

Earthworm-inspired penetration: energy consumption and power demand in the context of terrestrial and planetary landed exploration

Penetración inspirada en lombrices: consumo y demanda de energía en el contexto de la exploración terrestre y planetaria.

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ABSTRACT: Earthworm-inspired penetration has been shown to significantly reduce penetration resistance in dry coarse-grained soils and lunar regolith simulants when compared to conventional push-in penetration. The bio-inspired method seems particularly suitable for the characterization of terrestrial sediments using light-weight devices and for the subsurface exploration of reduced gravity celestial bodies such as the moon and Mars. In our bench-scale earthworm-inspired penetration device, a flexible membrane is affixed near the tip of a miniature cone penetrometer. The membrane is inflated and deflated at fixed depth intervals; thus, the device not only consumes energy to overcome the ground penetration resistance, but also the resistance to the expansion of the membrane into the soil. As a result, additional energy is consumed in the process (pressure-volume energy). This work presents the differences in energy consumption and power demand measured for the limited depth range of bench scale tests and extrapolates the results to explore differences in energy consumption with depth compared to conventional push-in methods. The analysis provides key insight into the sustainability advantages of earthworm-inspired penetration in terrestrial applications, and the potential for its deployment in celestial bodies.

KEYWORDS: Soil Penetration, Earthworm-Inspired Penetration, Bio-Inspired Geotechnics, Soil Cavity Expansion and Collapse.

1 INTRODUCTION

Geotechnical subsurface exploration is a crucial part of civil engineering, providing engineers with information on the composition, location, properties, and distribution of soil strata in a location. In a 2020 study of lawsuits involving geotechnical engineering firms, it was estimated that 44% of the cases studied were caused by an inadequate site investigation (Yabusaki et al. 2020). This can be caused by inaccurate testing performed by the contractor, incorrect interpretation of the results, or a low resolution of collected datapoints.

Cone Penetration Testing (CPT) has been a proven method of site investigation for decades. The test involves the insertion of a penetrometer with a conical tip of standard geometry (3.57 cm in diameter with an apex angle of 60°) at a standard rate (2 cm/s) into the soil (ASTM 2020). The instrumented probe is capable of recording several parameters such as pore water pressure, side friction, thermal conductivity, etc.

Following previous work by (Salgado, Mitchell, and Jamiolkowski 1997) it can be stated that:

$$q_c = q_c(D_r, \sigma_v, \sigma_h, \frac{B}{r_c}, BC) \quad (1)$$

where q_c = penetration resistance, D_r = relative density of sand specimen, σ_v and σ_h vertical and horizontal stresses at the point of penetration, which are in turn a function of depth, B = chamber radius in which penetration is taking place ($B \approx \infty$ for in-situ penetration), r_c = cone radius, BC = Boundary Conditions.

The direct correlation between depth of penetration and penetration resistance makes penetration depths of over 30 m difficult in regular soil conditions, however 100 m tests have been performed on weaker soils (Lunne, Powell, and Robertson 2002).

Current CPT technologies involve the deployment of a testing rig capable of producing 100 kN – 200 kN of penetration force by using a hydraulic jacking system. The rig itself is used to provide the reaction force through a combination of self-weight and superficial anchoring. CPT Testing Trucks will often be ballasted with a weight of around 20 tonnes (200 kN), however smaller testing rigs can also be employed. These smaller rigs use screw anchor systems to provide the required reaction force to the soil's penetration resistance (Lunne, Powell, and Robertson 2002).

Efforts have been made to improve current burrowing techniques by analyzing and mimicking plant and animal behavior (Dorgan and Daltorio 2023). In recent years, researchers have performed numerical modeling studies of bio-inspired penetration (Chen, Martinez, and DeJong 2022), as well as other advances in the field of bio-inspired and bio-mediated burrowing robotics (Wei et al. 2021). While promising, the numerical simulations tend to oversimplify the probe-sediment interactions. It is therefore important to rely on physically derived measurements to perform robust analysis. In particular when assessing the potential gains in energy efficiency derived by implementing bio-inspired solutions. Claims of enhanced sustainability through reduced energy consumption must always be backed by data.

