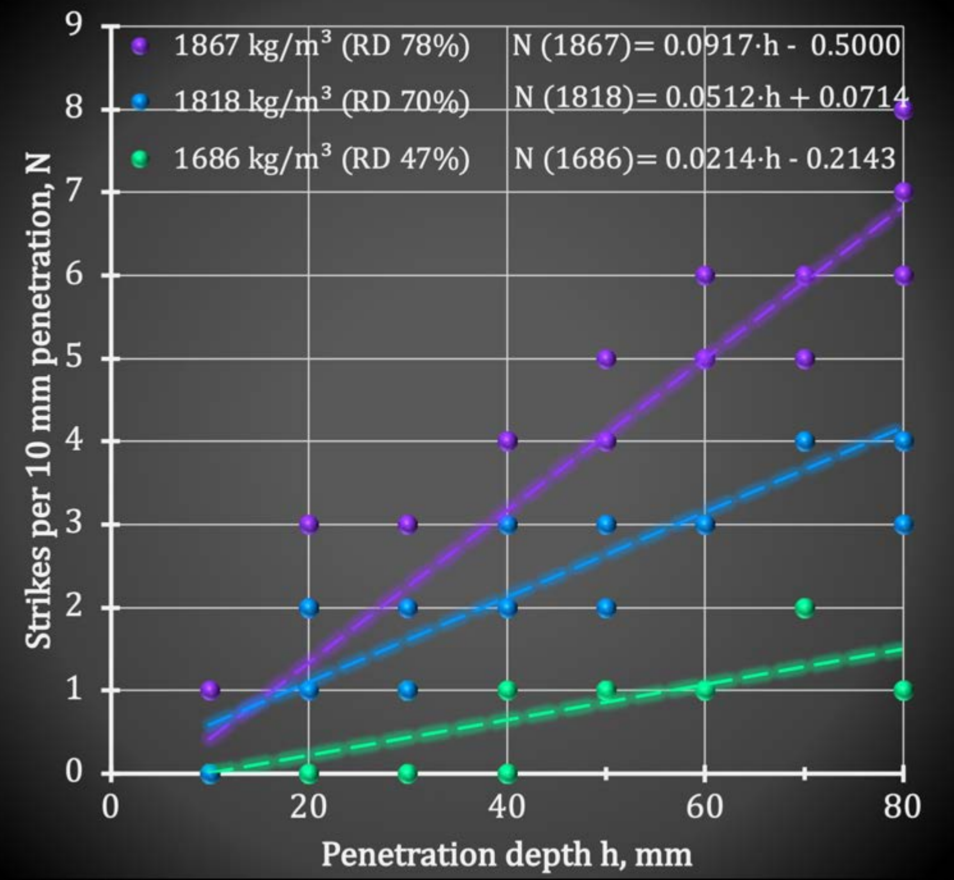
Vac-DCP inside RTVac.

Results

- 41 penetration in vacuum
- 63 penetrations in atmosphere
- Density range 1674 – 1893 kg/m³



