Effect of Vacuum on Force Response of an Ultrasonic Penetrator

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Background

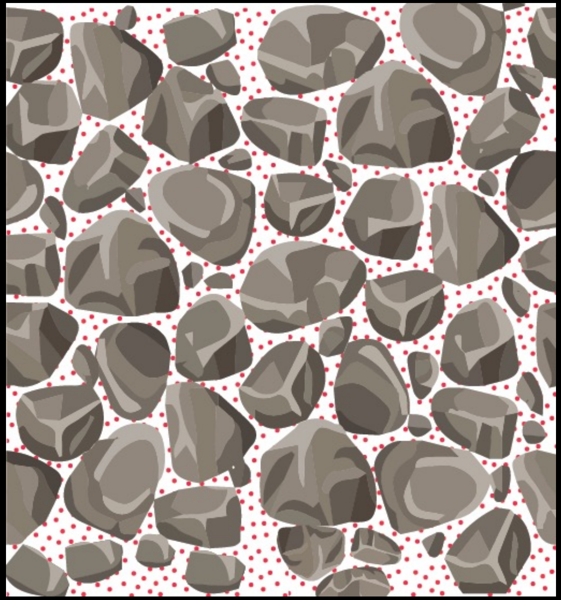
- Previous work has been conducted for simple ultrasonic penetrators in regolith simulants under ambient laboratory conditions and **exhibited significant penetration force reductions** (D. Firstbrook et al., 2017, 2018; D. G. Firstbrook et al., 2014, 2015; Rezich et al., 2021).
- The presence of ambient air is known to affect granular fluidization in that it can impact heaping effects (Pak et al., 1995).
- Multiphase fluidization is also impacted by the development of convective flow patterns (Pak et al., 1995; Valverde, 2015).

Will Vibrofluidization Force Reduction Work on the Moon?

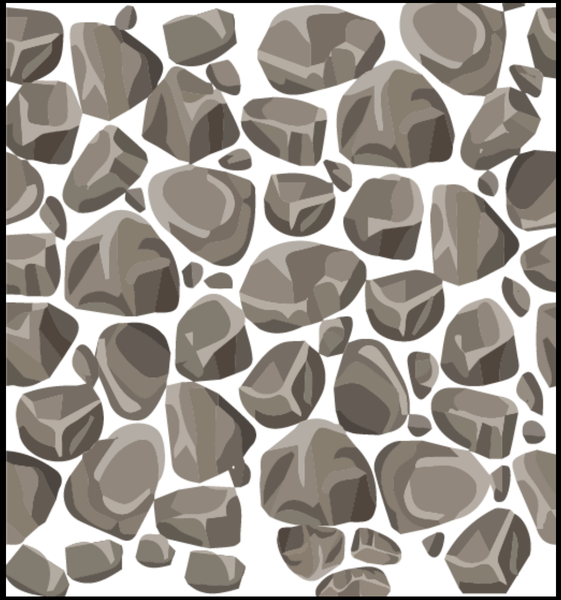
Does interstitial gas (air) within a granular medium (GRC-3 simulant) affect the force response of an ultrasonically vibrating penetrator?

- Does gas assist vibrofluidization via viscous momentum transfer thereby assisting force reduction?
- Does gas damp or dissipate energy transfer to the soil particles thereby reducing force reduction?

Ambient



Vacuum



CUBEvac Test Setup

Figure 1. The CUBEvac experiment setup.
1) Penetration actuation stack,
2) Primary chamber volume where most sensors interface, and
3) Auxiliary chamber volume where the soil bin is located.

Figure 2. Cylinder probe from Sonics and Materials measuring 1.27 cm (0.5 in) in diameter and 5.08 cm (2 in) from the tip to the beginning of the fillet curve.