The environmental impact that the construction industry generates has come into extreme focus by the international

community. It is estimated that in 2018, 39% of energy and process-related carbon dioxide emissions were produced by the buildings and construction sector (IEA 2019). A number of researchers have investigated the contribution of the geotechnical engineering field to the carbon footprint of the construction industry (Inui et al. 2011; Shillaber, Mitchell, and Dove 2016; Raymond et al. 2020).

A considerable percentage of the emissions produced by the construction industry can be attributed to overly conservative designs. When an insufficient amount of information has been collected through subsurface investigations, the designing engineer has to balance the uncertainty with a worst-case scenario design. If a technology was made available that would make CPT testing equipment more cost-efficient to acquire and easier to deploy, the resolution of a subsurface exploration would no longer be limited by budgetary or topographical constraints.

2 MATERIALS, METHODS, AND EXPERIMENTAL SETUP

Earthworms' peristaltic movement during burrowing has been studied extensively in the past (Dorgan and Daltorio 2023). The common earthworm's motion can be simplified into a cylinder that expands and contracts in its longitudinal direction (stretches and shortens) and in its radial direction (swells and shrinks). This simplified model has inspired researchers in their robotics design (Omori, Hayakawa, and Nakamura 2008; Borela et al. 2021).

The team at New Mexico State University has developed an earthworm-inspired miniature cone penetrometer described in (Cortes and John 2018; Naziri 2023; Naziri et al. 2024), see figure 1. The body of the probe consists of a stainless-steel tube 9.5 mm in diameter. A conical tip is attached at the end of the tube. The cone is 12.7 mm in diameter and has an apex angle of 62°. A silicon membrane is affixed to the tube near the tip using two O-rings. Orifices in the stainless-steel tube at the membrane location connect it to a hydraulic system capable of injecting up to 70 mL of water to inflate the membrane. The hydraulic system consists of a linear actuator attached to a hydraulic cylinder. The actuator is operated by an Arduino microcontroller; thus, preset linear displacements on the linear actuator are translated into controllable water volume flow in or out of the flexible membrane. A pressure transducer connected directly to the hydraulic system is used to monitor the pressure in the system. The Arduino microcontroller is also used as a data logger to record the system pressure and the volume in the membrane. The inflation and deflation is independent of the vertical movement of the probe, allowing for different configurations of inflation volumes, penetration depths or inflation-deflation intervals. This silicone membrane is the innovation presented in this work, by inflating and deflating the membrane the soil can be manipulated to reduce the penetration resistance.

Penetration into soil does cause wear in the flexible membrane. Indeed, it must be replaced after 2 to 3 tests to avoid sudden bursting during inflation.

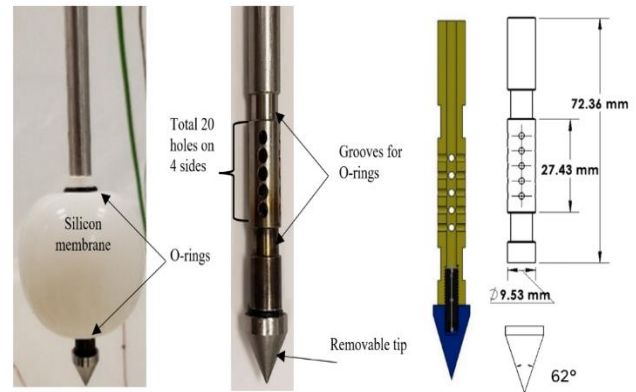


Figure 1 Earthworm-Inspired Cone Penetrometer

Penetration tests are conducted by pushing the probe into a local sand, see figure 2. A sieve analysis was conducted on the sand using approximately the procedure from ASTM Standard D-422. The soil exhibits a mean particle size $D_{50} = 0.35\text{mm}$, a Coefficient of Uniformity $C_u = 2.86$, and a Coefficient of Curvature $C_c = 1.04$, and can be classified according to the USCS as a poorly graded sand. The minimum and maximum void ratios were determined to be $e_{min} = 0.47$ and $e_{max} = 0.73$, and the average sphericity and roundness of the particles was 0.76 and 0.51 respectively. Test specimens are prepared by filling a 45 cm x 45 cm x 60 cm plastic container. Two specimen preparation methods are used to produce loose ($e = 0.67$) and dense ($e = 0.54$) specimens. In the preparation of the loose specimens, the container was filled via the air-pluviation method. The dry sand was poured through a funnel set at a height of about 1 cm from the surface of the deposited material. The procedure results in a specimen with a density of 1642 kg/m^3 and void ratio $e = 0.67$. To achieve a high-initial density, the specimen was compacted using a mechanical shaking table. The test chamber was placed on the shaking table and was filled in three lifts (20 cm each). After pouring each lift, the specimen was shaken at a frequency of 10 Hz for a duration of 10 seconds. This method results in a specimen with a density of 1786 kg/m^3 and void ratio $e = 0.54$.