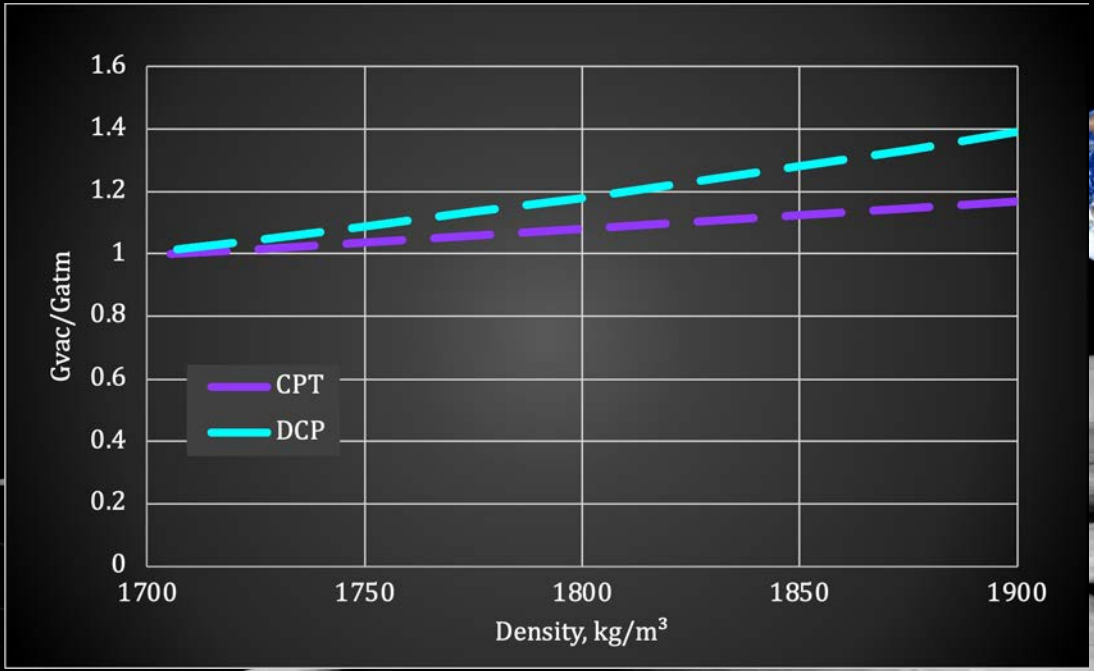
Cumulative hammer strikes



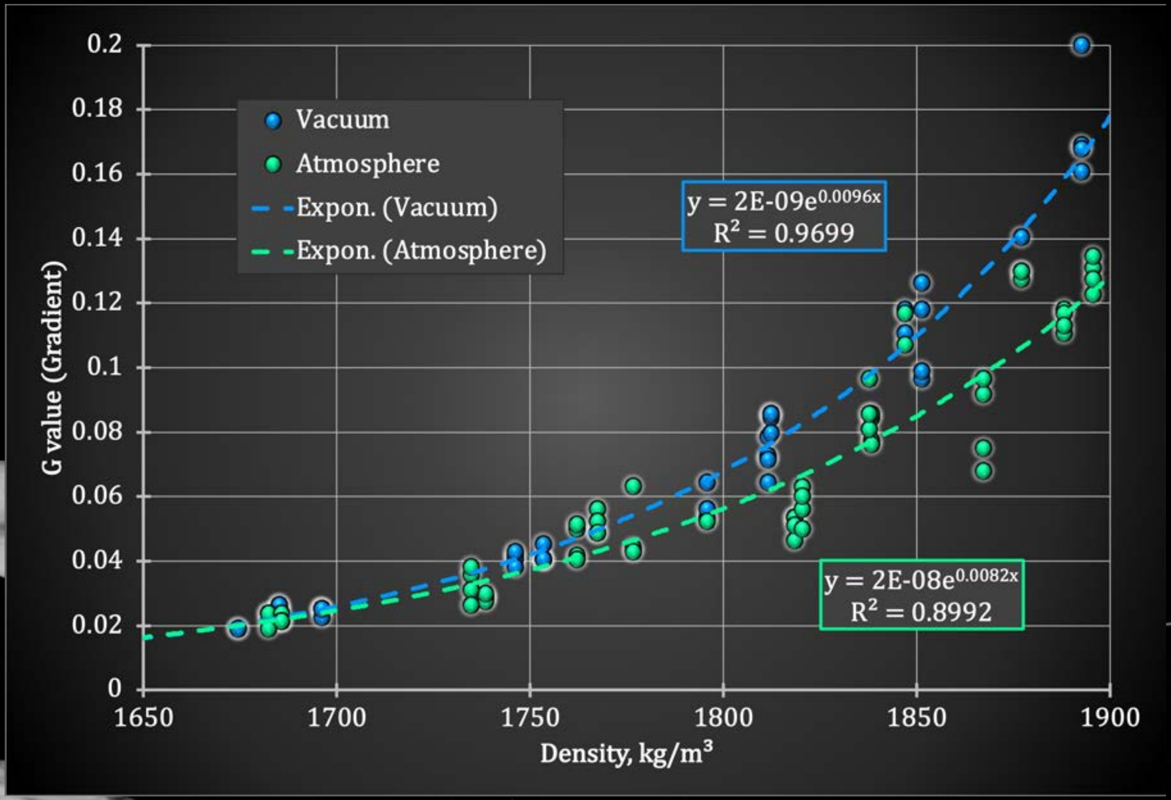
Hammer strikes per 10 mm penetration and gradient

Analysis

- DCP gradient exponential with density
- Gradient / penetration resistance is higher in vacuum
- Gradient / penetration resistance increases with density
- Ratio $= \frac{G_{vac}}{G_{atm}}$



G_{vac} / G_{atm} ratio



DCP gradient and density

Discussion

- Vacuum effects on dynamic penetration difficult to predict
    - Capillary forces removed
    - Volatiles desorb
    - Van der Waals forces
- Pump down speed effect on the sample
    - Slow pump down
    - No disturbance observed
- Other results suggest that percussive and vibrating penetration resistance decreases in vacuum (Green et al. 2014, Rezich et al. 2025)
- Boundary effects eliminated