CUBEvac Sensors and Interfaces

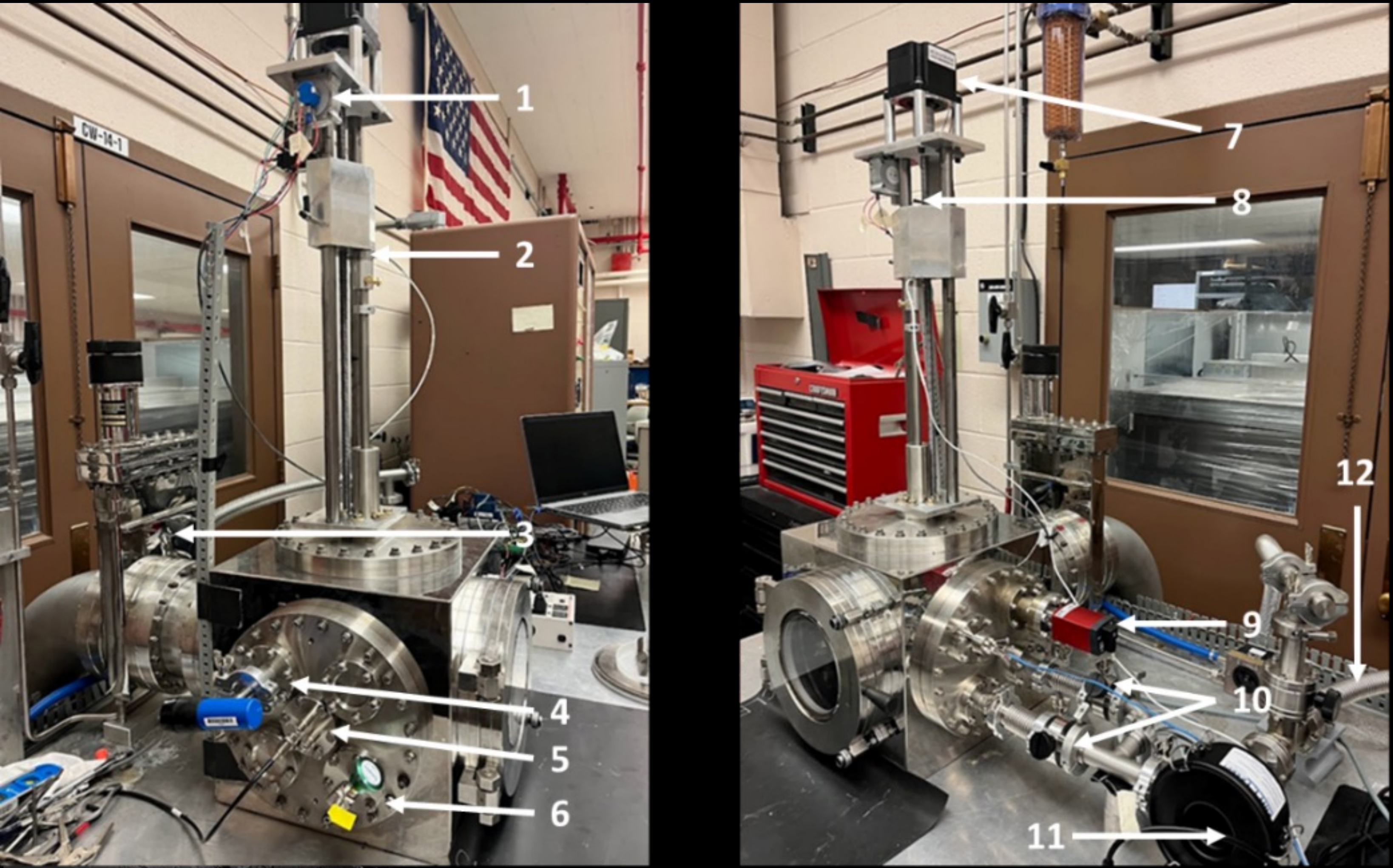


Figure 3. Detailed side views of the CUBEvac test setup.

1) String potentiometer,
2) in-line, uniaxial tension/compression load cell,
3) gate valve to diffusion pump,
4) Pirani pressure gauge,
5) SHV power connector to ultrasonic piezo transducer,
6) chamber vent valve,
7) stepper motor used to drive the actuation assembly,
8) actuation limit switch,
9) combination Pirani and cold cathode pressure gauge,
10) chamber roughing valves,
11) HEPA filter, and
12) line to dry scroll roughing pump.