The earthworm-inspired probe is mounted on a universal loading frame. The frame used in this study is able to provide a force of 1.1 kN and extends to a maximum stroke length of 30 cm. A load cell is used to monitor the penetration resistance encountered by the probe. A Newton Test Machine Controller (TestResources®) monitors the penetration force applied as well as the depth of penetration. The bio-inspired penetration test starts with the probe resting on top of the sand specimen so that only the conical tip is buried. The probe is pushed into the soil to a depth of 10 cm at a constant speed of 2 mm/s. At this depth, the probe stops, and the flexible membrane is inflated to a maximum volume of 70 mL. The inflation process takes about 45 seconds. Once the pressure readings stabilize, the membrane is deflated (45 sec).



Figure 2. Testing Material Specimen

When the membrane is fully retracted, penetration resumes to a depth increment of 1 cm. The probe stops again, and the inflation-deflation cycle is repeated. The process is repeated until the probe reaches a depth of 26.1 cm

The control tests consist of a continuous push-in penetration into each specimen at a rate of 2 mm/s using the earthworm inspired probe. In control tests the inflation-deflation mechanism is not utilized. New loose and dense specimens are prepared for the control tests.

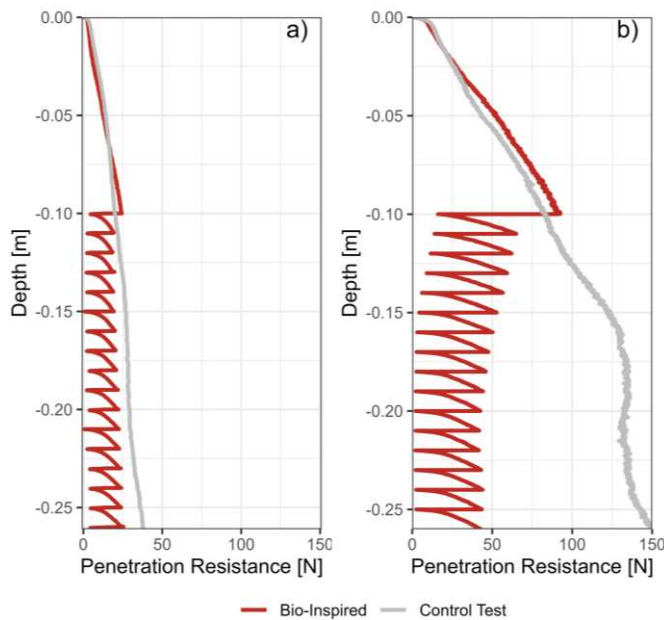


Figure 3. Penetration Resistance in Direct-Push and Bio-Inspired Penetration. a) Loose Specimen $e = 0.67$ b) Dense Specimen $e = 0.54$

3 TESTING RESULTS

Penetration resistance increases with depth up to 10 cm, where the probe makes the first stop, see figure 3. At this point the flexible

membrane is inflated to a maximum volume of 70 ml. The corresponding pressure-volume signature is presented in figure 4. As the membrane inflates, a cavity is created within the sand. When the membrane is deflated, the cavity collapses and the soil penetration resistance decreases, in some cases down to zero. Upon resuming penetration, the soil resistance increases rapidly up to a maximum value at the end of the 1cm penetration interval. The maximum resistance value observed in each step of the bio-inspired penetration procedure is plotted vs its depth in figure 5. In loose sands, the maximum penetration resistance is reduced by 21% from the first to the second inflation-deflation cycle. However, subsequent intervals show a linear increase in maximum penetration resistance of about 0.4 N/cm . In dense sands, there is a 30% reduction in the maximum penetration resistance between the first and second steps of bio-inspired penetration. The maximum resistance of each step then decreases linearly at a rate close to 2.5 N/cm . The reduction continues down to a depth of 20cm (10 steps of bio-inspired penetration). Afterwards the maximum resistance observed in each step remained at around 43 N.

