Bio-inspired Penetration in the Regolith Subsurface Exploration Testbed

Presenter: Saeedeh Naziri Co-authors: Cyrena Ridgeway, Salvador Ibarra, Jose A. Castelo, Katherina Provenghi

Advisor: Douglas D. Cortes Institution: New Mexico State University

Background & Objectives

Developing the earthworm inspired penetrometer had a smooth transition from the first generation with pneumatic anchoring system to the second generation with the hydraulic system.

First generation

Second generation

In the last two generations of Gusano, the anchoring system design lacked the precision control needed to monitor the anchor deployment process in detail. In the current generation (3rd gen), the anchoring controlling system has been improved. 3D printed polymer components were replaced by machined stainless steel, and the probe has been deployed in Lunar regolith simulant using the Regolith Subsurface Exploration Testbed at NMSU.

Regolith Subsurface Exploration Testbed (R-SET)

Load cell & bio-inspired probe

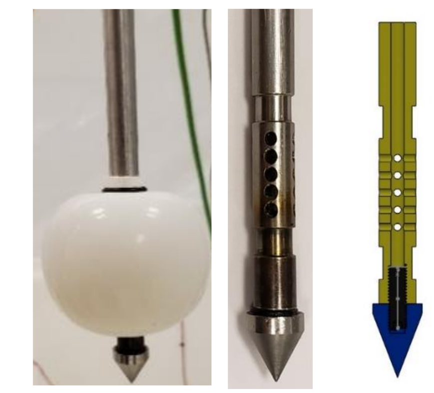
- Stainless steel machined probe
- Silicon rubber membrane
- TEST RESOURCE load cell

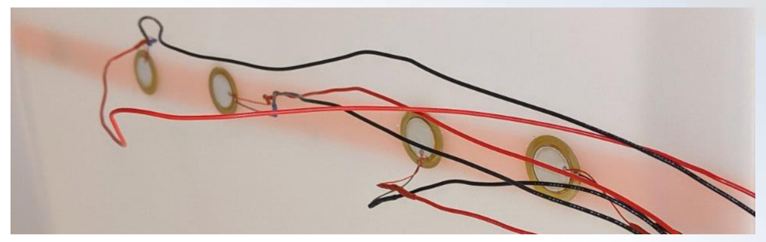
Testbed

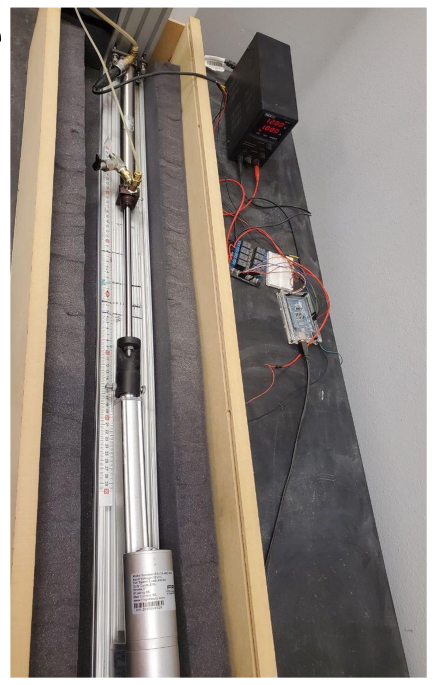
- Acoustic Emission sensors and Interface
- Lunar regolith (LMS-1 Mare Simulant)
- 130L rectangular chamber

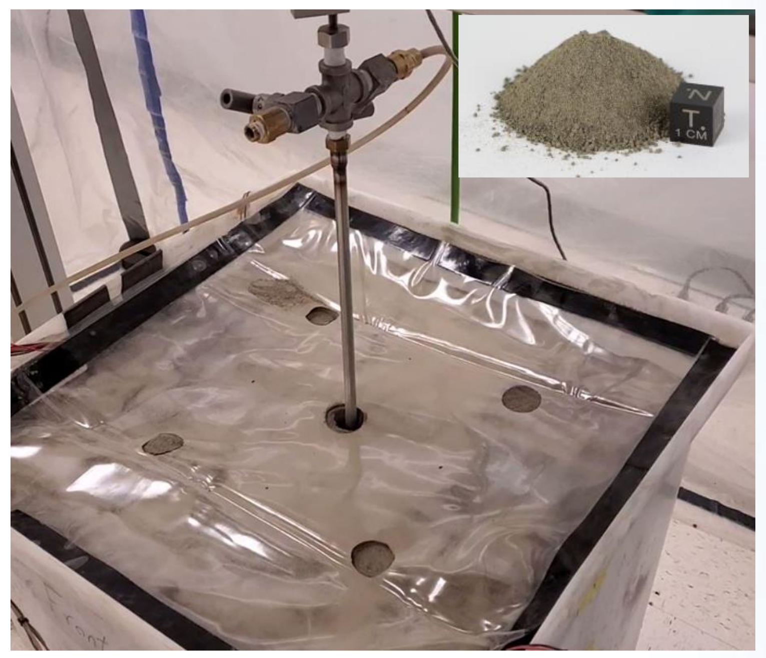
Hydraulic system

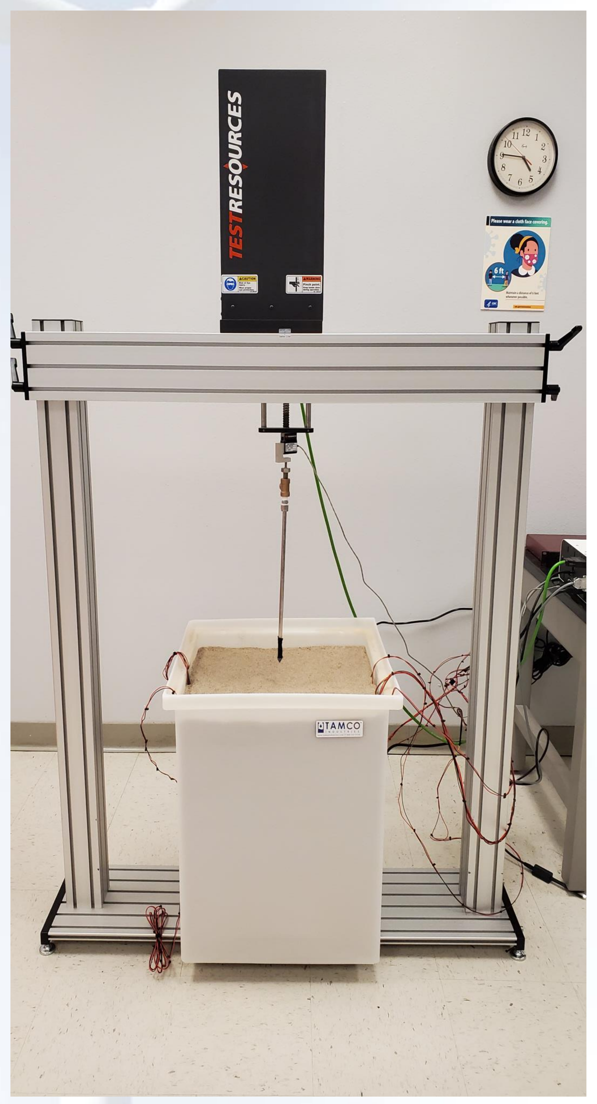
- Linear actuator
- Hydraulic cylinder
- Pressure transducer
- Micro-controller (Arduino)



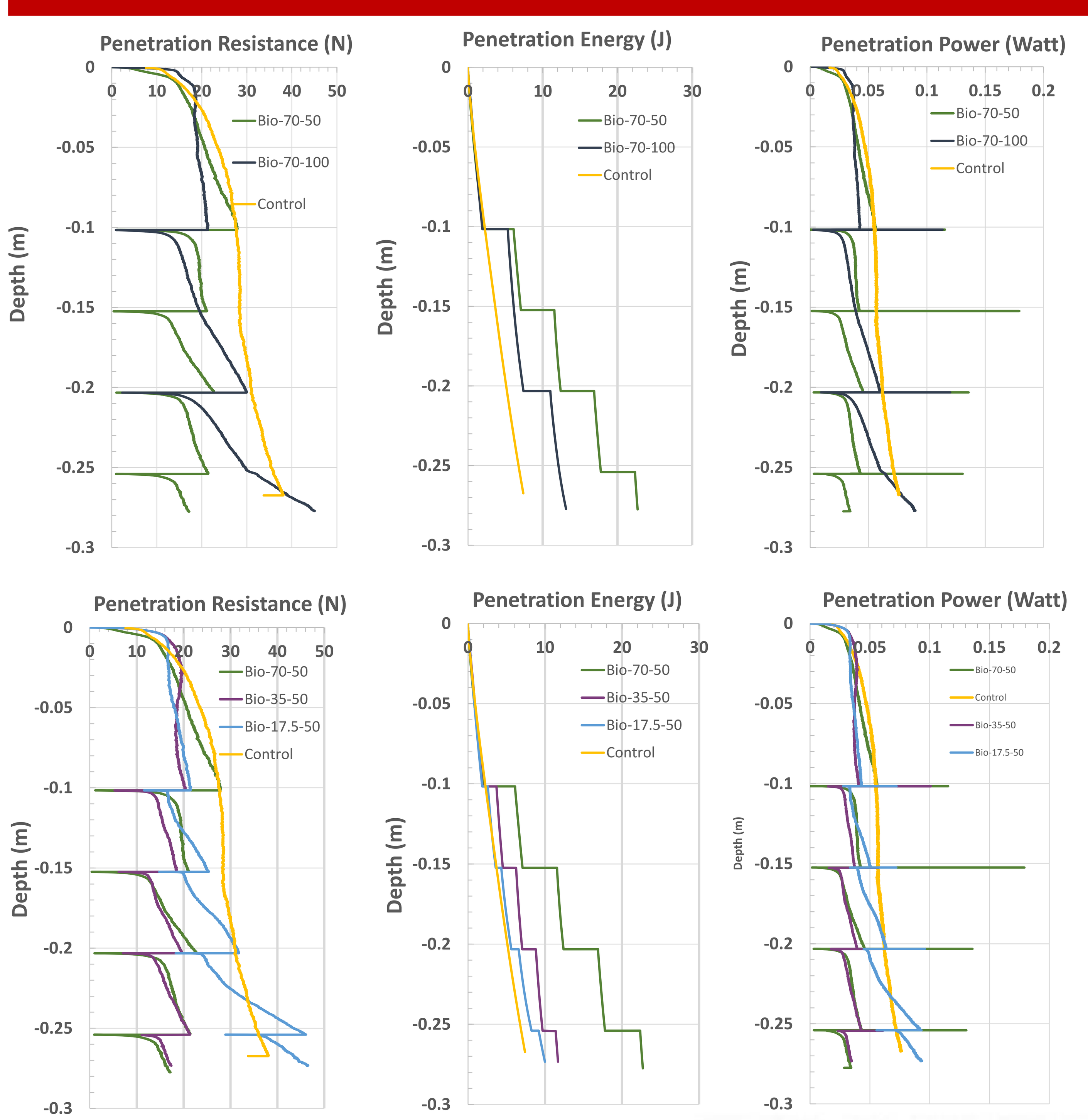








Test Results



Test	Depth (mm)	Injected vol (mL)	Max membrane pressure (kPa)
Control	-270	-	-
Bio-70-100	-100	70	48.26
	-200	70	51.02
Bio-70-50	-100	70	57.23
	-150	70	63.43
	-200	70	63.43
	-250	70	64.80
Bio-35-50	-100	37.68	48.26
	-150	35.32	48.95
	-200	35.32	50.33
	-250	32.87	51.71
Bio-17.5-50	-100	17.27	42.06
	-150	16.64	43.44
	-200	18.840	51.02
	-250	16.96	55.16

Conclusions & Future work

Conclusions

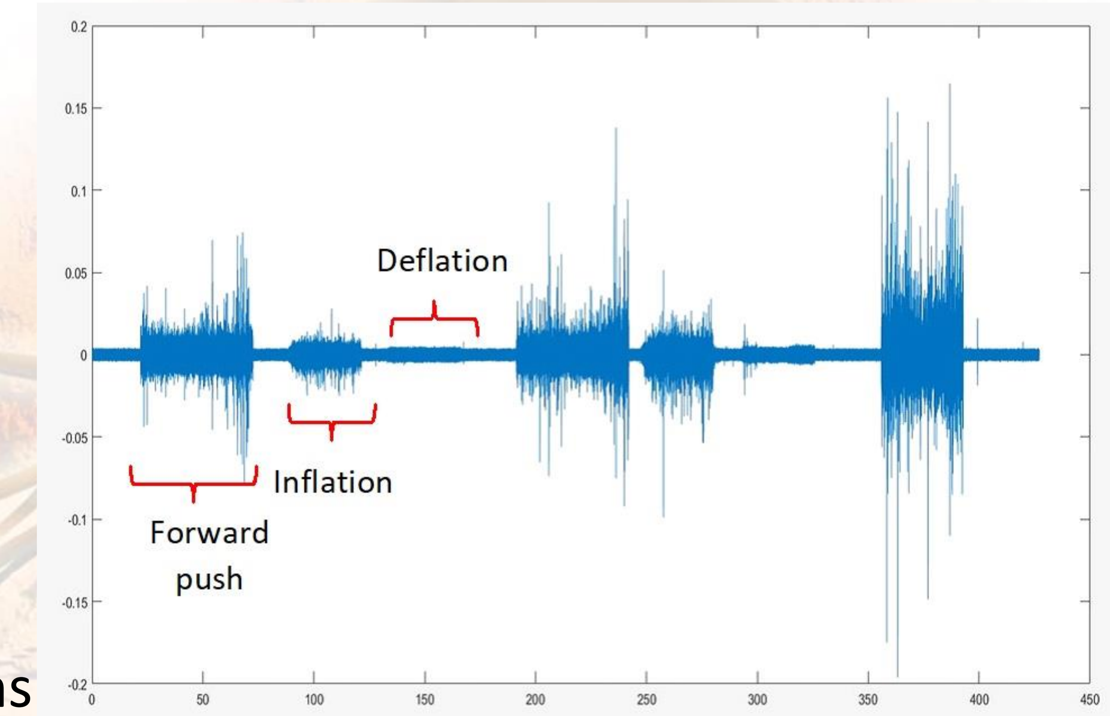
- Bio-inspired penetration can effectively reduce the penetration resistance for the device; however, this comes at the cost of an increase in penetration energy due to the expansion and contraction of the soft anchor.
- Total energy consumption and peak power demand are well within the capabilities of available exploration rover infrastructures.

Future work

Incorporating acoustic emissions data into the soil penetration analysis.

Analysis of soil-fabric evolution as a function of inflation volume and pressure.

Incorporation of relevant environmental conditions into the testing matrix (P and T).



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PR21: 2D DEM Simulations of Ant Nest Cavity Geometry and Orientation

Presenter: Karie Y. Yamamoto **Advisor: J. David Frost** **Institution: Georgia Tech**

Background & Motivation

Solution-driven approach to bio-inspiration to find efficient methods for tunneling through soils.

- Tunnel stability
- Efficient excavation methods
- Machine technologies
- Sensing ground conditions

Trenchless technologies such as microtunneling and pipe jacking.
Staheli Trenchless Consultants

Research Objectives

Understand and quantify the stability of ant nest features at the particle level scale using soil mechanics

Harvester ant nest casting
Tschinkel (2004)

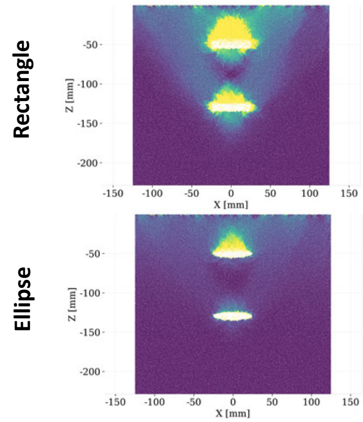
Method

2D Discrete Element Modeling – PFC2D 5.0 (*Itasca, Inc.*)
Test Specimen based on lab experiment conditions

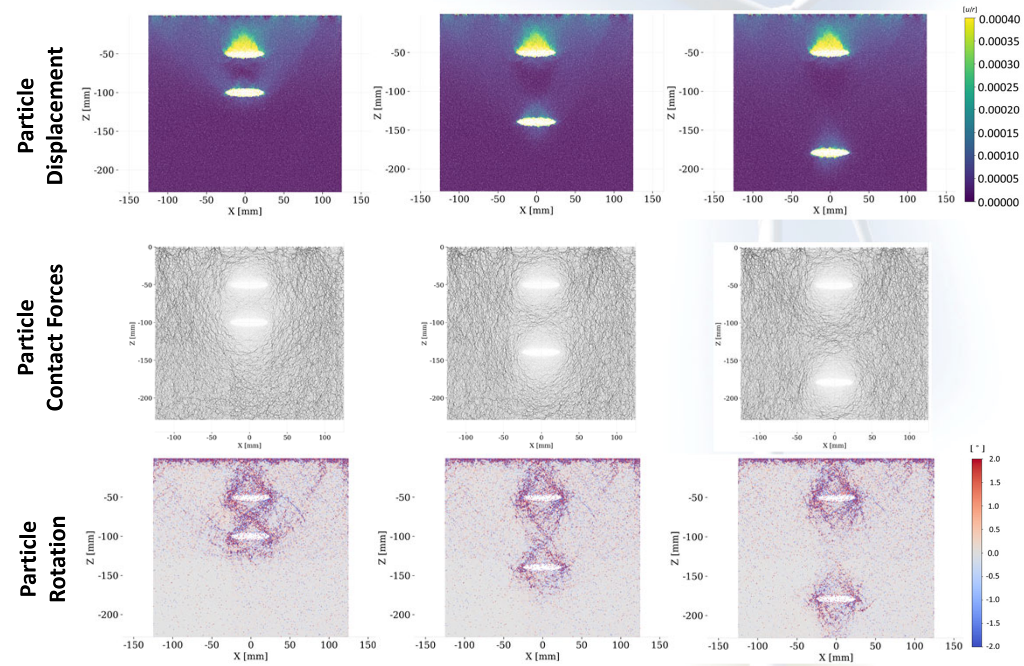
- Ottawa 20/30 sand (D_{50} = 730 µm)
- Water content = 6%
- Cavity aspect ratio = 5:1
- Cavity height = 0.01m
- Elliptical vs. Rectangular chamber geometries
- Vertical intercavity distance range = 0.05m – 0.1m