CUBEvac Stack Cross Section

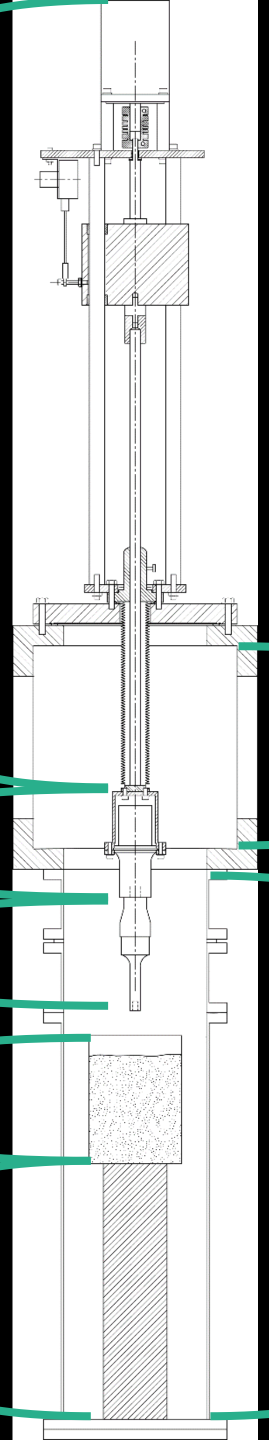


Figure 4. CUBEvac full test rig stack diagram.

Soil Preparation Methodology

1. Start with empty soil bin (steel pot internal diameter of approximately 15.56 cm (6.125 in) and a depth of 19.37 cm (7 5/8 in)
2. Add two scoops of GRC-3 simulant (approximately 0.5 kg) to the bin and tamp down flat. Repeat until soil is 2-3 cm from the top of the bin to allow for a surcharge to be placed on top.
3. Set up soil bin on a 60 Hz vibration table with 34kg surcharge (~ 4 psi) as shown in Figure 5.
4. Vibrate soil for 4 minutes
5. Move soil into chamber and pump down

GRC-3 has a theoretical maximum density of 1.939 g/cm3 (He et al., 2013), and the prepared simulant used in the trials had an estimated bulk density range of 1.895 – 1.934 g/cm3.

Figure 5. Soil preparation vibration table setup with a combined 34 kg of surcharge on the soil surface.

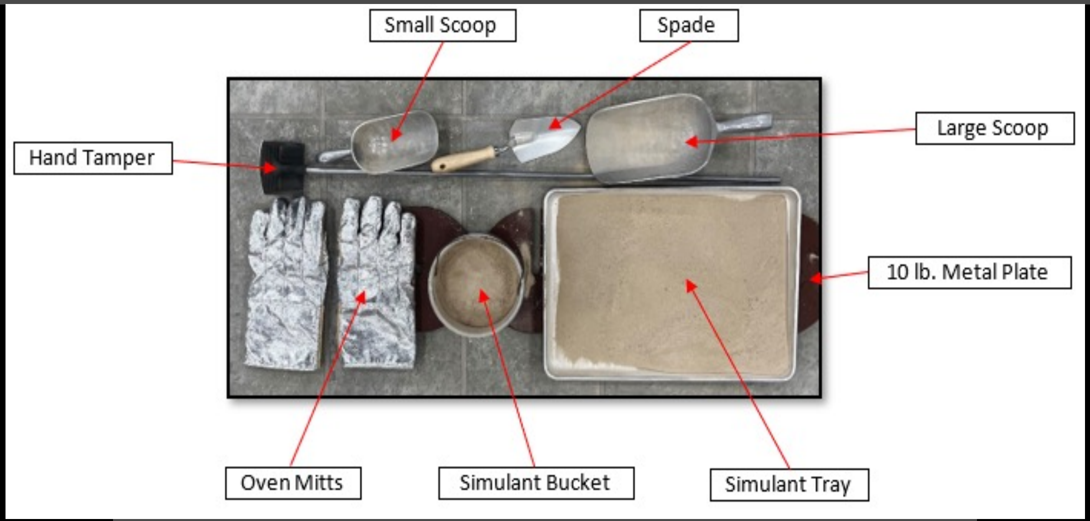


Figure 6. Soil preparation equipment.