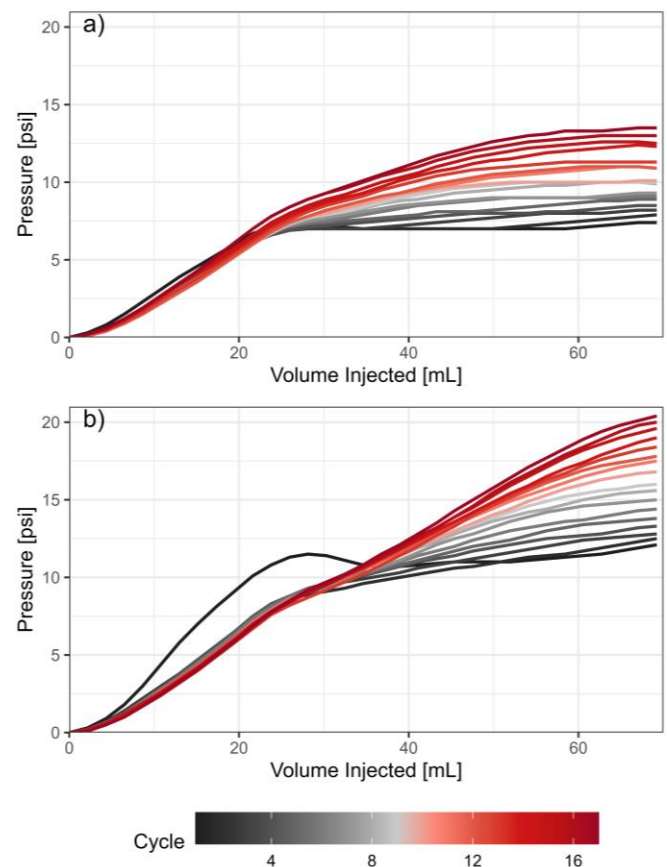


Figure 4. Pressure-Volume during inflation of flexible membrane in Bio-Inspired Penetration. a) Loose Specimen $e = 0.67$ b) Dense Specimen $e = 0.54$

Penetration resistance depends on the state of stress in the soil. Since the stresses in the soil are a function of depth, it can be understood that by creating a cavity and collapsing it along a certain depth interval, the soil can be 'reset' to similar stress conditions as the previous interval, leading to comparable penetration resistances between subsequent steps. The result of the bio-inspired penetration process after 16 steps is a reduction of 72% in penetration resistance at a depth of 26 cm.

3.1 Surface Anchor Reaction Force

The required surface reaction force is equivalent to the maximum resistance encountered by the probe up to the desired depth of penetration. In conventional direct-push penetration of a homogeneous soil, the maximum resistance is encountered at the maximum depth achieved. Thus, the required surface reaction force is directly correlated with the desired depth of penetration.

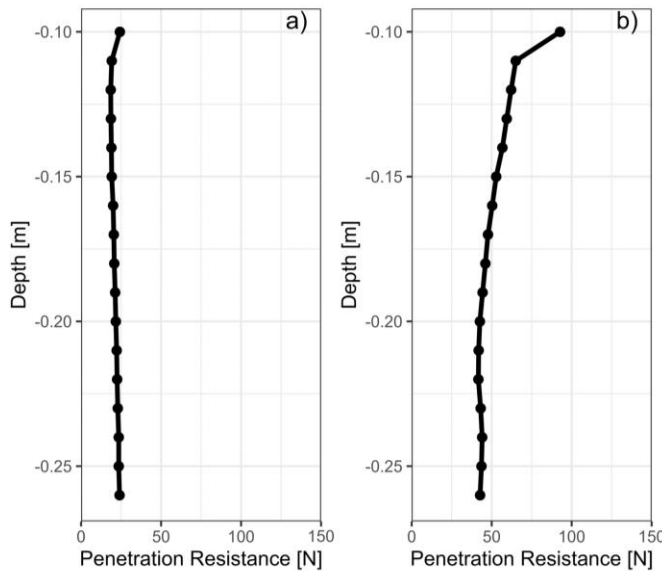


Figure 5. Maximum Penetration Resistance reached at each step of Bio-Inspired Penetration. a) Loose Specimen $e = 0.67$ b) Dense Specimen $e = 0.54$

When using the bio-inspired penetration process in a dry, dense, homogeneous sand, the maximum resistance is encountered in the first 10 cm of penetration. The required surface reaction force for bio-inspired penetration is therefore reduced to only 100 N in our testing, regardless of the desired depth of penetration, see figure 6.