Component	Property	Value
Specimen	Width x Height (m)	0.25 x 0.229
	Number of particles	249800
	Porosity	0.19
Bond	Normal stiffness (N/m)	0.0136
	Shear stiffness (N/m)	0.0136
	Friction coefficient	0.5
	Bond radius (m)	2*particle radius
	Tensile strength (N/m^2)	0.478
	Cohesion (N/m^2)	0.478
	Bond gap interval (m)	0.0003

Results & Analysis



Particle Displacement



Conclusions & Future Work

Conclusions

- Elliptical cavity geometry which is similar to chamber geometry in ant nests is more stable than rectangular cavity geometry
- The presence of a cavity oriented directly above a lower chamber can aid the stability of the lower cavity as well as the stability of the two cavity system

Future Work

- Analyze the effect of offset distances and inclination angle of cavities
- Use cavity geometries based on scans of ant nest castings from the field
- Analyze shaft and chamber coupled stability

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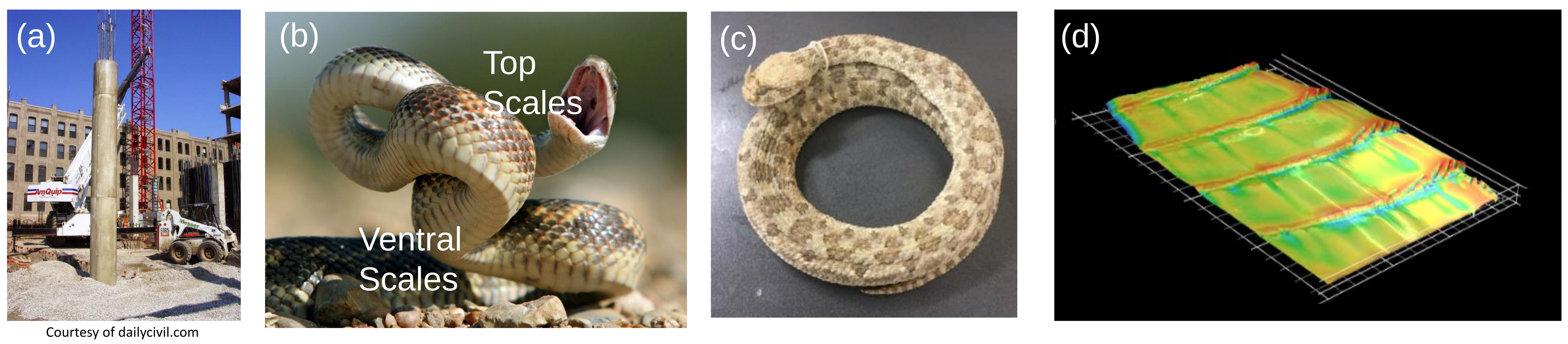
Load transfer behavior between snakeskin-inspired piles and sand

Presenter: Kyle O'Hara Advisors: Alejandro Martinez Institution: UC Davis

Background

Multifunctional and more efficient piles may be developed based on interfaces that develop higher shear resistances in one loading direction than another. This could be achieved using a biological adaptation present in snakes. The scales along the underbelly of snakes (ventral scales) mobilizes less frictional resistances during forward (caudal) movement than during backward (cranial) movement.

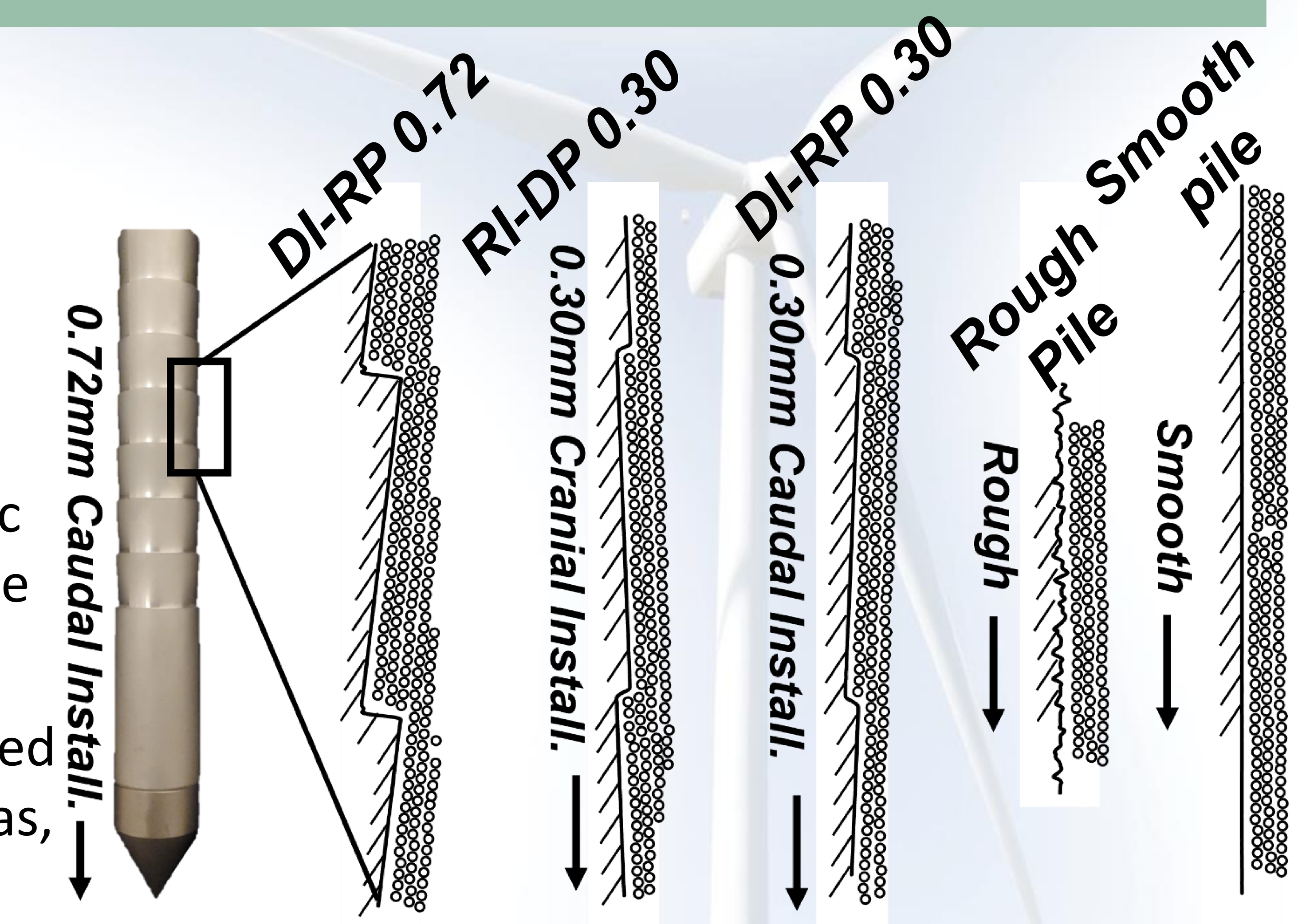


(a) Smooth pile surface (b) Model organism for development (c) Preserved snake specimen (d) 3D scan of ventral scales

Research objectives

Perform pile load tests in the centrifuge to:

- Quantify load transfer between sand and snakeskin-inspired pile shafts during installation and pullout
- Characterize initial and post cyclic capacity of snakeskin-inspired pile shafts
- Quantify stability of piles subjected to cyclic loading with a tensile bias, in terms of displacement accumulation and cycles to failure

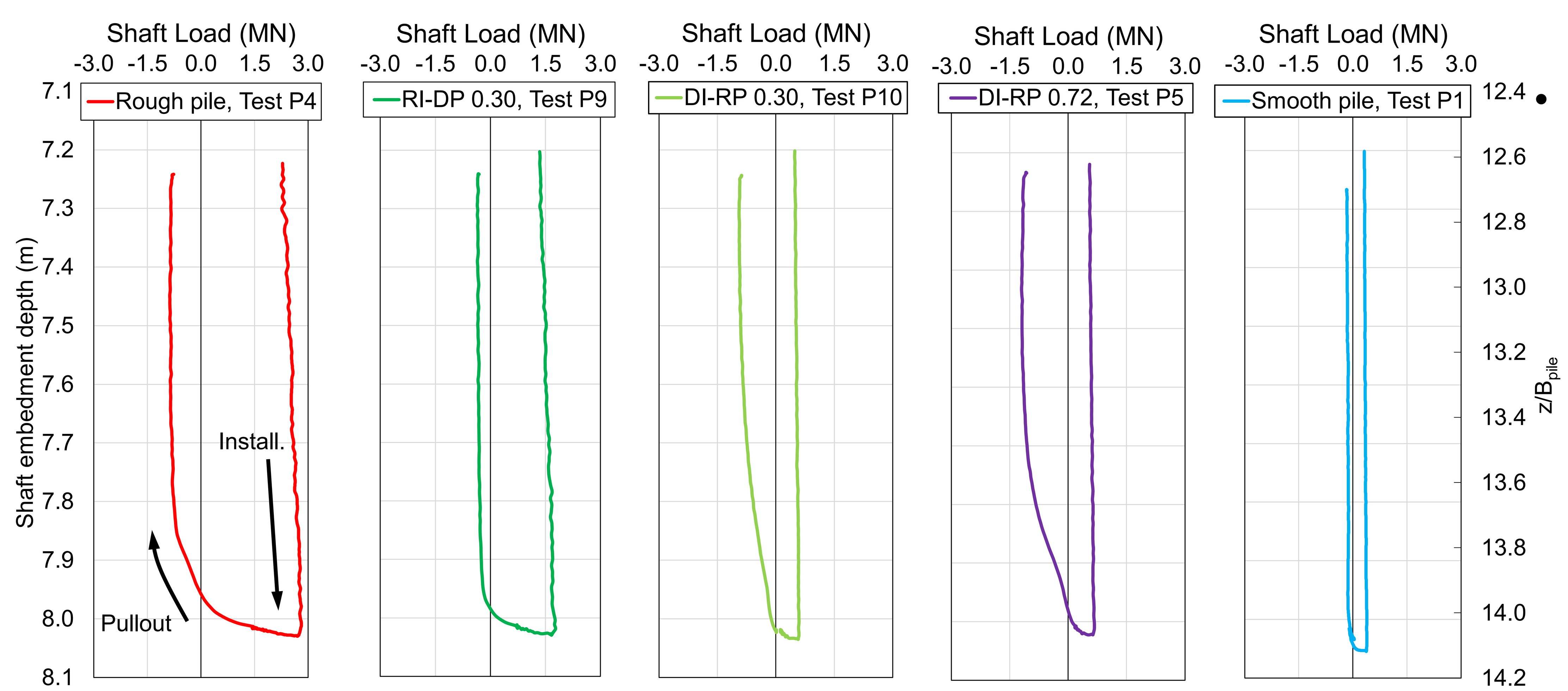


Bio-inspired and reference piles (to scale)

Installation and pullout loading

Observations from installation and pullout phase:

- Rough pile, Smooth pile, and RI-DP piles exhibit $Q_{pullout}/Q_{install.} < 1$
- DI-RP 0.30 and DI-RP 0.72 exhibit $Q_{pullout}/Q_{install.} > 1$, showing direction-dependent skin friction

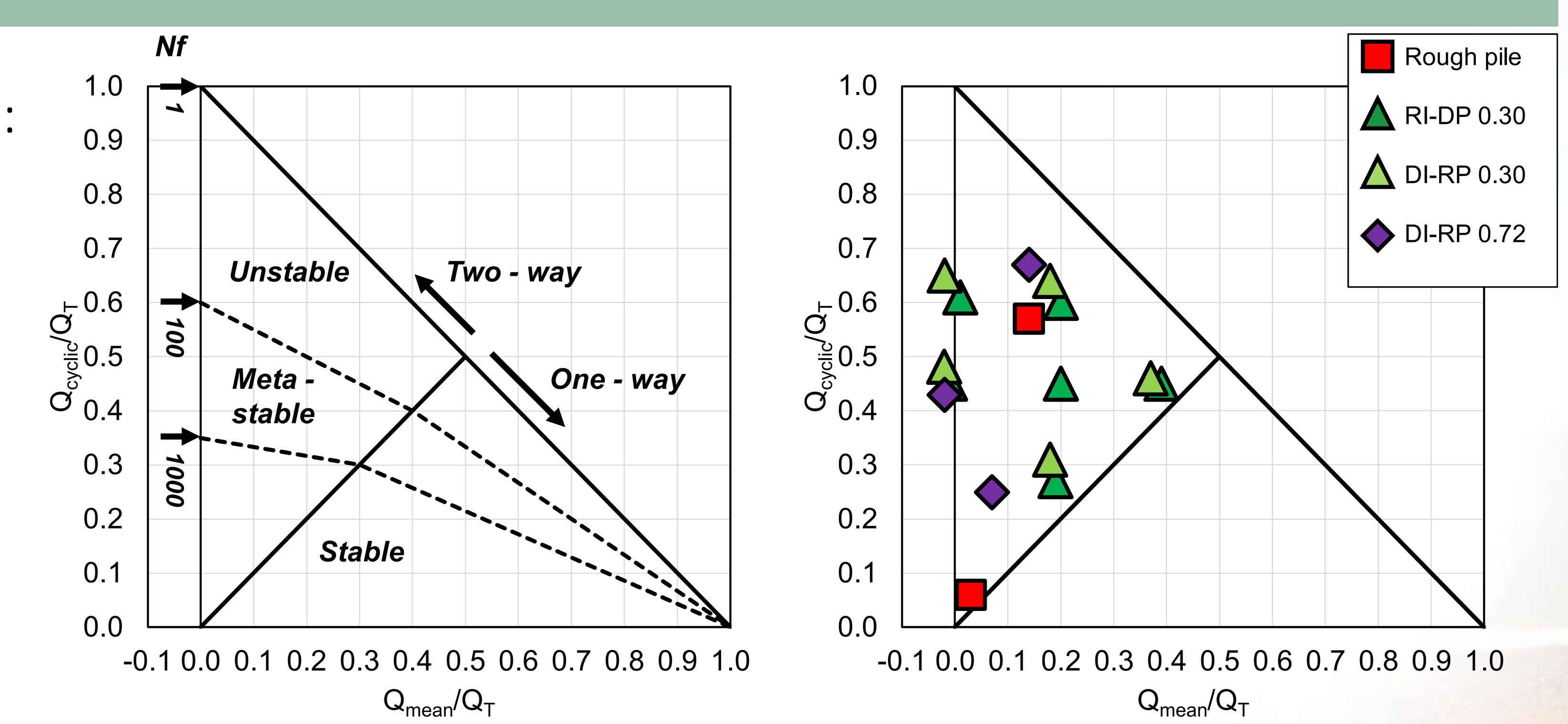


Installation and pullout shaft loads for all pile shaft types

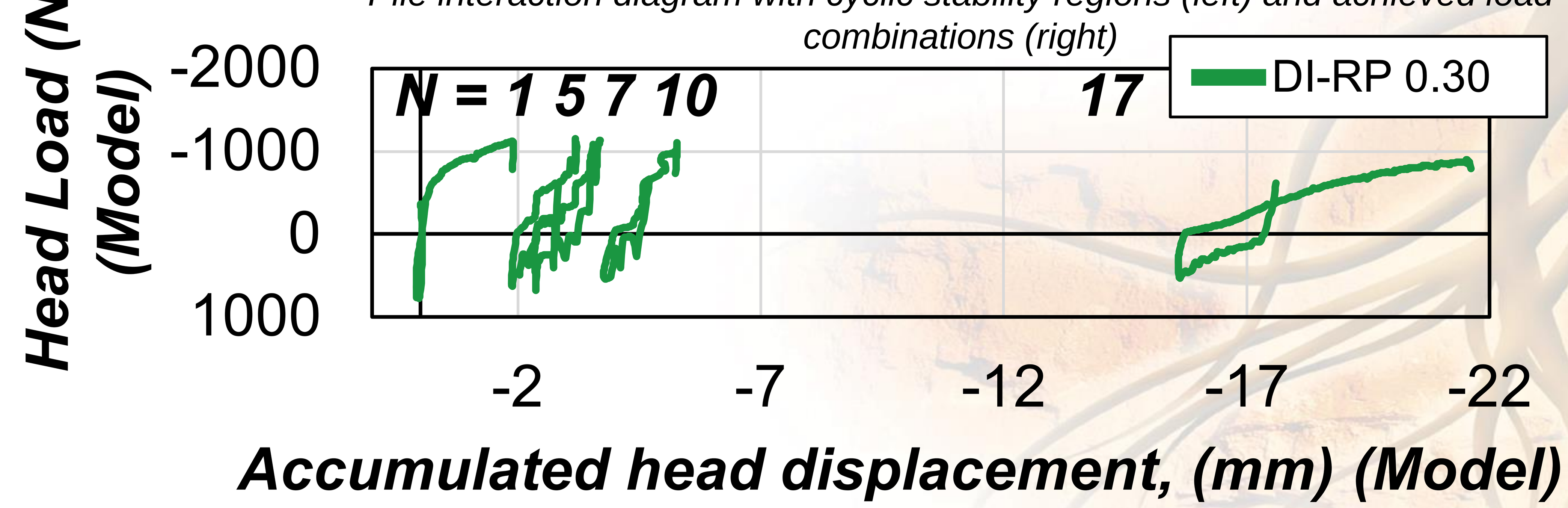
System level behavior via centrifuge modelling