Testing Cadence for Moisture Management

- Simulant was baked on sheets at 177 °C (350 °F) for ≥3 hours so moisture content was 0.2 - 0.4 wt%
- Soil prepared, installed, and pumped down in chamber for ~18 hours of high-vacuum pumping to achieve ~5x10^{-6} Torr
- Penetration test in vacuum performed
- Immediately after vacuum test complete, simulant was removed and re-prepared for ambient testing
- After ambient, separate fresh-baked simulant was removed from the oven and prepared for vacuum testing

Parameters for Cylindrical Probe Tests

Table 1. Test setup parameters for ambient and vacuum environment testing.

	Ambient Environment		Vacuum Environment	
	No Vibration Trials	Active Vibration Trials	No Vibration Trials	Active Vibration Trials
Penetration Speed	2 mm/s	2 mm/s	2 mm/s	2 mm/s
Penetration Depth	50 mm	50 mm	50 mm	50 mm
Vibration Frequency	0 kHz	20 kHz	0 kHz	20 kHz
Vibration Amplitude	0 µm	23 µm	0 µm	23 µm
Chamber Pressure	760 Torr	760 Torr	~5 x 10^{-6} Torr	~5 x 10^{-6} Torr

Cone Penetrometer Assessment

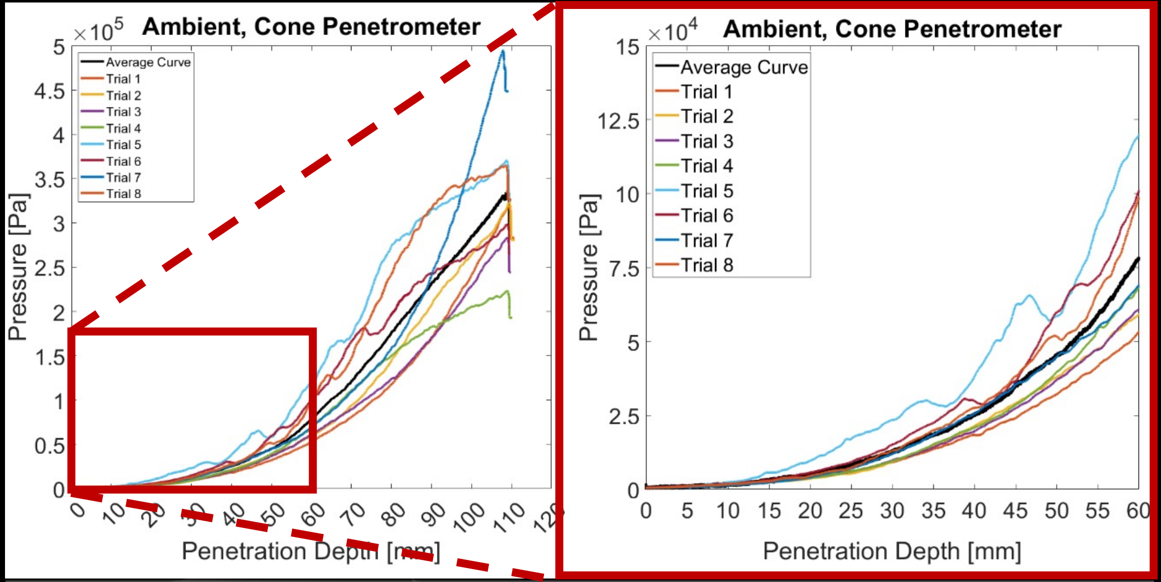


Figure 7. Ambient cone penetration results for full stroke (left) and testing depth only (right).