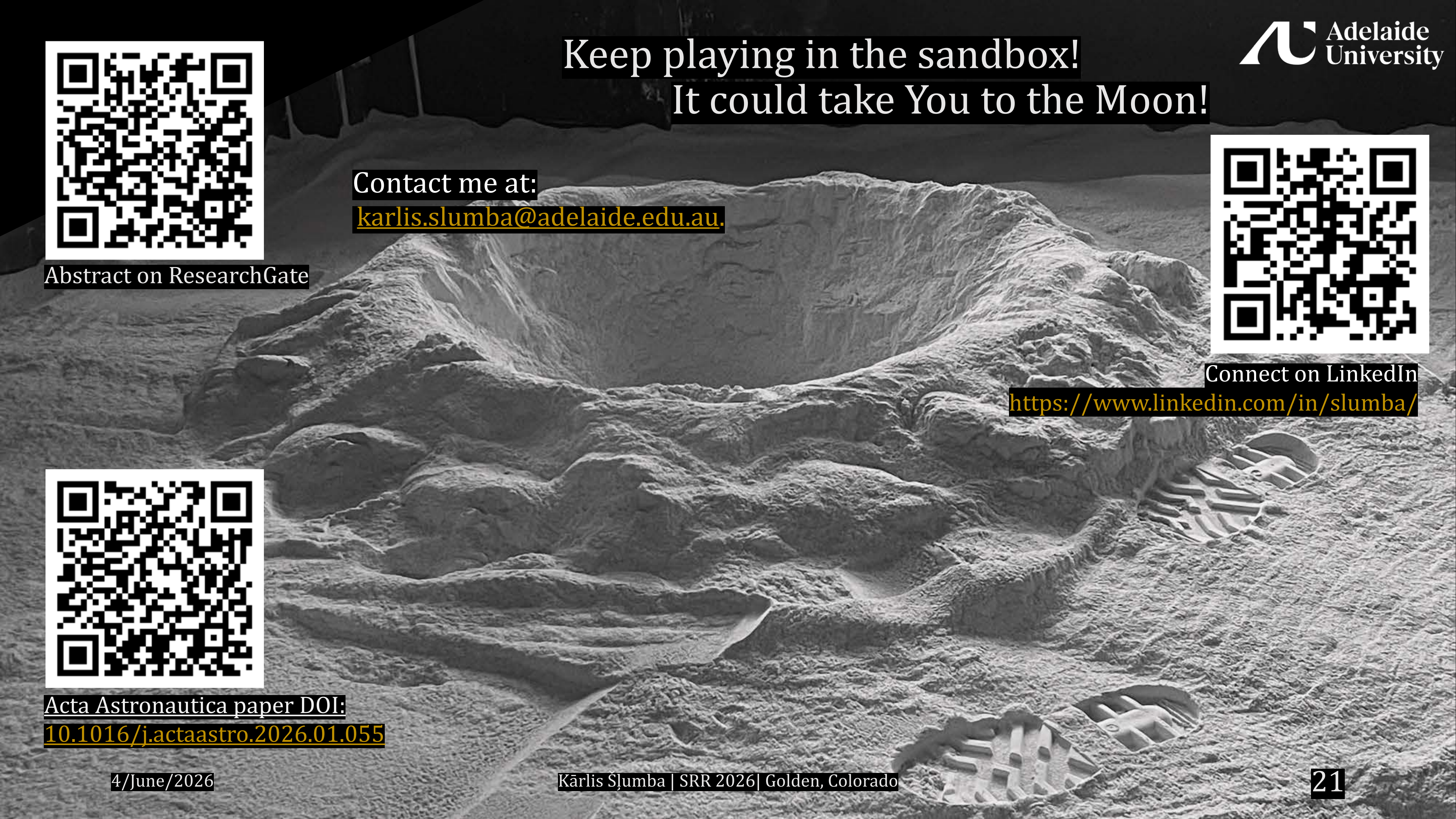
Summary and Conclusions

- First DCPT in vacuum
- TRL4 Vac-DCP, Vac-CPT, Vac-VST, Mini-DCP
- Dynamic cone penetration test results can be used to measure penetration resistance and density
- Dynamic cone penetrometer could be used and might be more applicable than static cone penetrometer for the geotechnical investigation in reduced gravity
- 300 N reaction force vs 30 hammer strikes to penetrate 100 mm deep in 1900 kg/m^3

Future work

- More vacuum
- More Vac-DCP tests
- Vac-CPT
- Vac-VST
- Correlations between Vac-CPT and Vac-DCP

Vac-CPT



Keep playing in the sandbox! It could take You to the Moon!

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Acta Astronautica paper DOI:
10.1016/j.actaastro.2026.01.055

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