Interaction diagram:

- Categorizes load based on mean and single amplitude
- Normalizes load based on *maximum tensile load of the pile*



Pile interaction diagram with cyclic stability regions (left) and achieved load combinations (right)



Load-displacement for DI-RPQmean/QT = 0 Qcyclic/QT = 0.45

Future Work

Future work:

- Finish interpretation of cyclic pile data Characterize initial and post cyclic capacity of snakeskin-inspired pile shafts
- Testing field prototype at clay site in Utah
- Quantify the relationship between strength and scale geometry while accounting for particle size effects

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Analysis of the Bio-Inspired Penetration Processes of a In-Situ Testing Probe

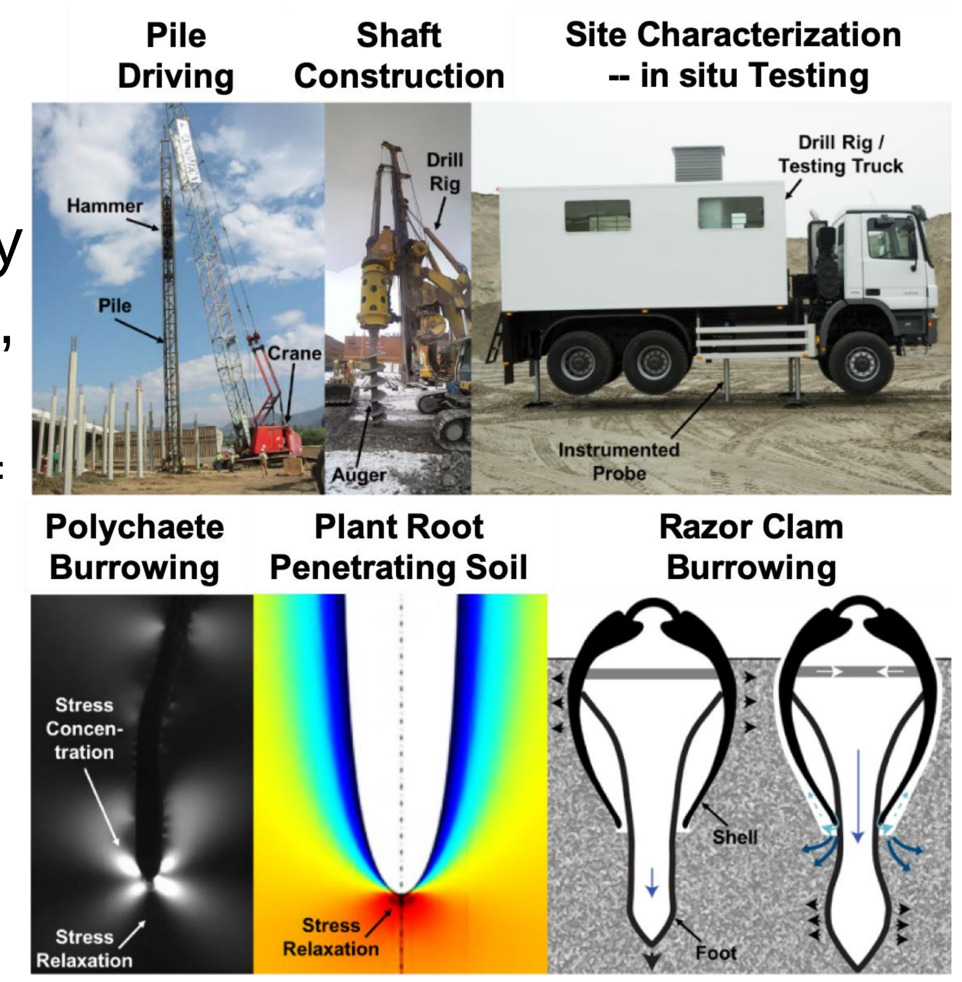
Presenter: Yuyan Chen Advisors: Alejandro Martinez, Jason DeJong Institution: UC Davis

Background and Motivation

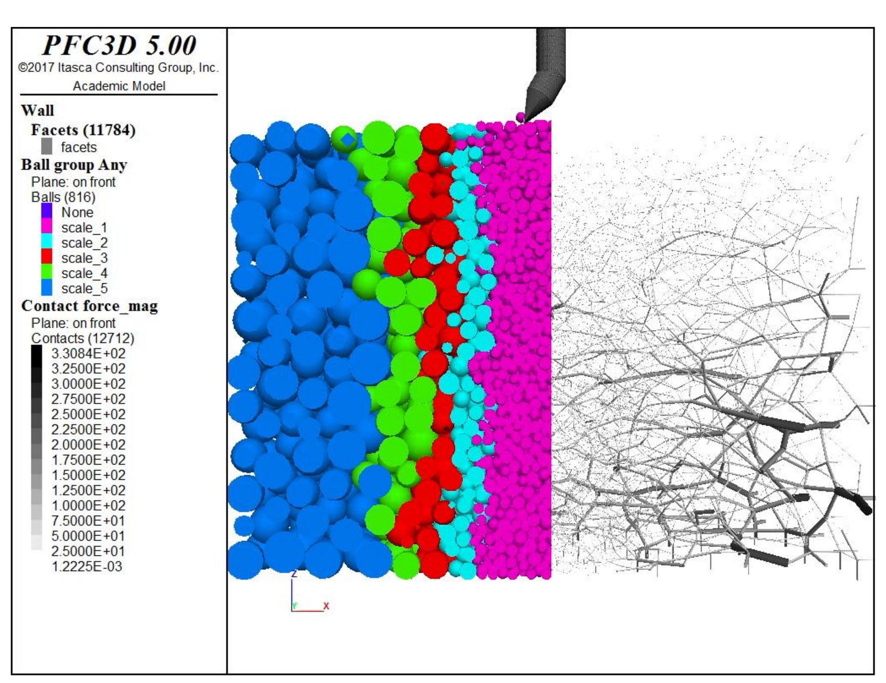
Soil penetration is an energy-intensive process that is common in both nature and civil infrastructure applications.

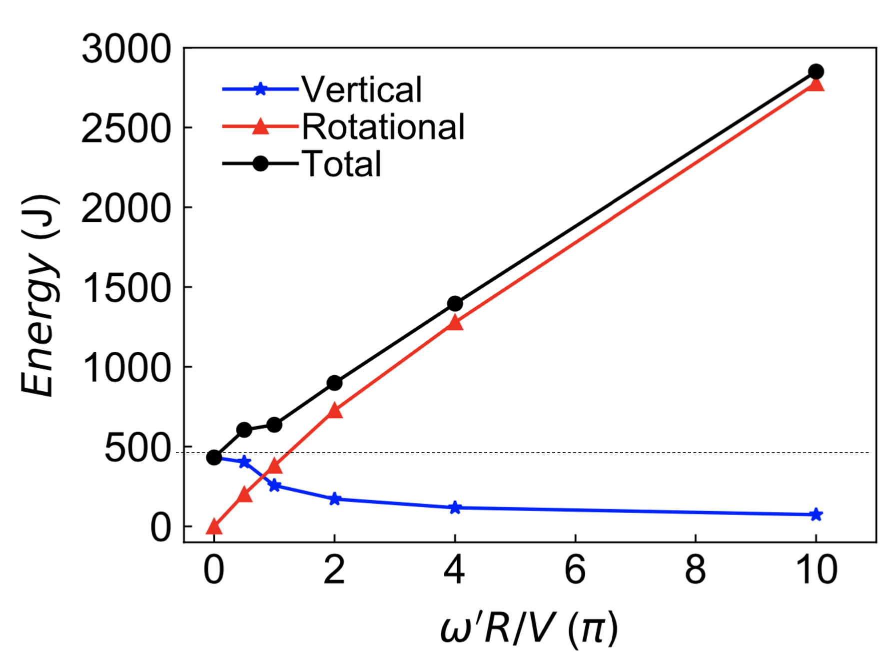
- Many human construction activities are energy intensive: involving impact-driving, excavating, or vibrating using large equipment.
- Animals and plants have developed a range of adaptations to burrow efficiently in soils.

Goal: Investigate the functionality and optimization of the bio-inspired penetration process that uses 'anchor-tip' or 'root circumnutation' strategy using discrete element modeling (DEM). Provide analysis base to the prototype construction.

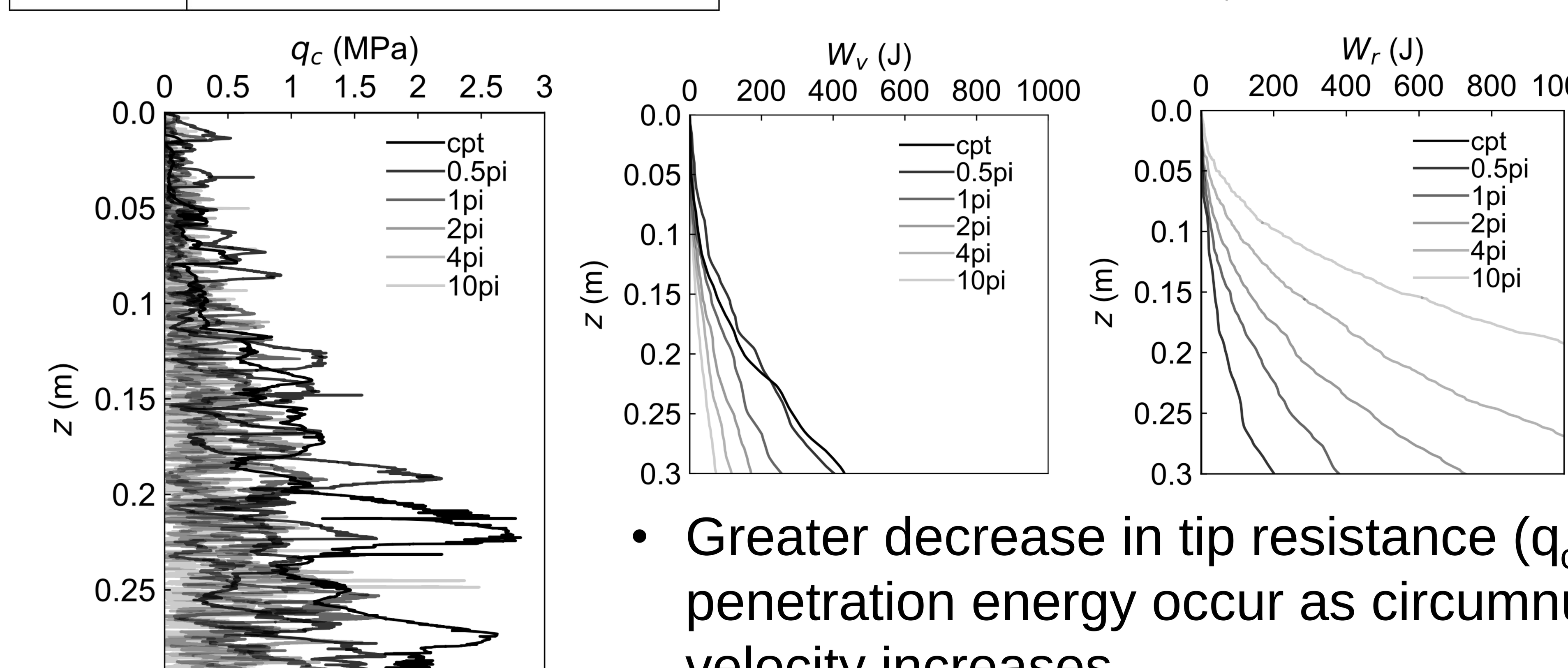


Strategy 2: 'Root Circumnutation' Penetration



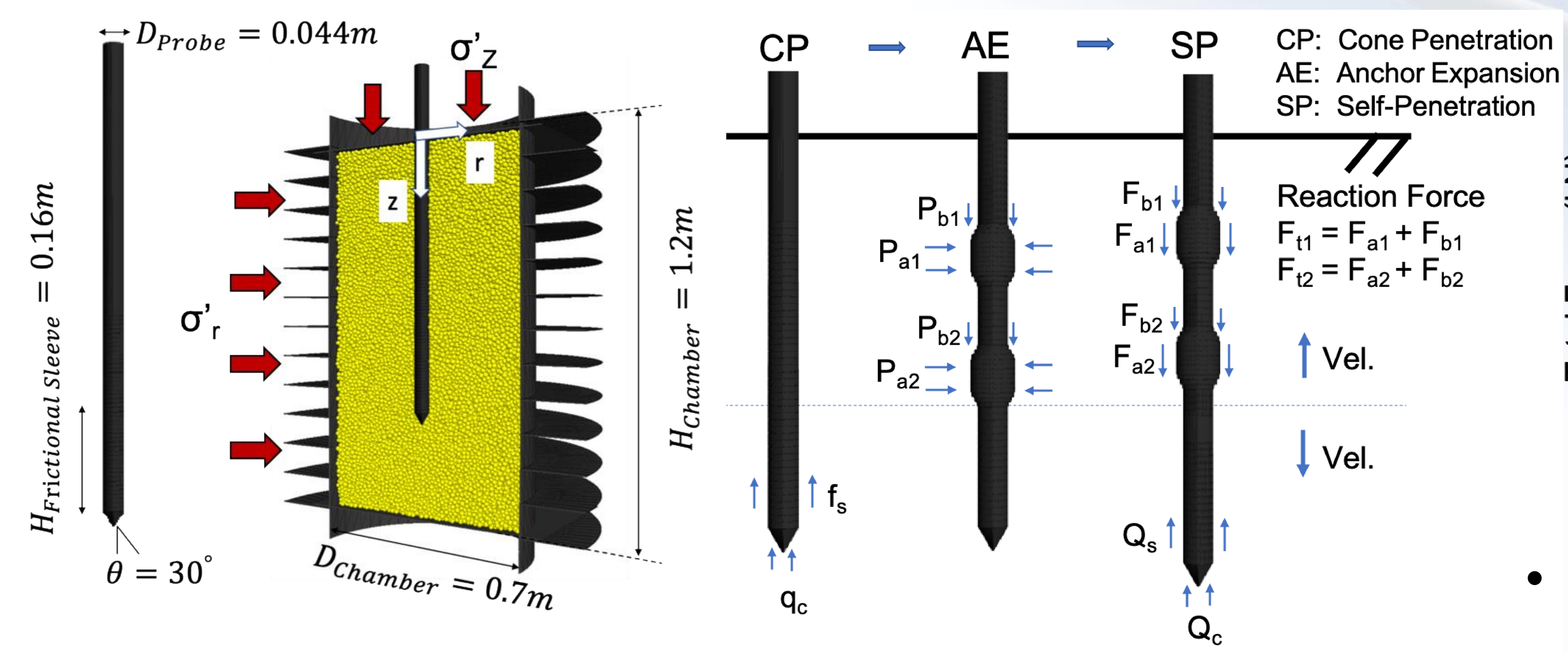


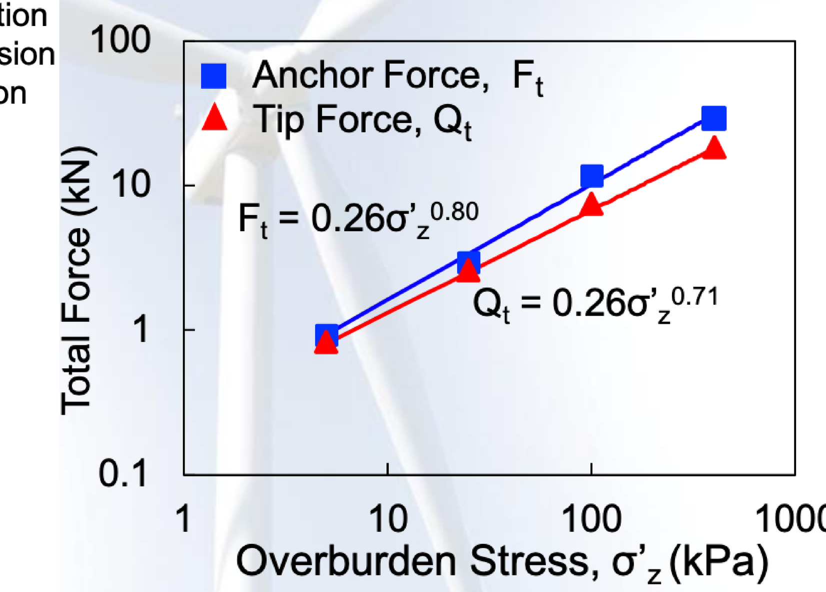
- Total energy required for 'circumnutation' is greater than CPT penetration and increases with radial velocity



- Rotational energy is higher than vertical energy
- Greater decrease in tip resistance (q_c) and vertical penetration energy occur as circumnutation radial velocity increases