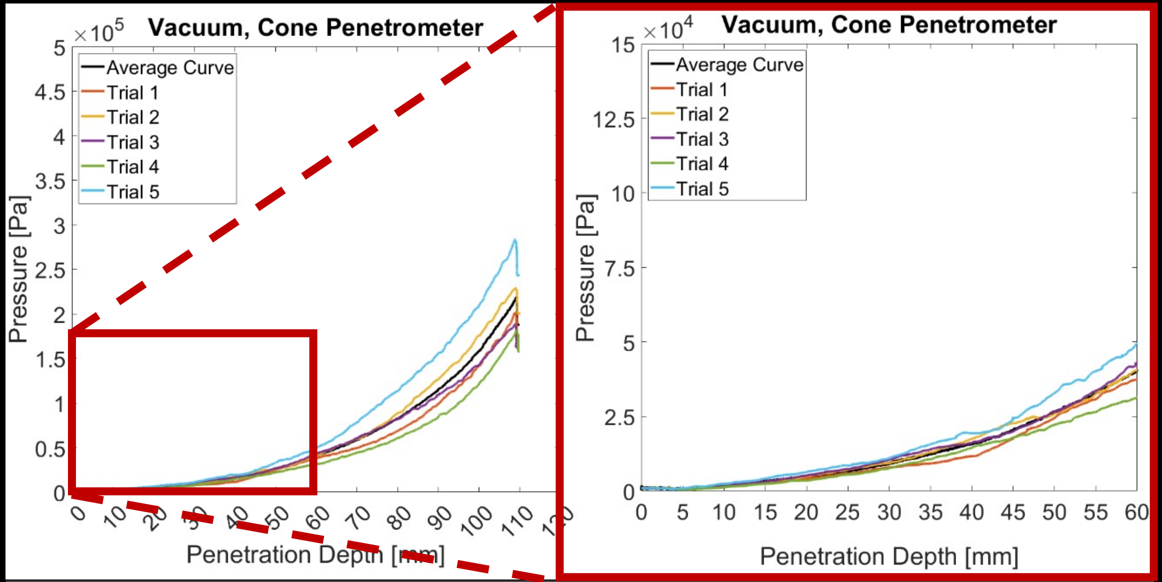


Figure 8. Vacuum cone penetration results for full stroke (left) and testing depth only (right).

NOTE: The cone had a nominal diameter of 12.7 mm (0.5 in) and a nominal height of 28.6 mm (1.125 in)

Ambient soil condition exhibits higher resistance than vacuum soil condition, even to the 50 mm test depth.

Ultrasonic Cylindrical Probe Results - Ambient

Observed advantages of active probe vibration:

- Mitigation of large initial contact force with soil surface
- Highly reduced force variation throughout penetration
- Decreased peak force
- Increased force curve repeatability at current sample size
- Consistently lower force throughout the penetration