3.2 Energy Consumption

The work performed by conventional direct-push penetration can be defined as a function of depth and penetration resistance.

$$W = \sum(q_c * \Delta D) \quad (2)$$

where W = work performed [J], ΔD = change in depth [m] and q_c = penetration resistance [N].

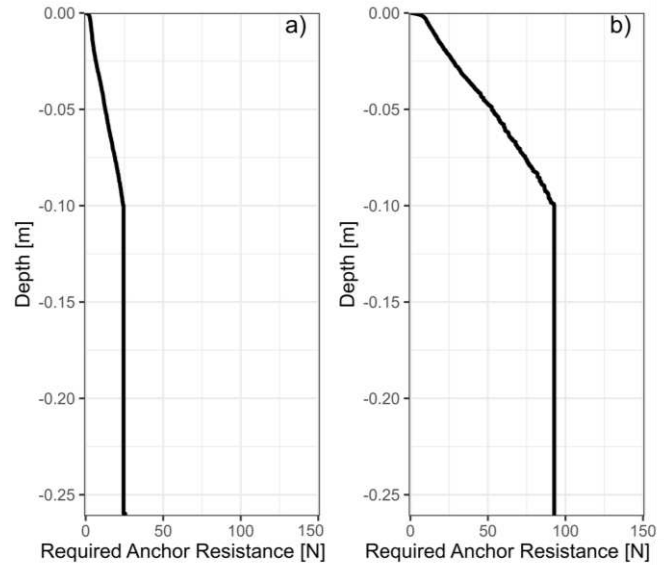


Figure 6. Required surface reaction force using bio-inspired penetration. a) Loose Specimen $e = 0.67$ b) Dense Specimen $e = 0.54$

In conventional direct-push penetration we consider that q_c is also a function of depth. Therefore, work performed would be expected to resemble a quadratic function where W increases exponentially with depth. Bio-Inspired Penetration not only consumes the energy needed for penetration, but also the energy needed for the inflation of the flexible membrane. Inflation work can be defined as $W = P * V$, where P = Pressure [Pa] and V = Volume [m^3].

Energy consumption in Bio-Inspired Penetration can be therefore calculated by:

$$W = \sum(q_c * \Delta D + P * \Delta V) \quad (3)$$

where q_c = Penetration Resistance, ΔD change in depth, P = Pressure, and ΔV change in volume. Energy consumption was calculated for conventional and bio-inspired penetration, see fig. 7. Pressure vs Volume was observed to have a bi-linear trend.

After the first inflation-deflation cycle, all other cycles' pressure-volume plots are identical from 0 to 25ml. After this point the pressure needed to continue inflation increases until reaching the peak pressure observed at that depth (see figure 4). When plotting peak pressure vs depth of inflation-deflation cycle as seen in Figure 8, a linear trend can be observed where pressure increases at a rate close to 0.312 psi/cm in Loose Sands and 0.546 psi/cm in Dense Sands. The projected pressure required at a depth of 30 m in a dense specimen is 1645 psi.

The energy required for membrane inflation was found to be directly proportional to the depth of the inflation-deflation cycle as seen in figure 10.

Given that the energy needed for penetration in the bio-inspired process is linear, and the energy needed for inflation increases linearly as well, the characteristic energy function in bio-inspired penetration is expected to be linear. In figure 7, it can be observed

that once inflation-deflation cycles start, the work performed increases linearly by 352 J/m in Loose Sands and 492.45 J/m in Dense Sands. Direct-push penetration energy trends however, approximate the quadratic equations:

$$E_{Loose\ Sand} = 53.993D^2 + 9.0845D - 0.1109 \quad (4)$$

$$E_{Dense\ Sand} = 285.31D^2 + 24.045D - 0.47 \quad (5)$$

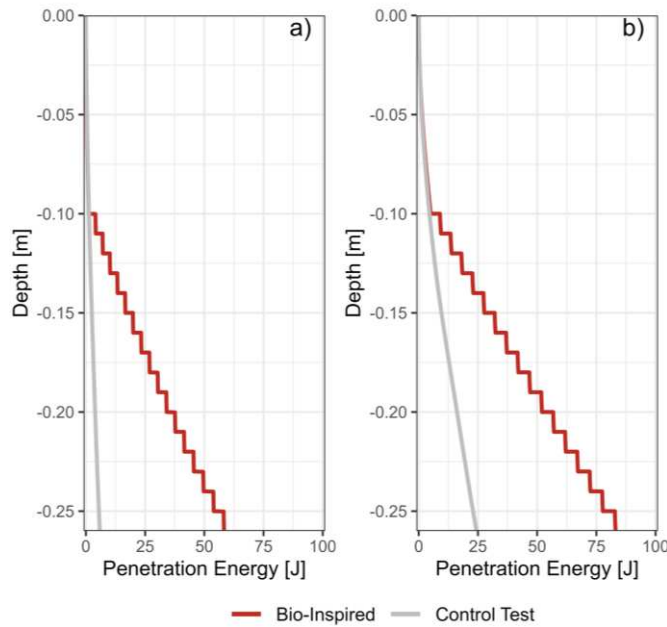


Figure 7. Work performed using direct-push and bio-inspired penetration. a) Loose Specimen $e = 0.67$ b) Dense Specimen $e = 0.54$

In low depth penetration, the reduction of penetration resistance is not enough to justify the increase of energy consumption from the inflation-deflation cycles. However, by projecting these equations for direct-push and Bio-Inspired Penetration processes it can be observed that Bio-Inspired Penetration can be energy efficient at penetration depths larger than 6.245 m in loose sands and 1.54 m in dense sands. See figure 9. At a depth of 30 m, energy consumption is reduced by 94.3% when using bio-inspired penetration instead of direct-push penetration in dense sands.

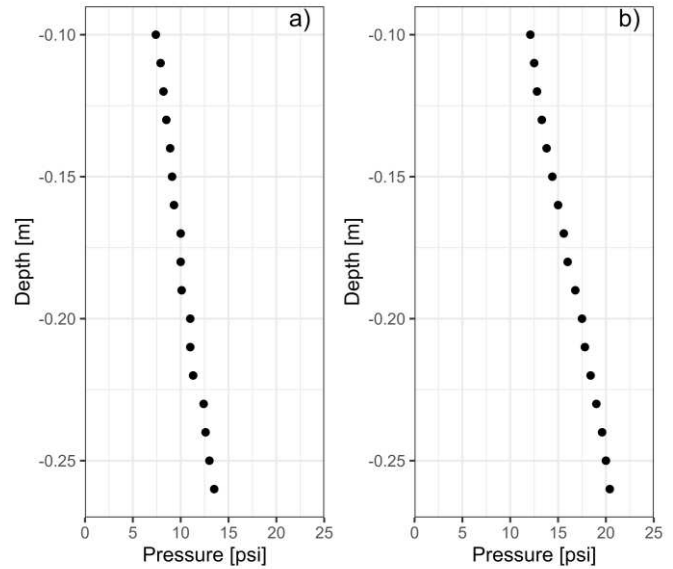


Figure 8. Maximum pressure observed in inflation-deflation cycles at depth of inflation. a) Loose Specimen $e = 0.67$ b) Dense Specimen $e = 0.54$

3.3 Sustainability Considerations

A conventional CPT testing rig is usually deployed in a large truck which is then ballasted to produce enough deadweight (around 15 to 20 tons) as to achieve the required penetration depths for a test (Lunne, Powell, and Robertson 2002). The bench-scale testing rig used for the earthworm-inspired geo-probe is much lighter, under 200 kg. Assuming a linear relationship between the weight of the vehicle and its CO₂ emissions (Mock 2017) meaning a vehicle that weighs 2 tons will produce 10% of the emissions that a 20 ton vehicle would produce. This would result in a 3-orders of magnitude advantage to the bio-inspired penetration method in CO₂ emissions associated to equipment mobilization alone.

The current bio-inspired penetration process advances into the soil at 2 mm/s and starts an inflation-deflation cycle every 10 mm. The equipment being used in the bench-scale equipment is capable of inflating and deflating the membrane in 90 seconds. This translates to an equivalent speed of penetration of 0.37 m/hr. With the energy model stated before, Bio-Inspired penetration for a 30 m exploration would use 14.7 kJ of energy. A study performed by (Purdy et al. 2022) on the sustainability and energy efficiency of conventional CPT reported an energy consumption of 4.52 MJ/m or 135.6 MJ in a 30 m exploration. According to our analysis, the penetration energy associated to conventional push-in penetration is of the order of 258kJ.