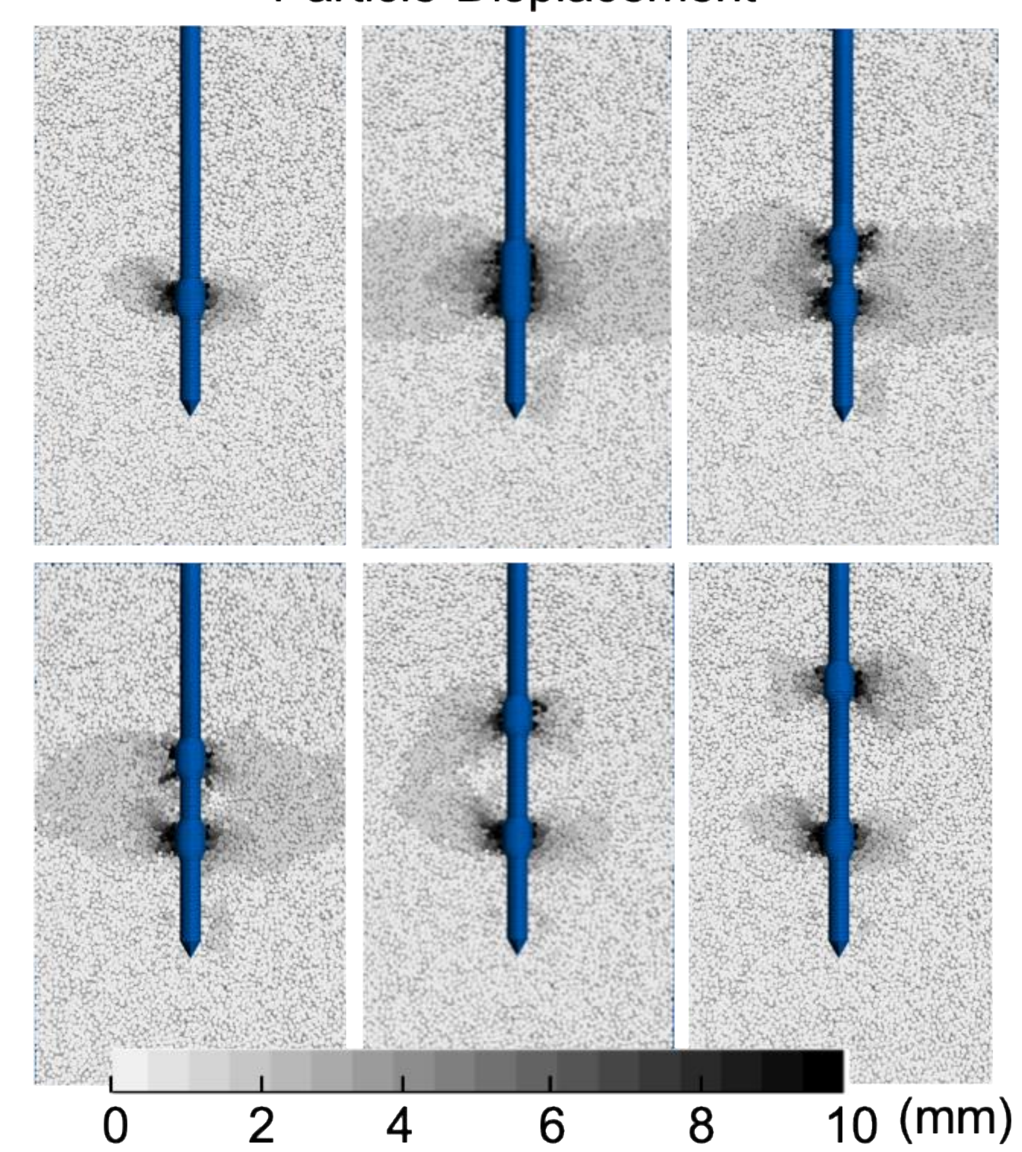
Strategy 1: 'Anchor-Tip' Self-Penetration



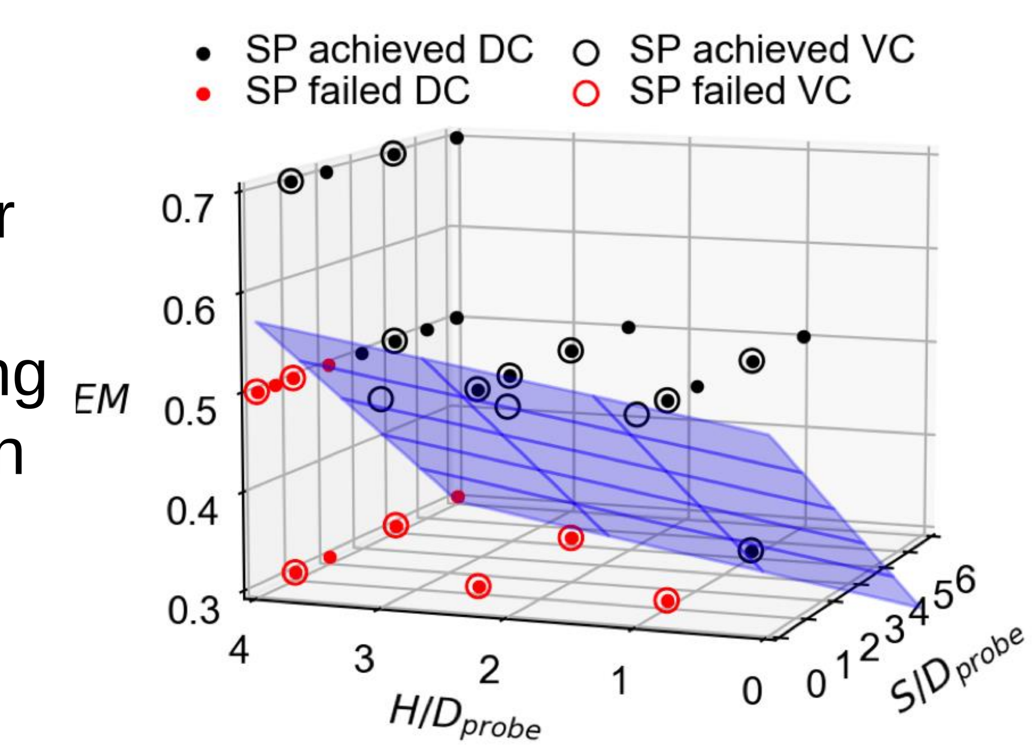


- DEM model and bio-inspired penetration process
- Field application towards deep soil condition is possible: F_t increase at greater rate than Q_t

Particle Displacement



- Interactions between anchors occur when the anchor spacing is smaller than $4D_{probe}$



Critical Plane: EM = -0.046 * S+ 0.020 *H+ 0.488

- Based on simulation results, a critical plane for self-penetration realization is defined in 3D space considering the effects of EM, S and H.

Future Plan

- Further investigate the root circumnutation strategy in a refined DEM sample; will look into the optimization of this strategy by considering other parameters.
- Simulate the 'anchor-tip' penetration process considering multiple cycles with more realistic and comprehensive control algorithms; investigate the dynamic self-penetration process in different soil conditions.

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Angelwing shells (*cyrtopleura costata*) inspired hard rock drilling

Presenter: Yumeng Zhao **Advisors: Sheng Dai** **Institution: GT**

Background

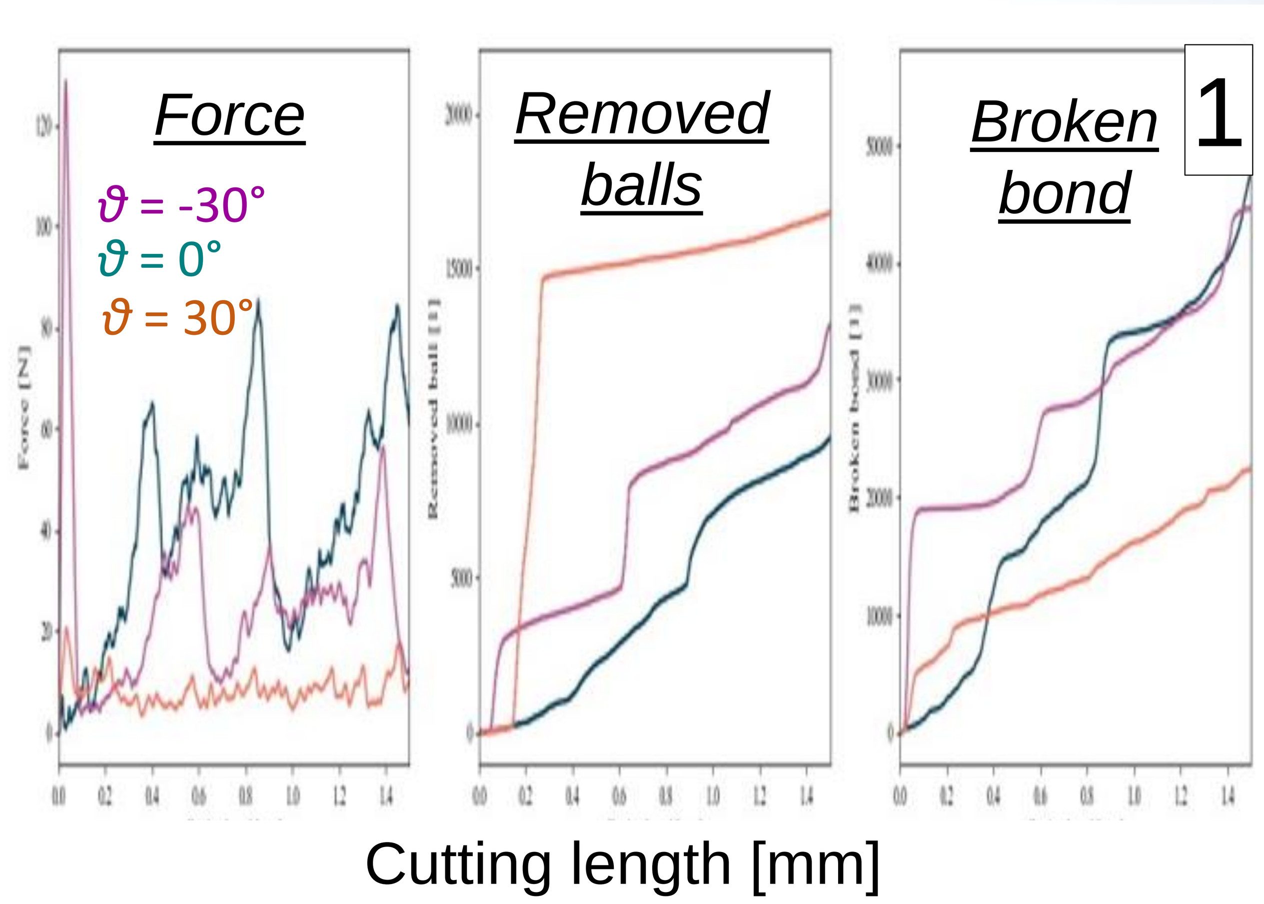
Angelwing clam can drill into soft rock or hard clays.

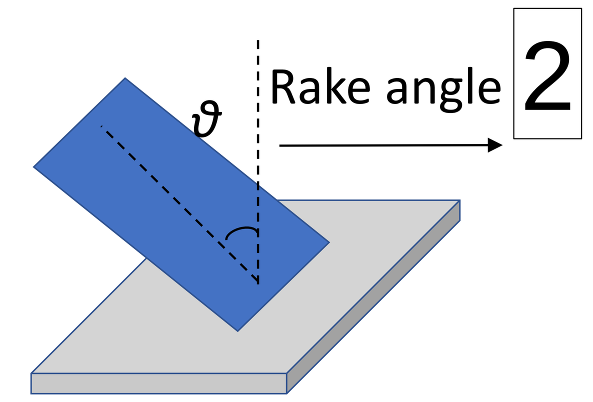
- Denticle shape & orientation, rib patterns, shell morphology may help scratching and cutting removal.

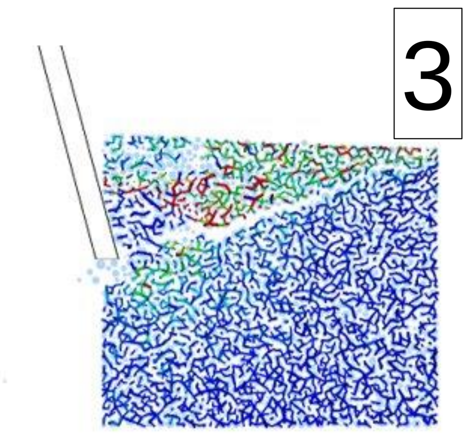
Research Objectives

1. Understand the angelwing drilling process from morphology, material properties, locomotion etc.
2. Optimize the dill bit design inspired by angelwing.
3. Design and test a prototype rock drilling Robot.