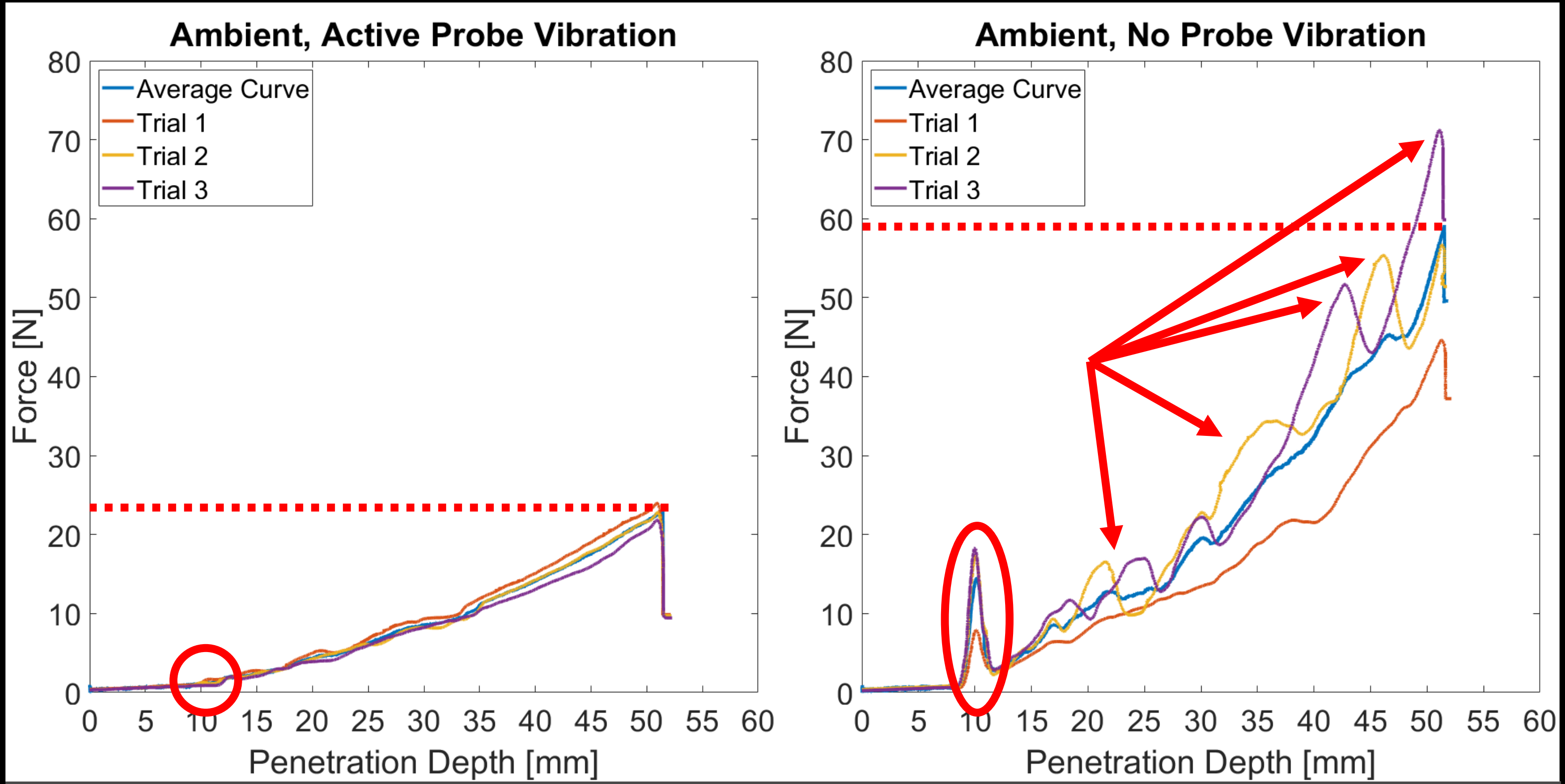


Figure 9. Ambient cylinder penetration trials with active vibration with a 23 µm amplitude (left) and ambient cylinder trials with no active vibration (right).

Ultrasonic Cylindrical Probe Results - Vacuum

Observed advantages of active probe vibration:

- Mitigation of large initial contact force with soil surface
  - NOTE: Soil surface slightly raised in vacuum tests (i.e. contact < 10 mm)
- Highly reduced force variation throughout penetration
- Decreased peak force
- Force curve repeatability not obviously affected at current sample size
- Consistently lower force throughout the penetration