Denticle level cutting – DEM simulation







Plot #1: Rake angle on cutting efficiency

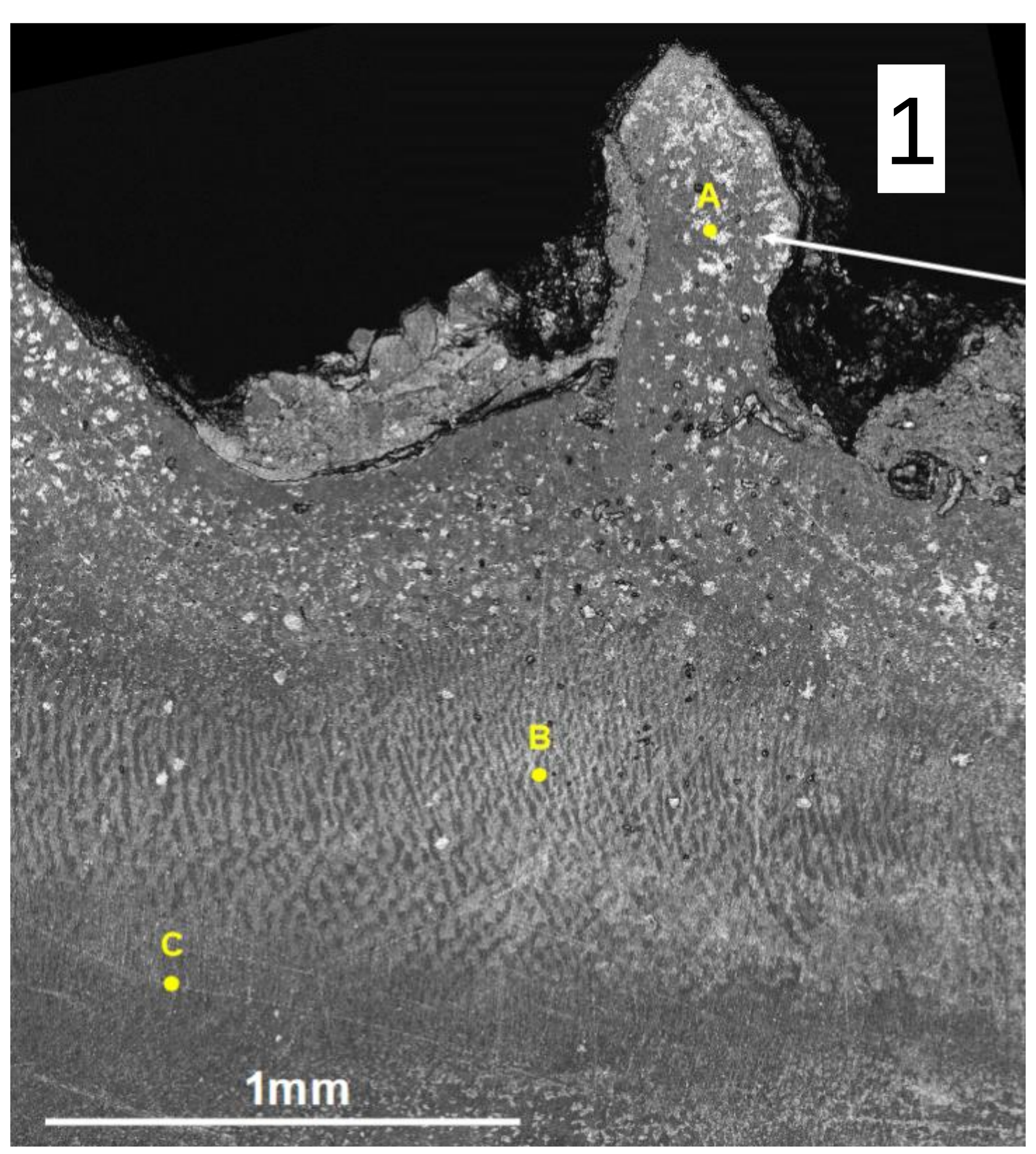
Plot #2 Schematic rake angle

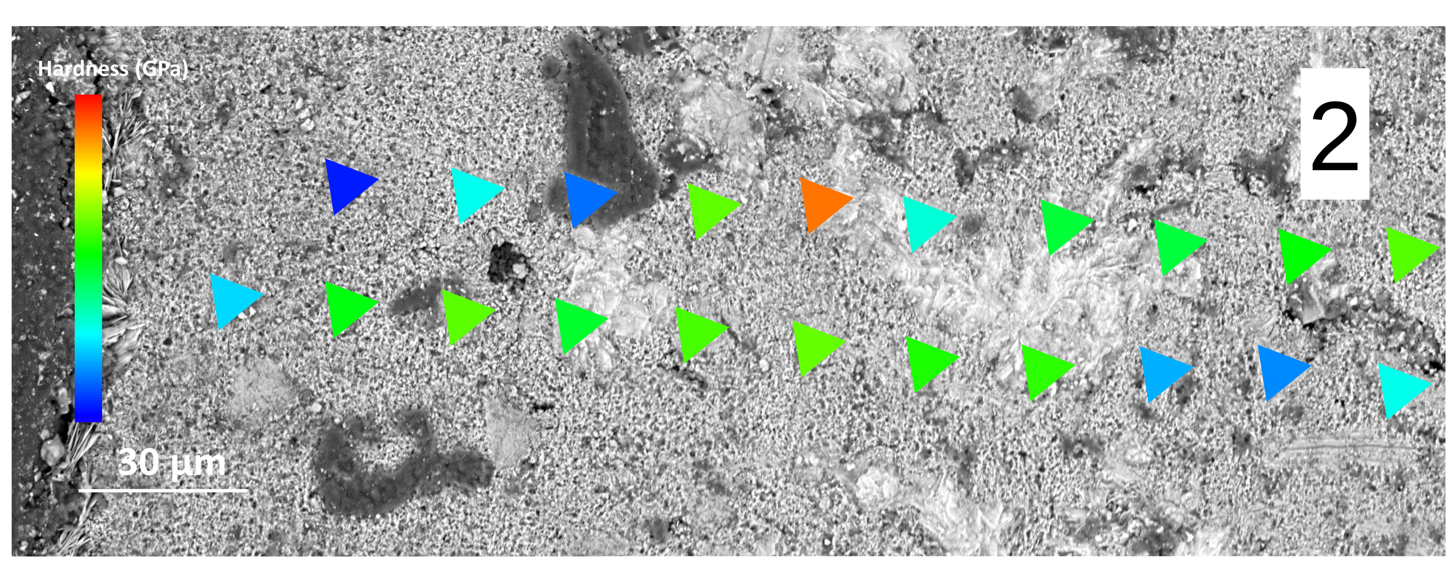
Plot #3: DEM simulation

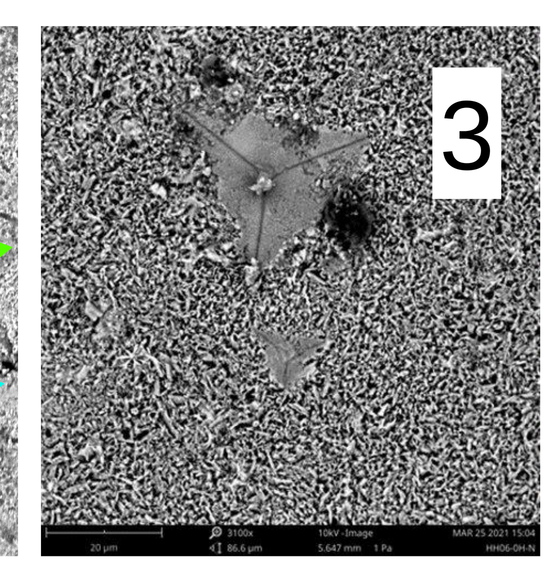
Plot #4: Different cutter shapes

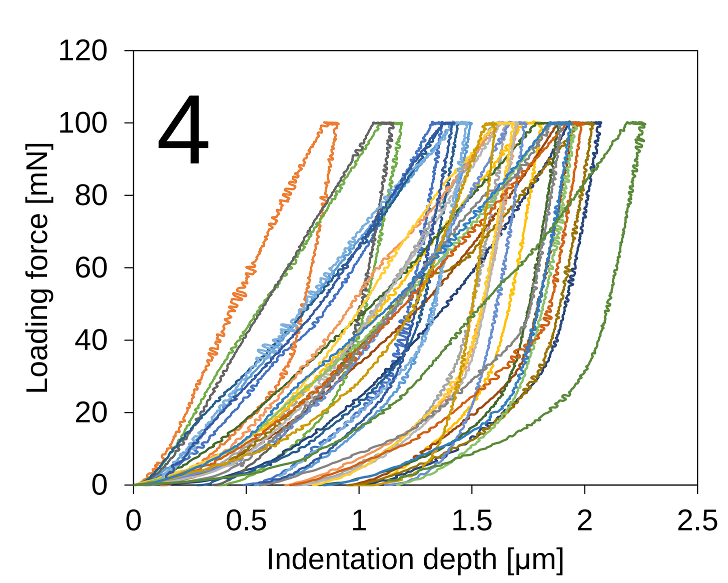
- Positive rake angle - more efficient cutting
- Curved cutter cuts more in the front but shallower.
- Brittle materials fail in tensile, ductile materials fail in shearing.

Denticle level cutting – nanoindentation hardness test









Plot #1: SEM denticle side

Plot #2: Indentation hardness distribution

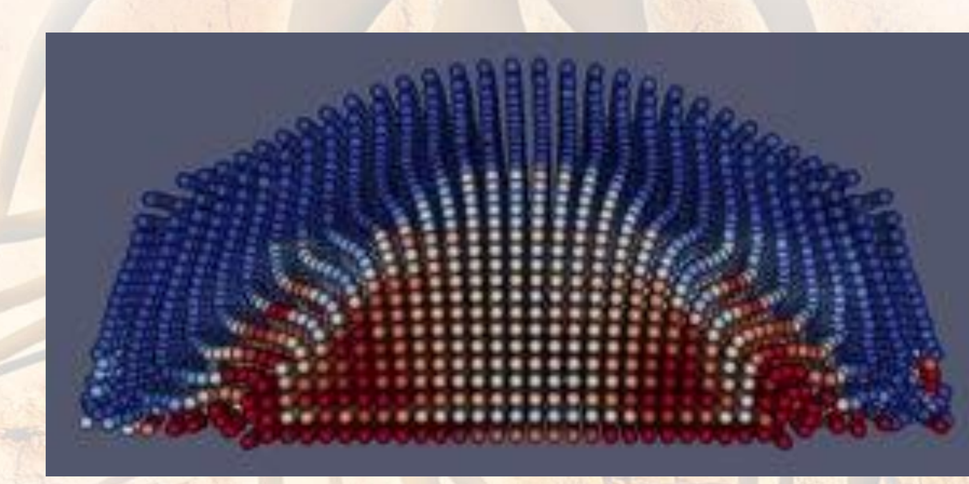
Plot #3: SEM indentation mark

Plot #4: Indentation curves

- Typical $CaCO_3$ hardness
- Relatively homogeneous
- Confirmed by EDS analysis

Future work

- Design drill bits
- 3D print prototype drill bits
- Prototype experiment to find optimal design
- Smoothed particle hydrodynamics (SPH) simulation on cutting removal process



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Bio-inspired Seismic Wave Based Wireless Underground Communication System

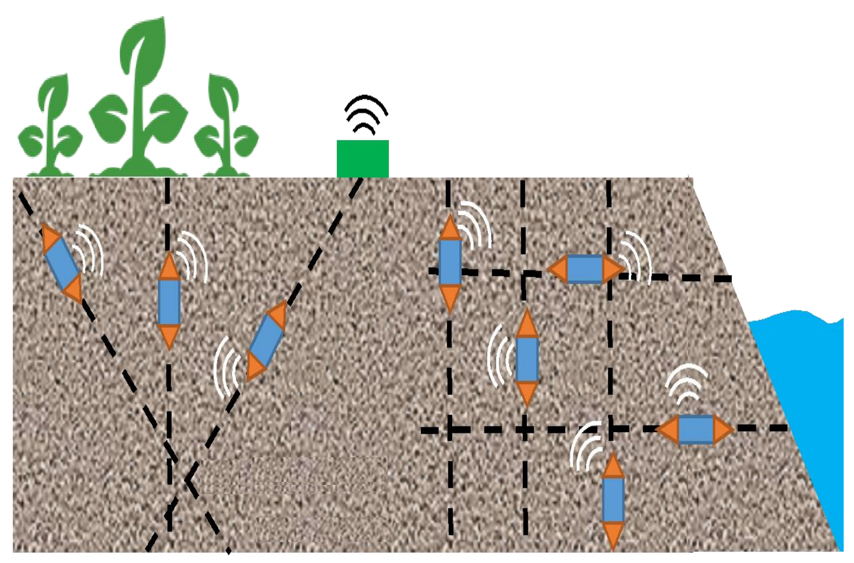
Presenters: Yi Zhong Advisors: Julian Tao Institution: Arizona State University

Motivation & Objectives

- Mole-rats generate seismic signals through drumming
- Communicate with each other as far as several meters

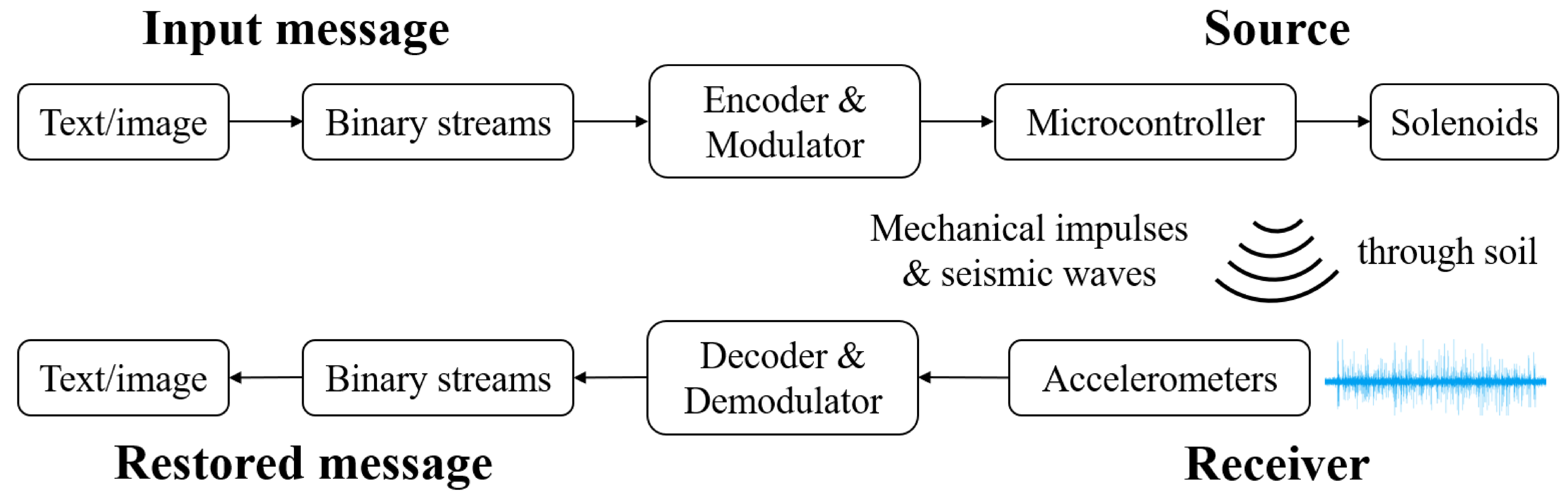
Goals:

- Design and fabricate a drumming-inspired vibrational source
- Develop an underground communication system using seismic waves

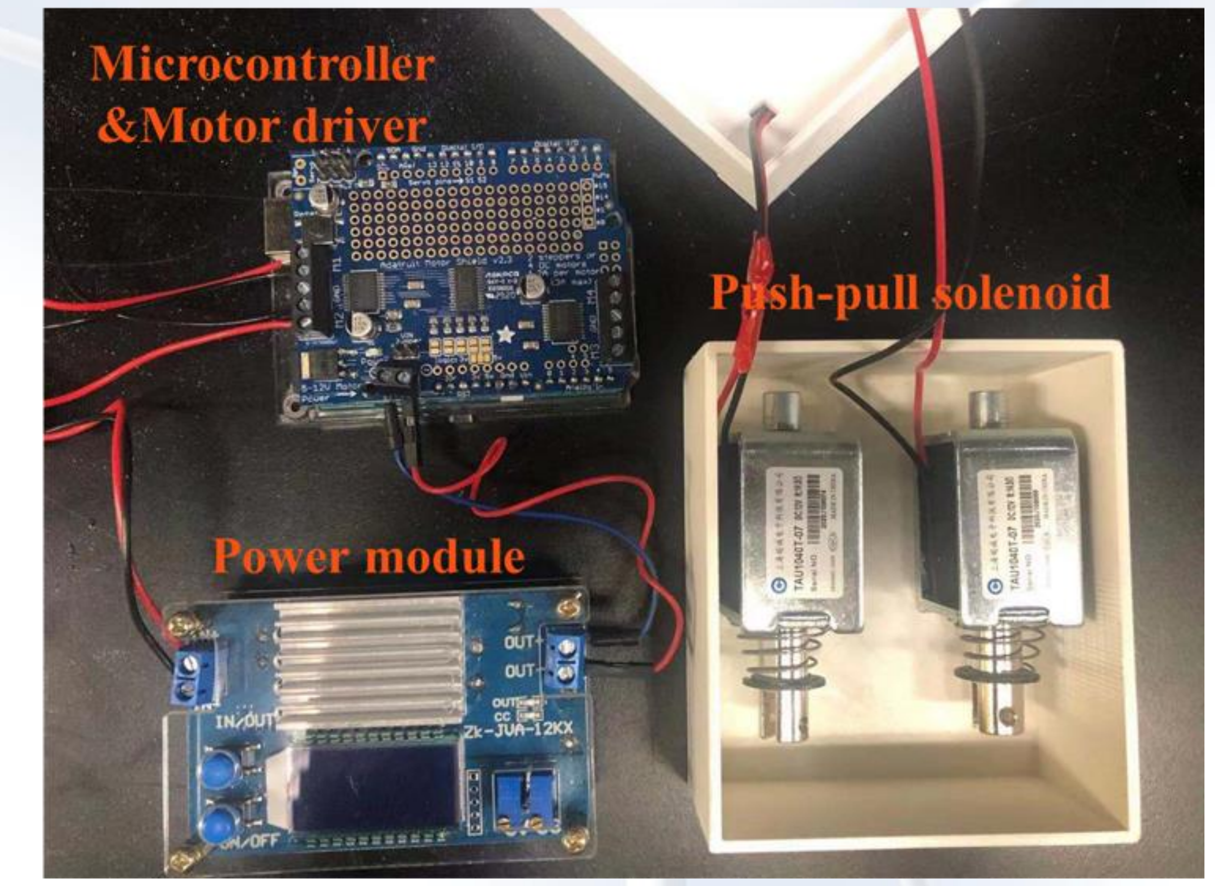


System Design and Description

- Communication system: transmitter, communication channel, receiver
- Transmission loss, noise, reflection, refraction, and temporal and spatial variability of the soil channel
- On-off keying (OOK) & Error correcting code (Hamming code)

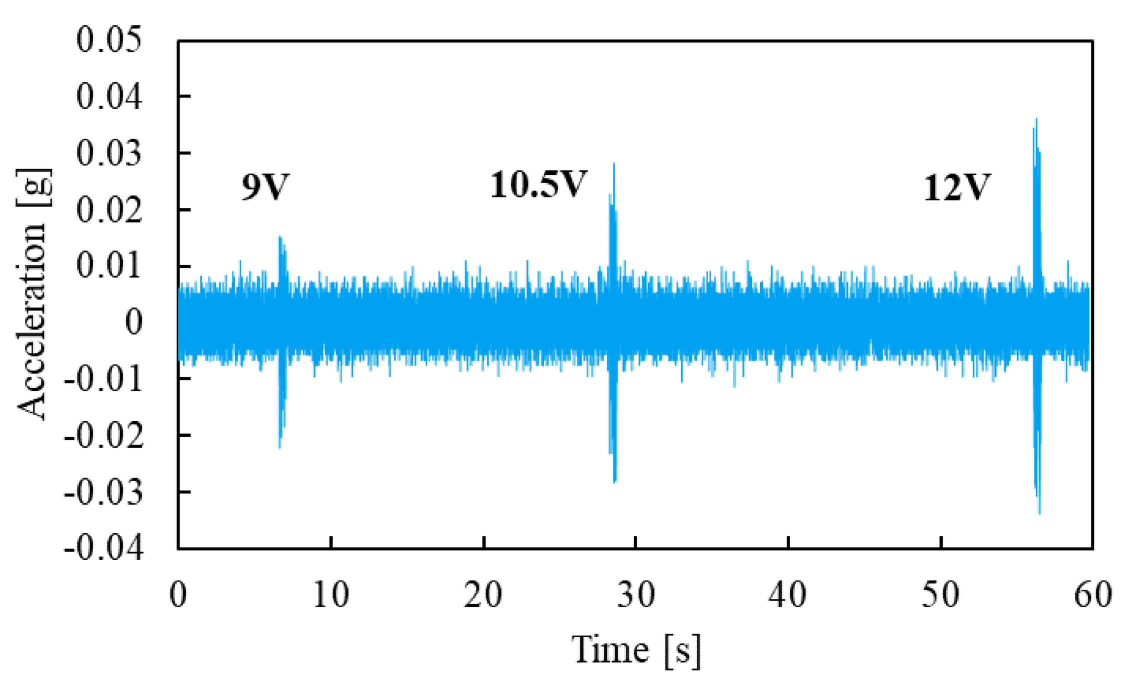


Schematic of the developed bio-inspired underground communication system using OOK modulation.