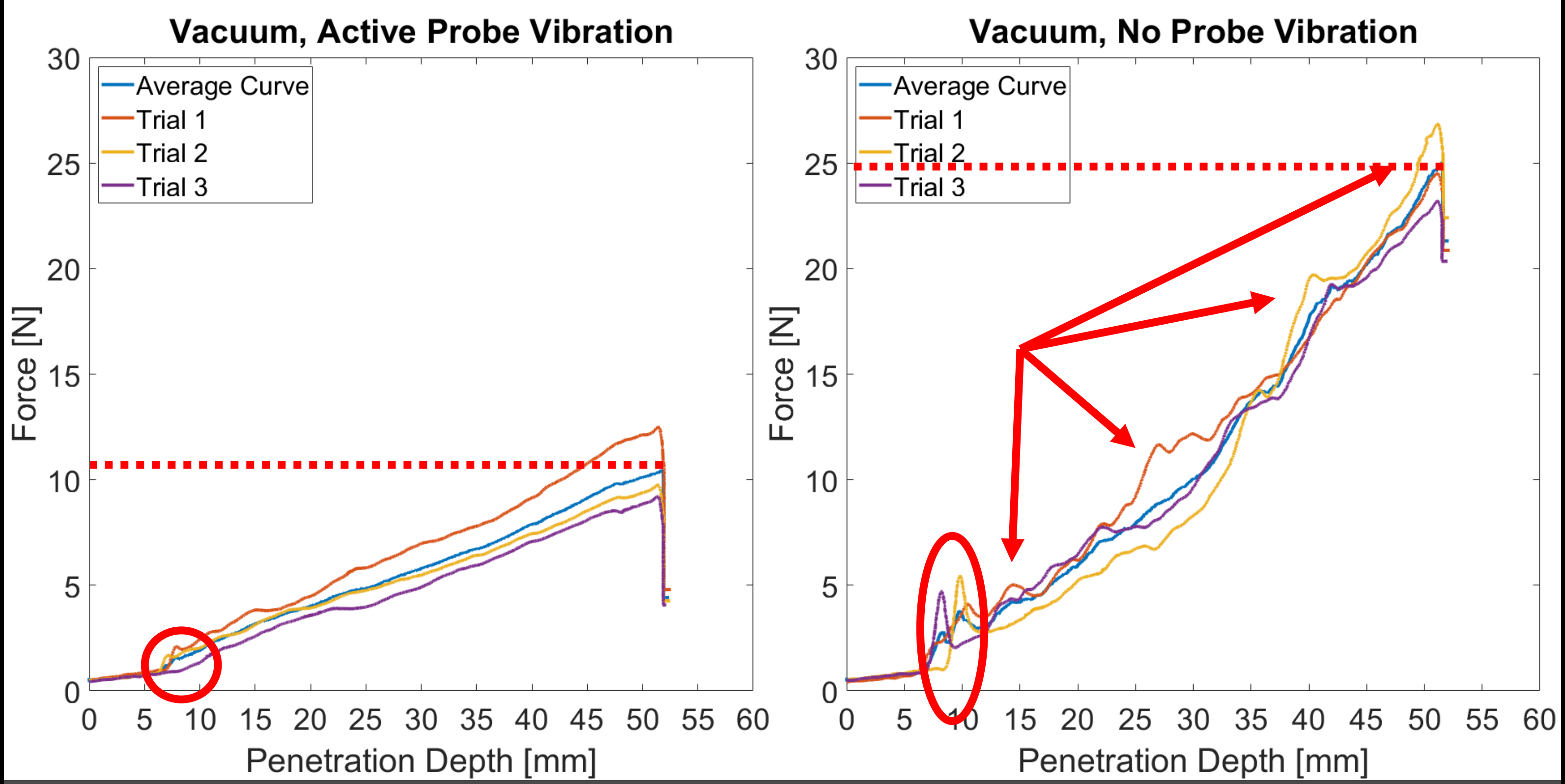


Figure 10. Vacuum cylinder penetration trials with active vibration with a 23 µm amplitude (left) and vacuum cylinder trials with no active vibration (right).

How Much Did the Force Change?

- Y-axis value = ~100%,
  implies the forces applied by the probe with and without active vibration are **equivalent**
- Y-axis value > 100%,
  force applied with active vibration was more than without active vibration
- Y-axis value < 100%,
  force applied with active vibration was less than without active vibration