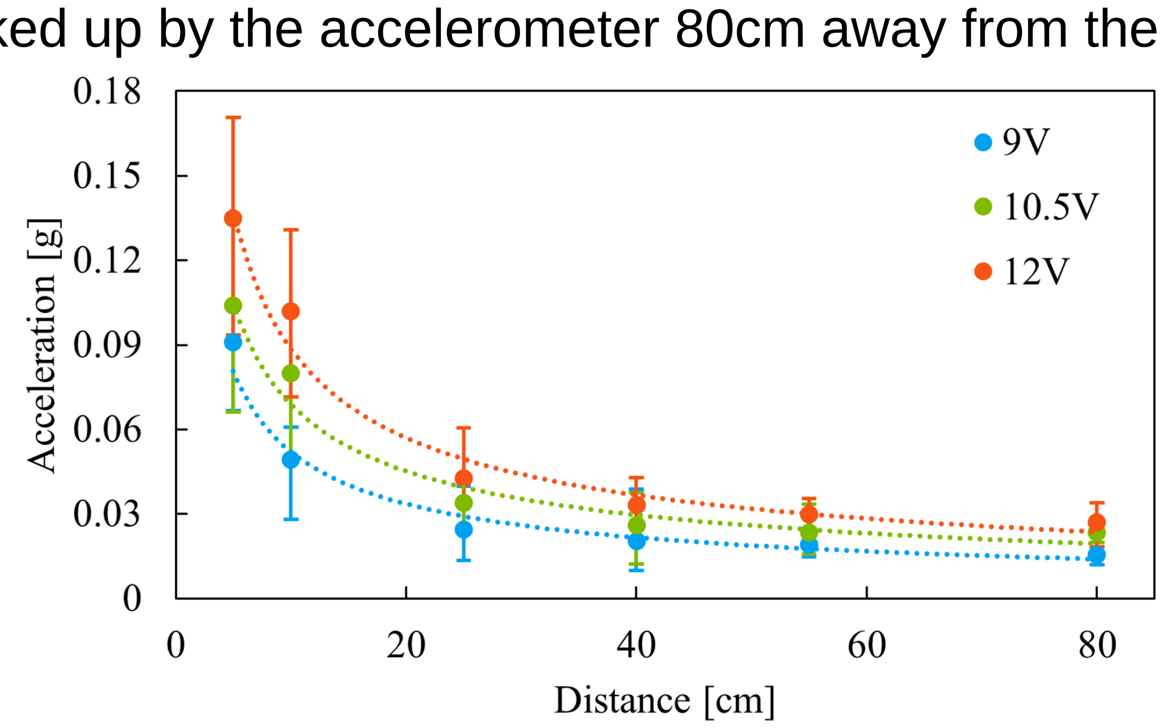


Drumming-inspired vibrational source based on push-pull solenoids

Source Evaluation



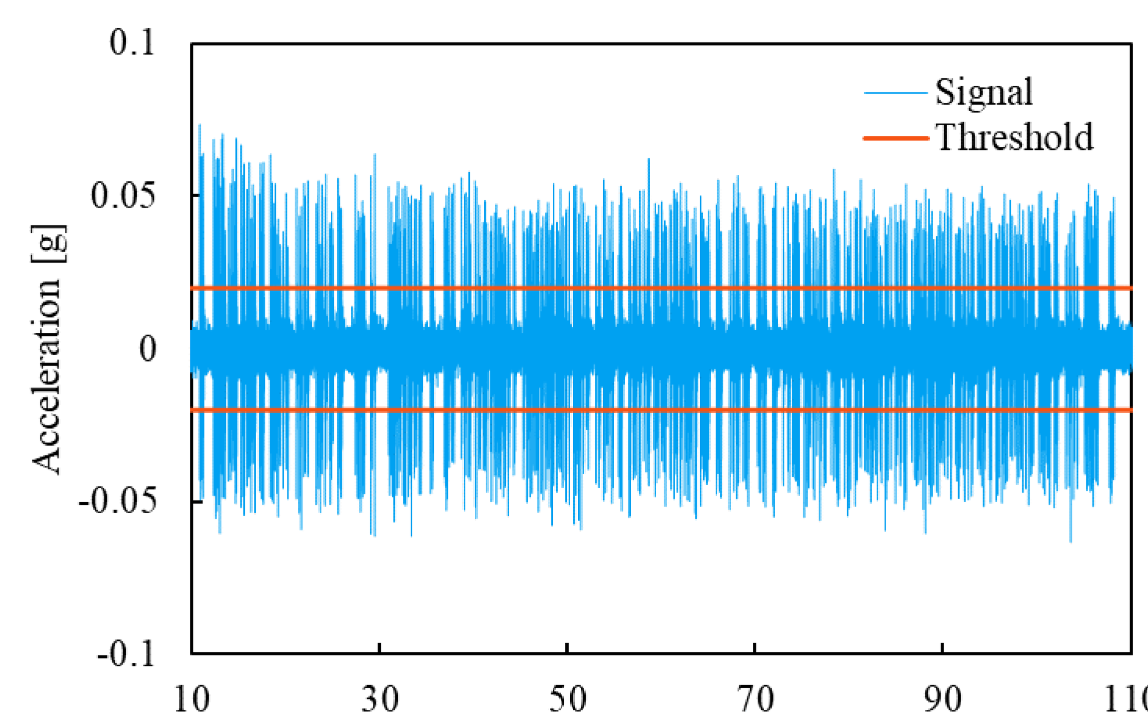
Signals picked up by the accelerometer 80cm away from the source.

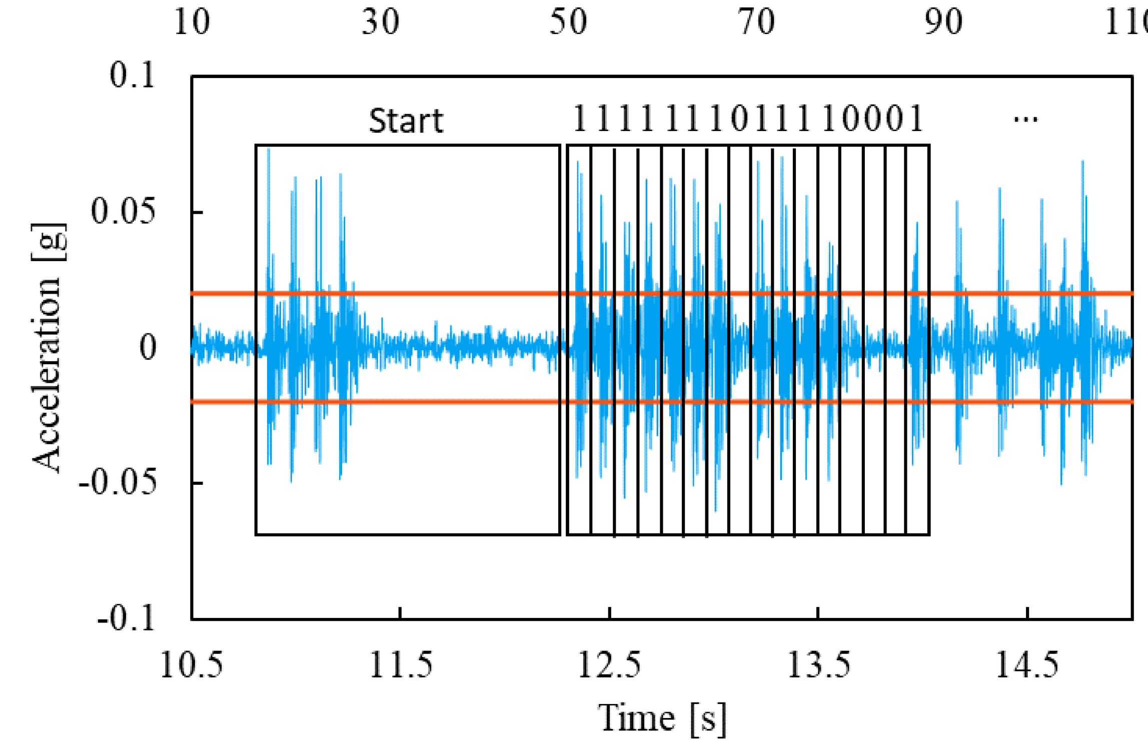


The acceleration response with distance from the drumming-inspired vibrational source and input voltage.

- Broadband seismic waves
- $A \propto r^{-0.63}$

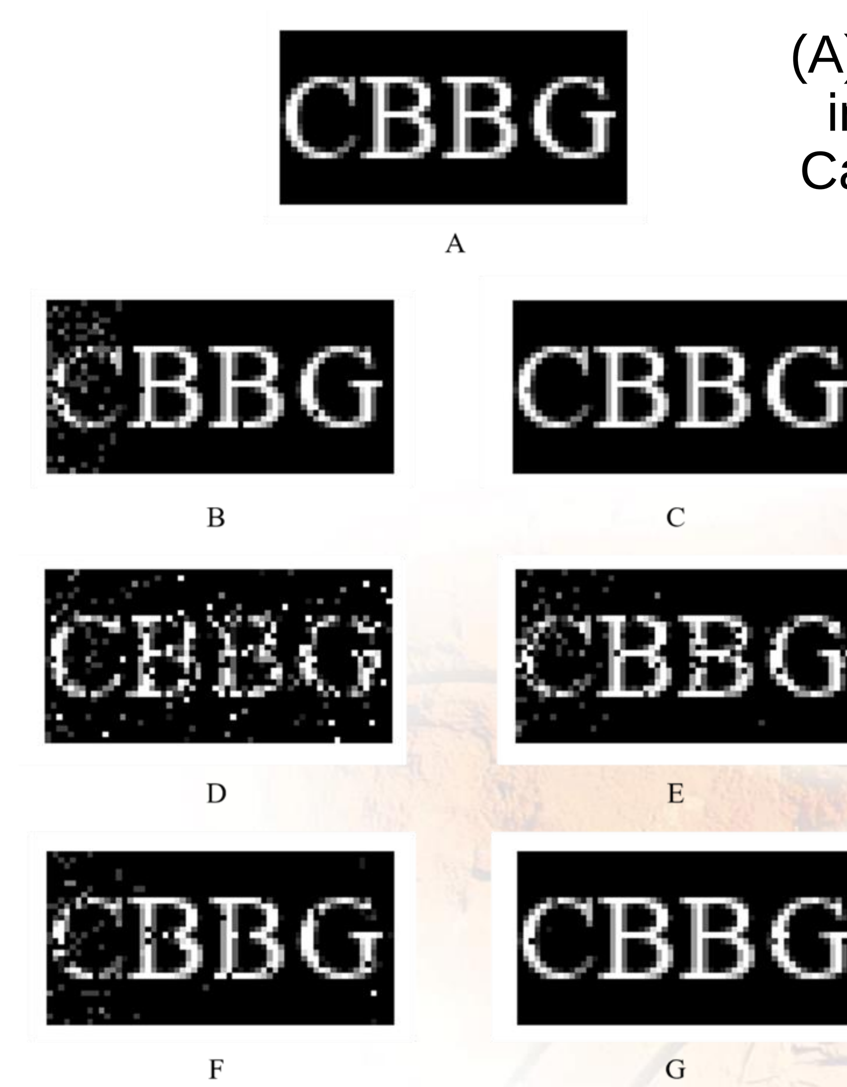
System Evaluation





(A) Received signals when sending a plain text file through sand; (B) start sign and restored binary codes.

	No. of Solenoids	Hamming Code	Guard Interval	BER	Bit Rate
Case I	2	×	√	2.58%	10 bps
Case II	2	√	√	0.10%	10 bps
Case III	1	×	×	8.99%	17 bps
Case IV	1	×	√	3.86%	10 bps
Case V	2	×	×	3.19%	16 bps
Case VI	2	√	×	0.54%	16 bps



(A) Original image sent through soils; restored images at receiver's end for (B) Case I, (C) Case II, (D) Case III, (E) Case IV, (F) Case V, and (G) Case VI.

Future Work

- Evaluate the performance of developed system in saturated soils
- Theoretical model for the developed system and built source
- Field tests

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Mole rat - Inspired Bidirectional Propeller for Self-excavating Probes

Presenter: Haozhou He   Advisors: Chloe Arson   Institution: Georgia Tech

Background

Self-excavation probes are needed to explore areas with limited accessibility. We are interested in probe retrieval

The main challenge is the design of anchors for backward motion in a bore burrowed forward, because of the soil strength loss generated during excavation.

To address this issue, we take inspiration from mole rats, which are known for their ability to move forward and backward on steep slopes.

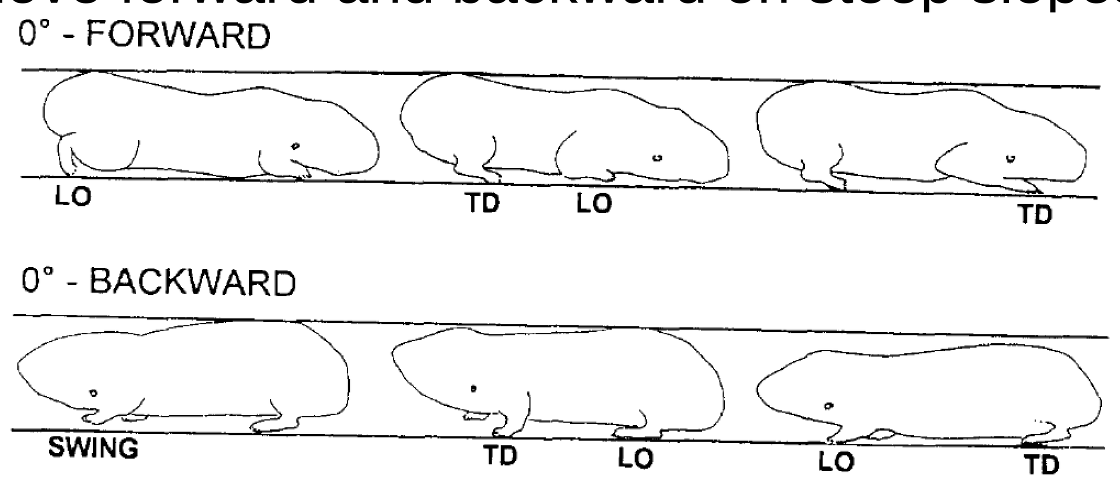


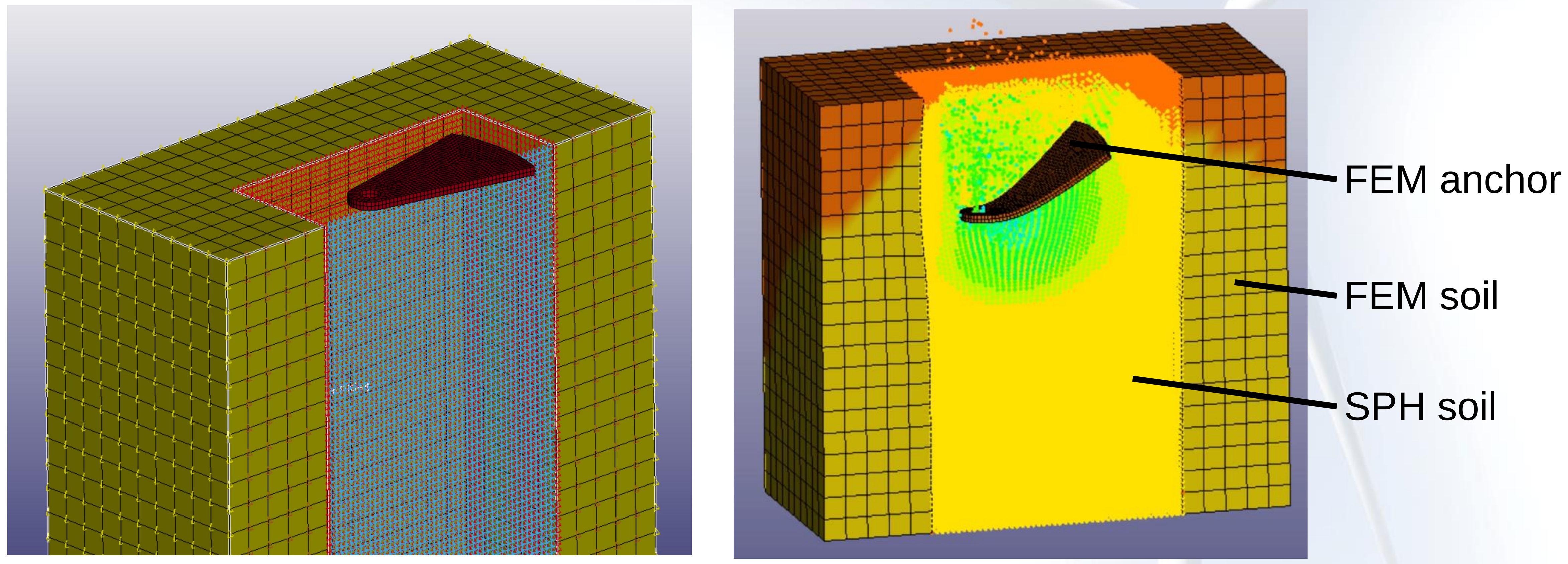
Figure 1. Locomotion of mole rat (Eilam and Adijes, 1995). LO: Lift off. TD: Touch down.

Research Objective

In order to analyze the mechanical interaction between the mole rat – inspired anchors and the surrounding soil, we propose a modeling approach that can be used to simulate anchor penetration and pull out at reasonable computational cost.

- The Finite Element Method (FEM) is widely used to analyze cone penetration experiments or design anchoring systems. It is computationally efficient. However, excessive element distortion limits the efficiency and accuracy of FEM simulations.
- Smooth Particle Hydrodynamics (SPH) is a particle-based mesh free technique that naturally allows large particle displacements to take place by tracking material points directly. But the computational cost of SPH increases significantly in large size simulation while small particle size is necessary to ensure the accuracy.