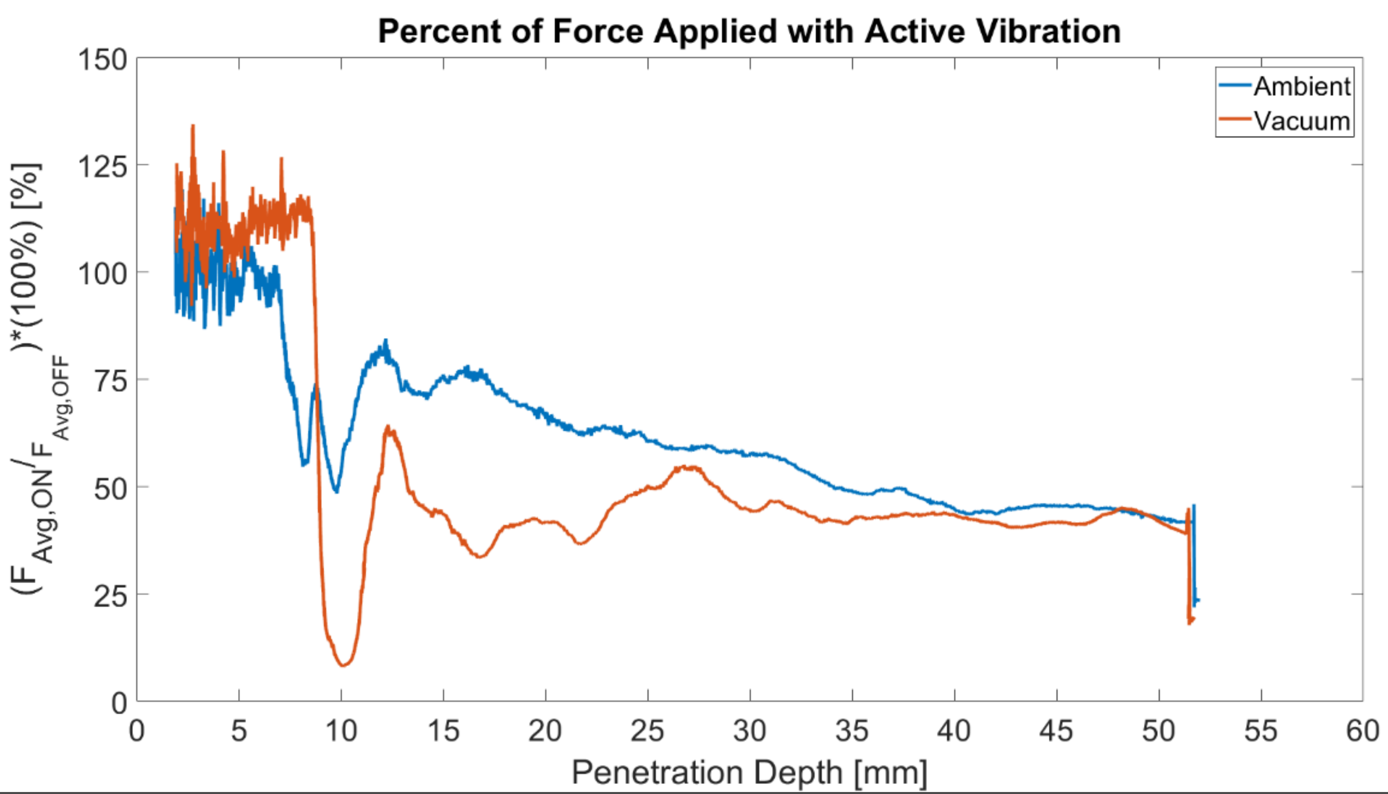


Figure 11. The ratio of penetration force with ultrasonic vibration to penetration force without active vibration in the cylinder probe averaged across repeated trials is shown as a percentage against average penetration depth.

Discussion and Conclusions

- In ambient tests, ultrasonic resonant vibration is an effective method of penetration force reduction including more monotonic force response
- In vacuum tests, ultrasonic resonant vibration is an effective method of penetration force reduction including more monotonic force response
- A direct comparison of ambient and vacuum tests is difficult with this dataset due to soil characterization changes in vacuum
  - Soil in-vacuo is inherently drier than the ambient tests. Soil moisture might be causing the measured difference in force response, which can be tested.
- Due to limited trials, it's difficult to confidently say that force reduction due to ultrasonic resonance is ***more effective*** in a vacuum environment as Figure 11 indicates.
- The data does show that the force reduction is ***at least as good*** in a vacuum environment as it is in ambient testing
  - This indicates that interstitial gas is not required for meaningful force reduction and Figure 11 supports the idea that it acts as an energy dissipation mechanism

Current Path Forward

- Conduct additional testing to better understand the role of interstitial gas in ultrasonic resonance induced vibrofluidization
  - Is force reduction with this method more efficient in vacuum?
- Collect and assess input power data to characterize energy trades between added power requirements and decreased force response
- Develop a theoretical basis to describe vibrofluidized soil motion to assess validity of interstitial gas acting as an energy dissipation mechanism.

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Questions?