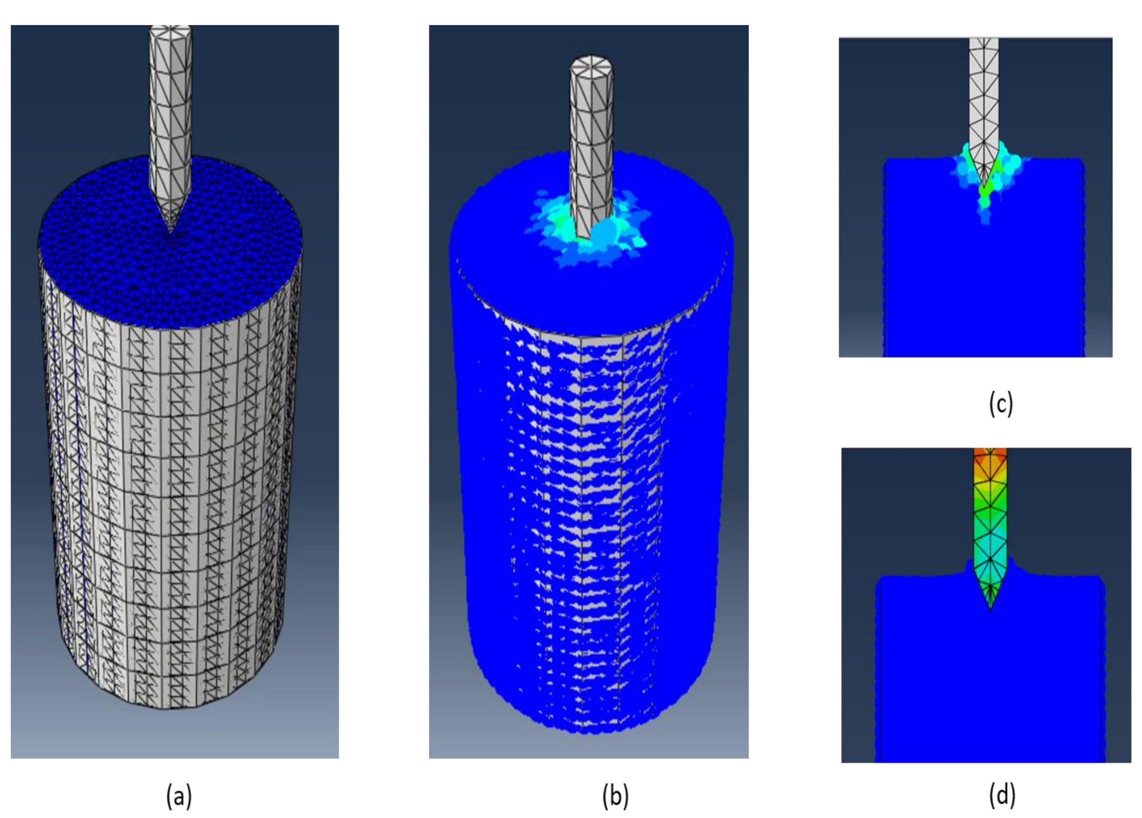
Proposed Methods

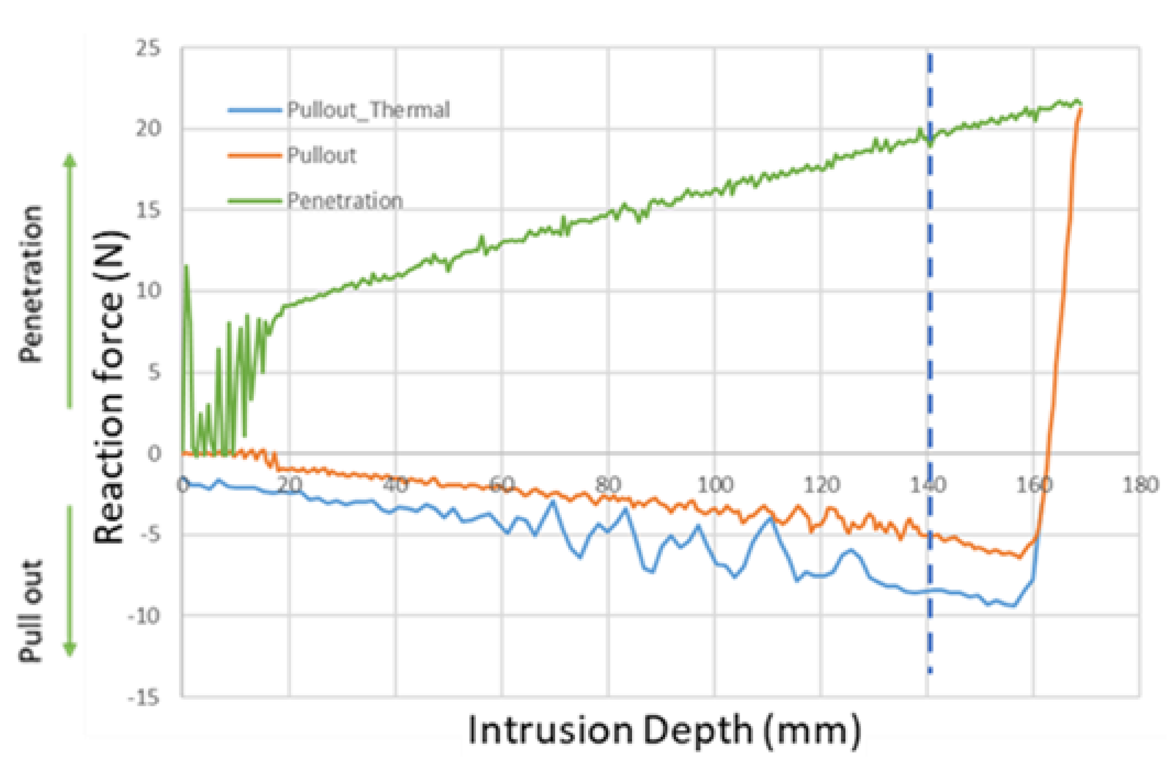


We propose a numerical approach that couples the FEM and SPH (FEM+SPH):

- The SPH method is used to simulate the soil close to the penetration zone where large deformation of soil takes place.
- The portions of the model only generate small strain (i.e., probe and far-field soil) is simulated by FEM to improve the computational efficiency.

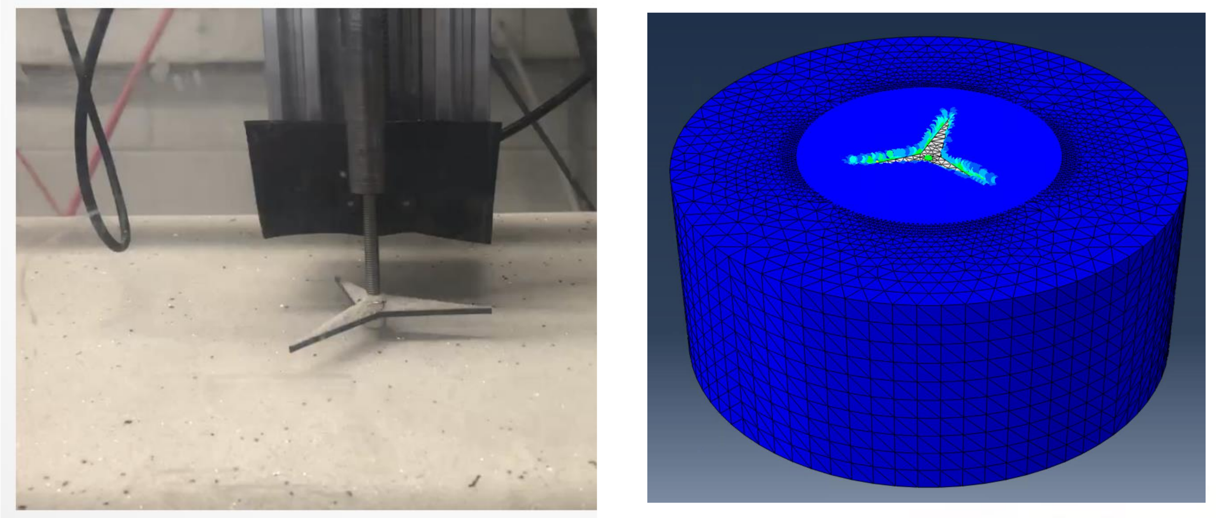
FEM+SPH Cone Penetration Benchmark

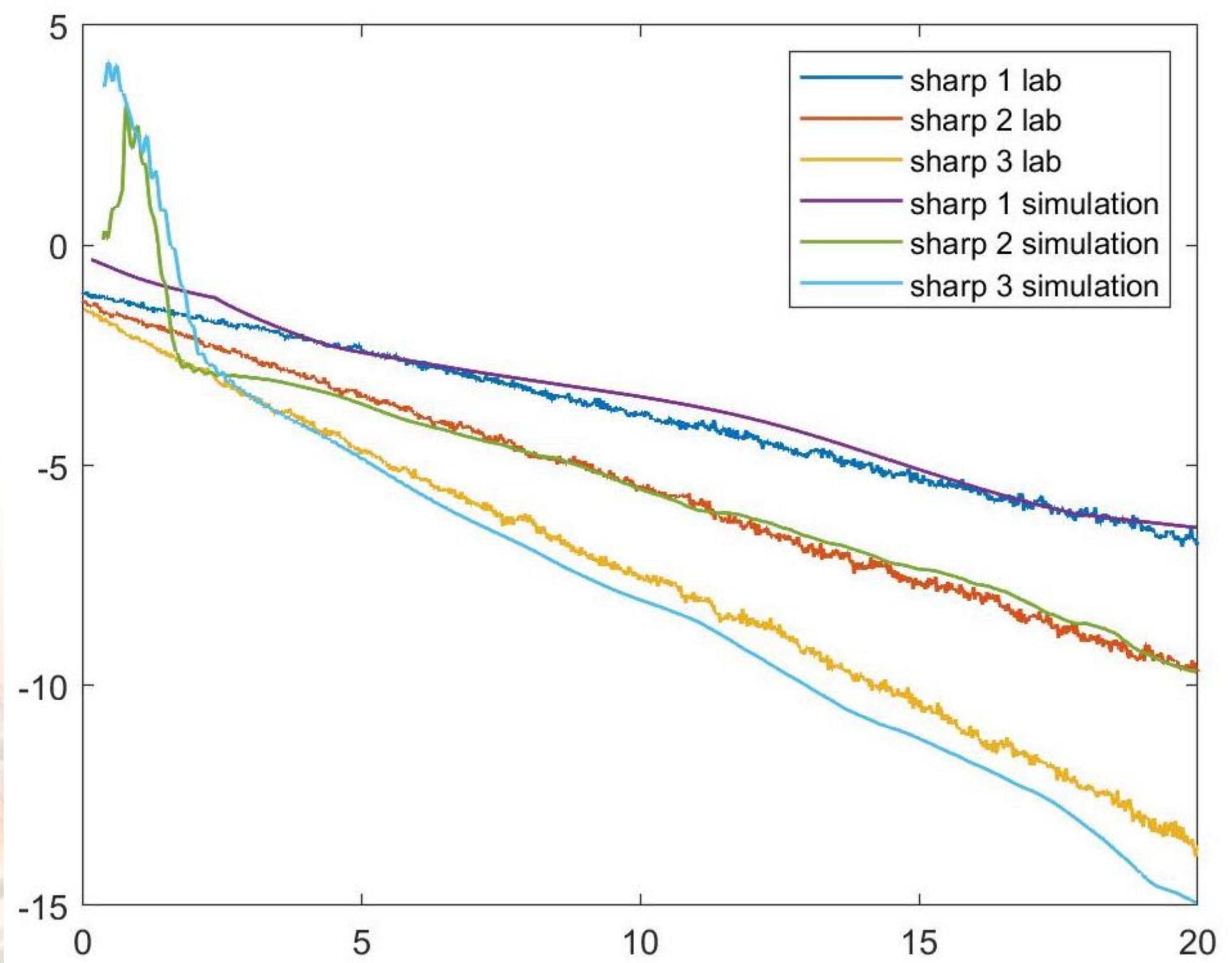




FEM+SPH cone penetration simulations were benchmarked successfully against FEM results, which proved the concept of the proposed numerical approach.
Figure (left): Simulation setup of the FEM+SPH simulation of cone penetration test.
Figure (right): The reaction curves of a Cone Penetration Test (CPT) simulation.

Anchor Push-in Simulation





- The early anchor push-in simulations show promising results. The reaction curve obtained in simulations can well match experimental data.
- Will keep calibrate the model and start analyzing local mechanism around anchor.

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EFFECT OF TIP SHAPE ON PENETRATION RESISTANCE OF GEO-PROBES

Presenters: Rodrigo Borela

Advisors: David Frost

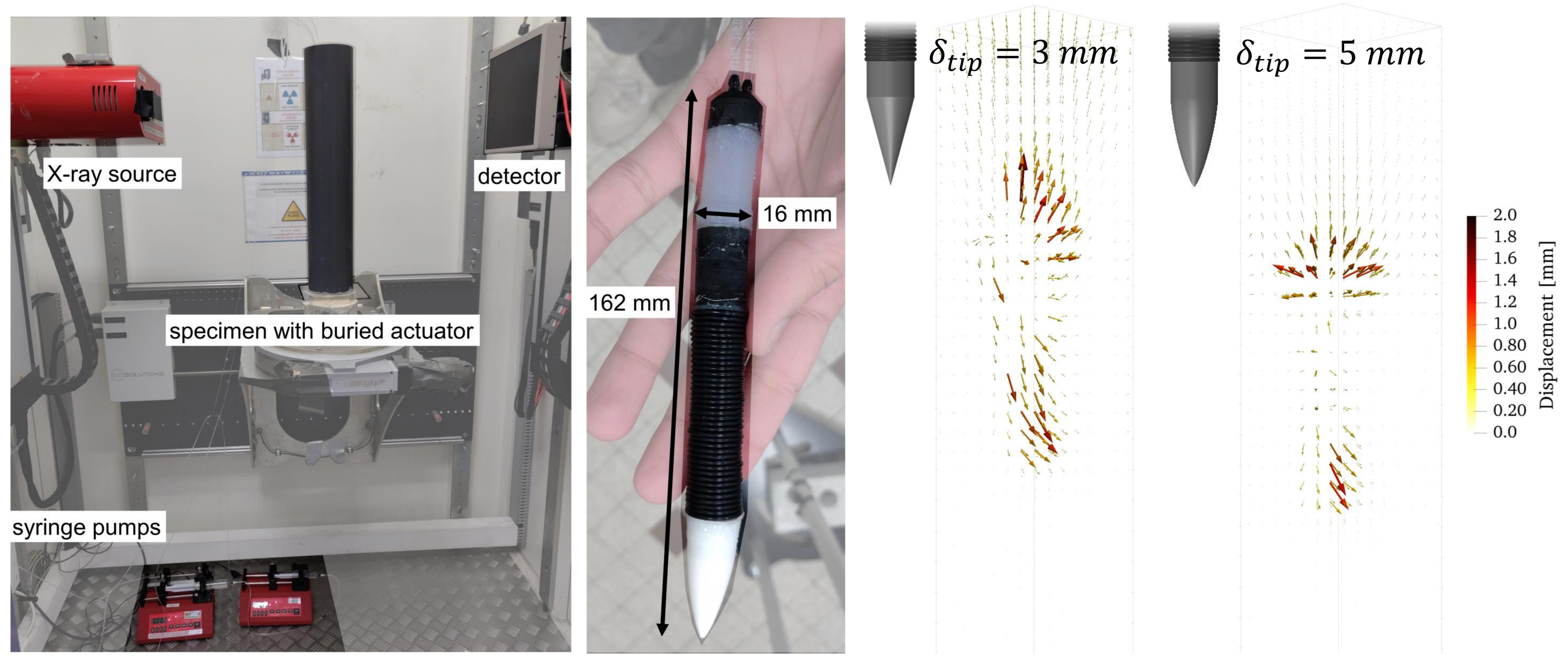
Institution: Georgia Tech

Introduction

This project aims at developing an earthworm-inspired self-propelling device to deploy sensors in the subsurface.

Testing our soft robotic prototype in sand using x-ray microtomography imaging, revealed the tip shape to play an important role in tip advancement.

In the present study, a series of numerical simulations are carried out to investigate the effect of tip shape and soil anisotropy on penetration micromechanics.

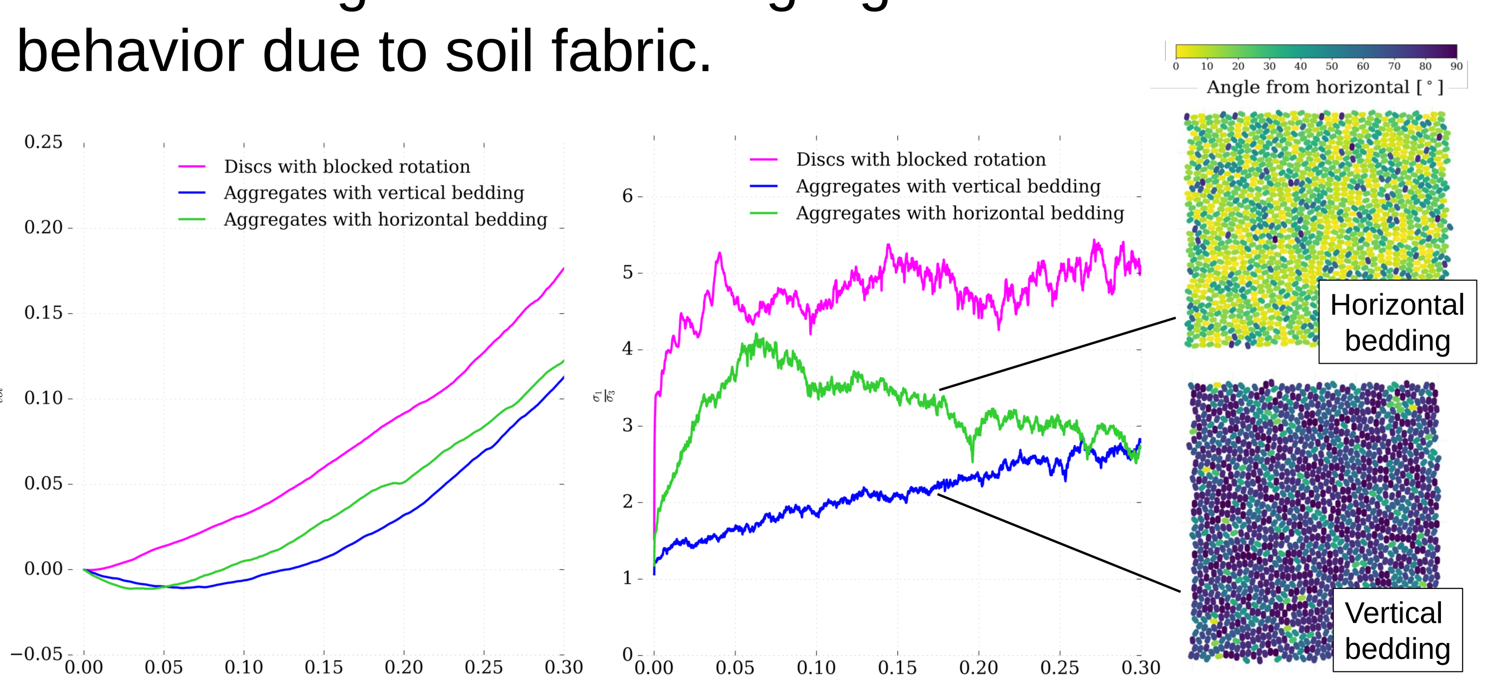


Modeling approach

The two-dimensional discrete element method is used to investigate the penetration resistance in specimens composed of discs, as well as aggregates with preferential bedding.

In specimens with discs, isotropic stresses ($\sigma_1 = \sigma_3 = 100\ kPa$) are prescribed for the boundaries while in preferentially bedded specimens an anisotropic state of stresses ($\frac{(\sigma_1+\sigma_3)}{2} = 100\ kPa$) is imposed to model the penetration of the geo-probe in both horizontal and vertical directions.

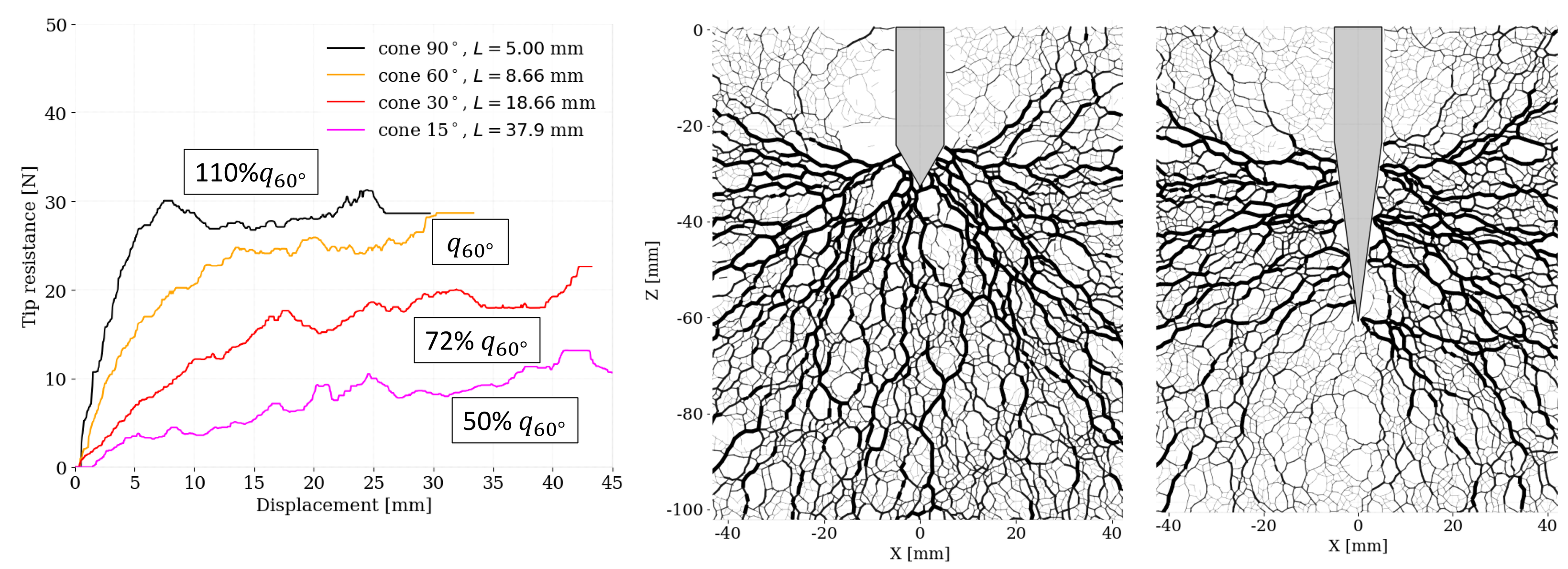
The following biaxial tests highlight the difference in shear behavior due to soil fabric.



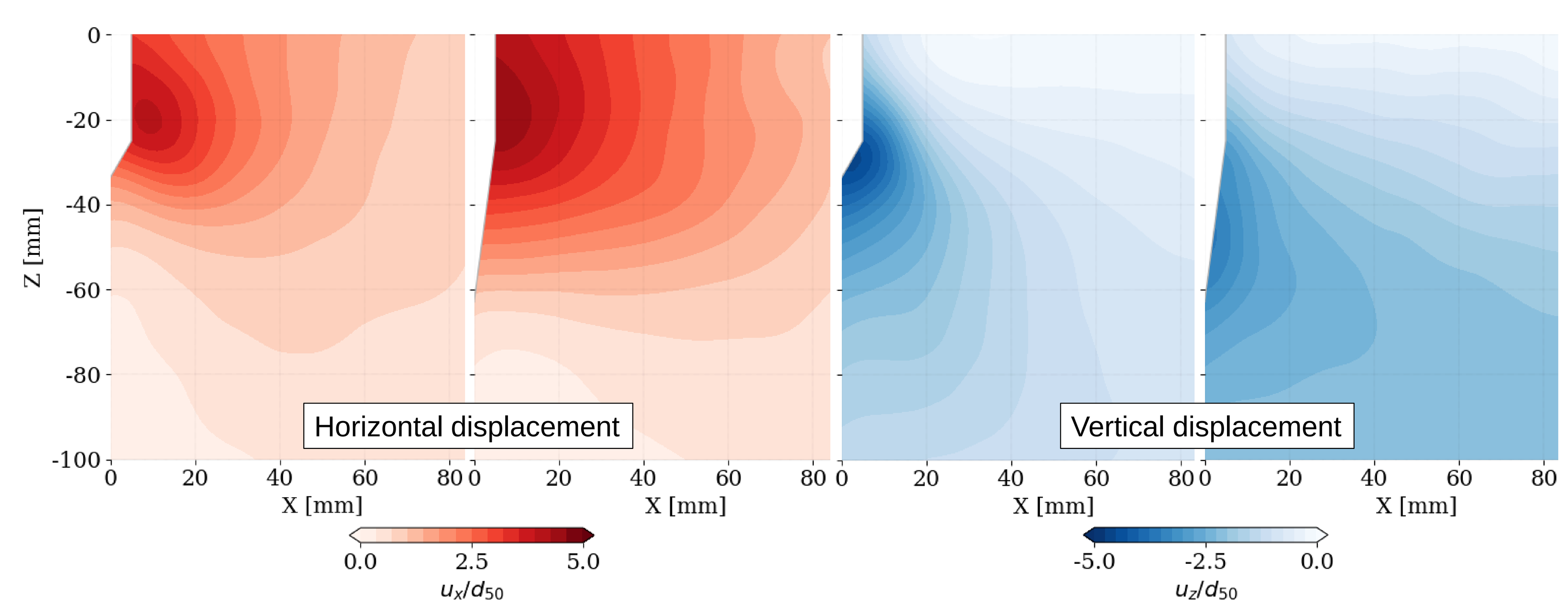
Impact of tip sharpness with conical tips

Reducing the tip apex angle from the standard 60° used in CPTs to 15°, reduces the penetration resistance by approximately 50% in frictionless tips.

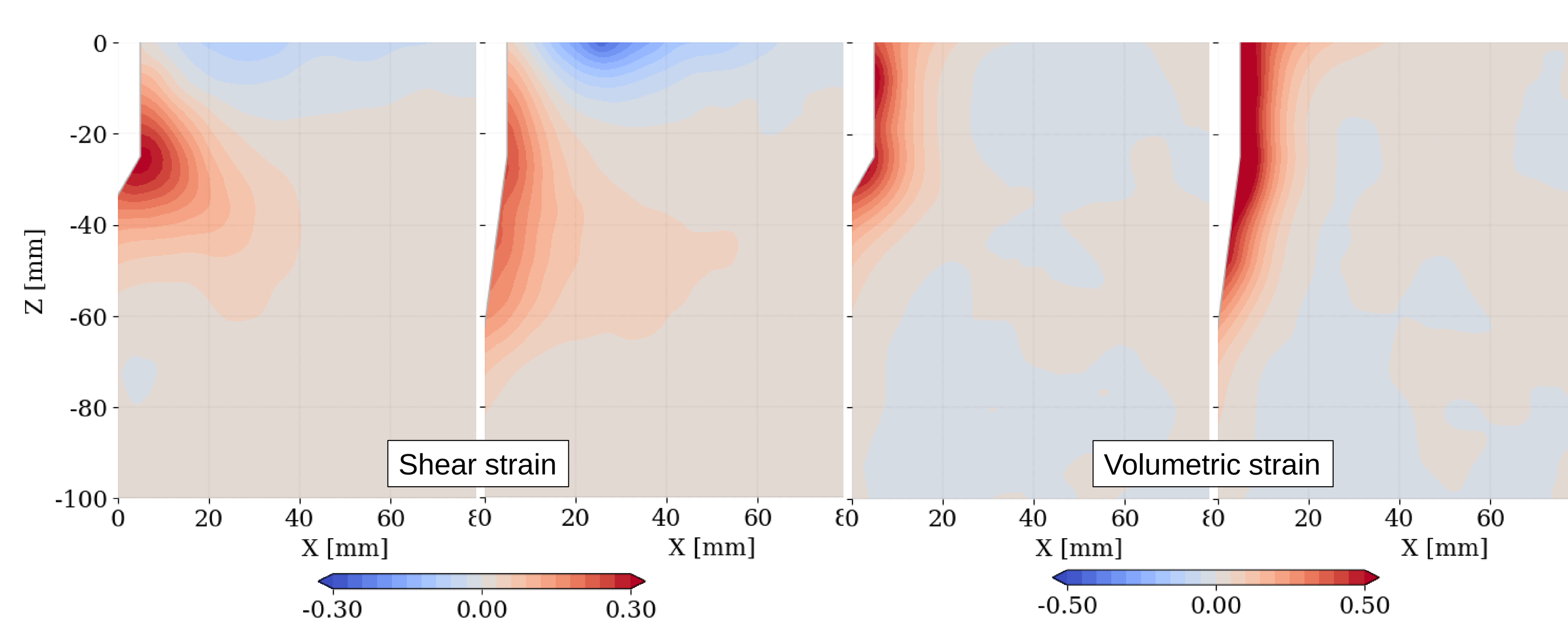
These results reflect the change in the force networks from mostly vertical to a horizontal orientation.



The soil mechanics around the tip changes with increasing tip sharpness. By computing a displacement field over the discrete elements it can be observed that as tips become sharper, horizontal displacements become larger, while the vertical displacements become smaller.



Furthermore, calculating the micro-strain field illustrates that the specimen endures lower shear strains with sharper tips, in contrast to the standard 60°.

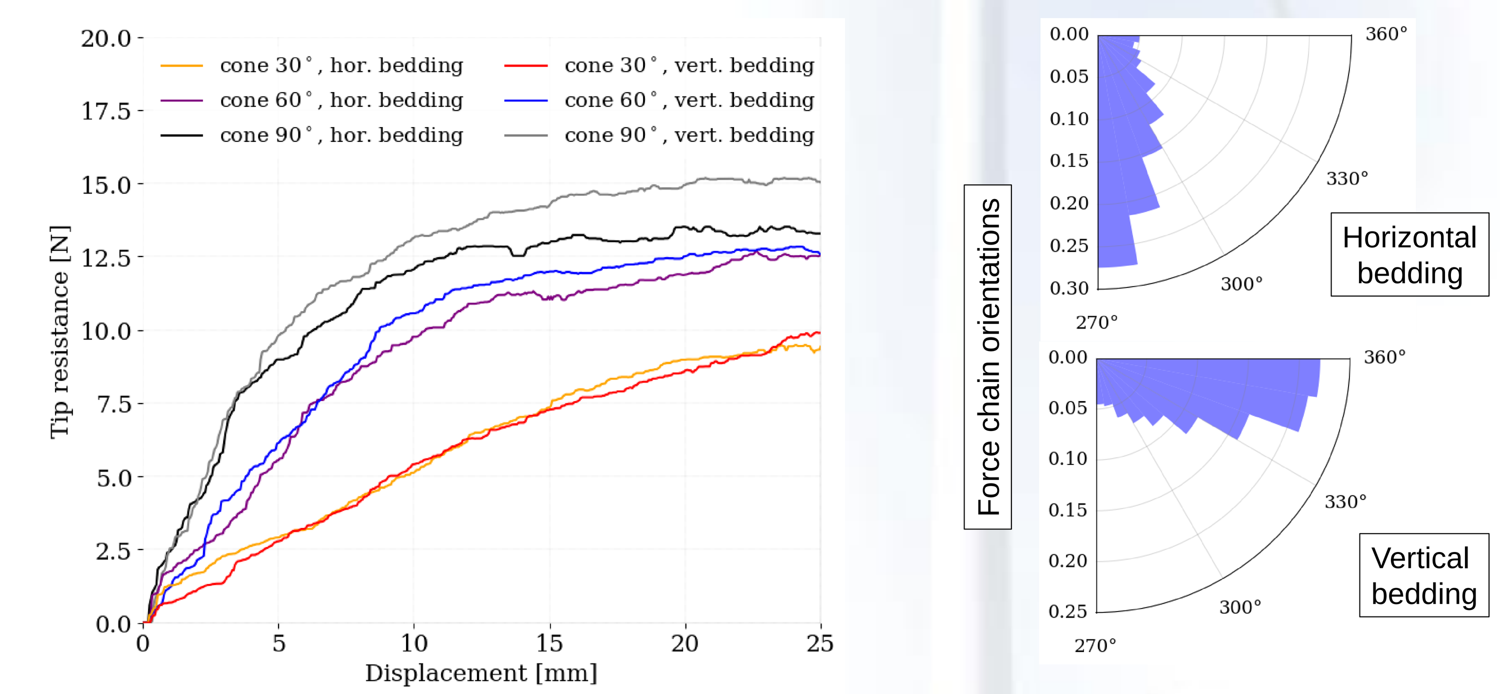


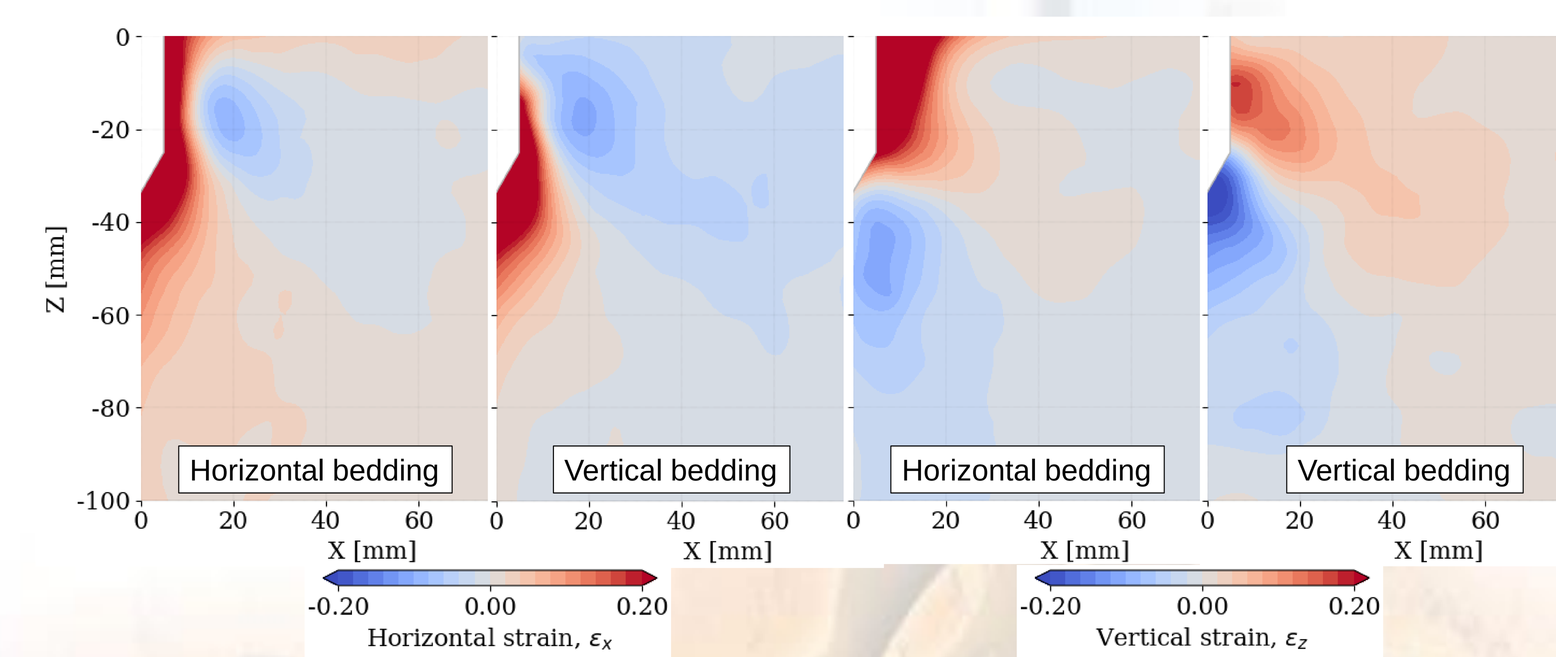
Impact of anisotropy

Tests with a horizontally bedded specimens correspond to vertical tip penetration, whereas those with a vertically bedded specimens correspond to the geo-probe traveling horizontally in the ground.

When the geo-probe travels horizontally, the penetration resistance is larger than when advancing from the top.

This result reflects a shift in kinematics of the specimen, where the material is significantly compressed vertically and horizontally when the geo-probe is traveling horizontally, due to the tight interlocking in the direction of the of predominant particle displacement.





Final considerations

The study provides further insight into penetration mechanics of probes of different shapes, and alternatives to reducing the necessary effort to advance into the soil, making the geo-probe more energy efficient.

Acknowledgement

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