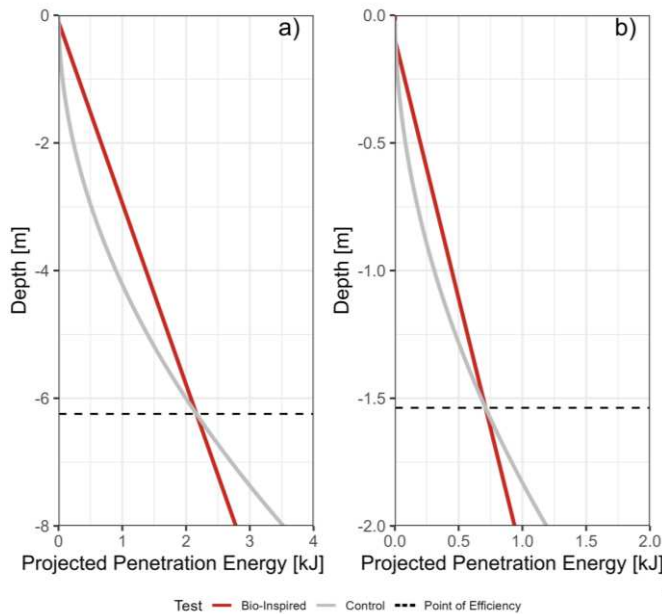


Figure 9. Projected energy trends and depth of efficiency. a) Loose Specimen $e = 0.67$ b) Dense Specimen $e = 0.54$

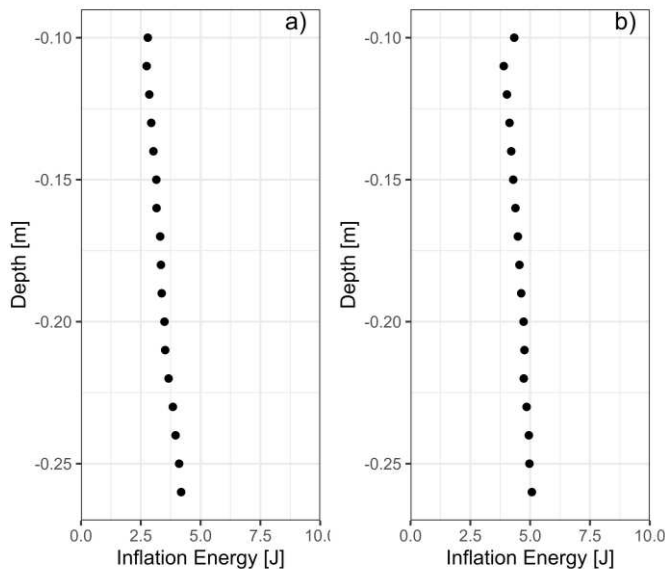


Figure 10. Energy consumed during inflation of membrane at each cycle depth. a) Loose Specimen $e = 0.67$ b) Dense Specimen $e = 0.54$

Assuming a 64% system efficiency (the Carnot limit), using bio-inspired penetration consumes about 23kJ for 30 m subsurface exploration. This is one to three orders of magnitude lower than conventional CPT.

4 CONCLUSIONS

Earthworm-Inspired penetration and conventional Cone Penetration Testing are fundamentally different tests yielding different types of results. CPT testing aims to test undisturbed soil to obtain direct correlations with soil properties. Meanwhile, Earthworm-Inspired penetration disturbs the soil intentionally to ease penetration resistance. Further correlations could be made in the future to characterize soil strata.

Earthworm-Inspired penetration has been compared against direct-push penetration in terms of penetration resistance, energy consumption, required surface reaction force and potential carbon footprint. By creating and collapsing a cavity in the vicinity of the burrowing tip in adequate depth intervals, we were able to reduce the penetration resistance provided by a dense, dry sand by around 72% at a depth of 26 cm when compared to conventional direct-push penetration.

When performing the earthworm-inspired penetration process on a dry, dense sand specimen, the maximum penetration resistance observed was 93N (at 10 cm), a reduction of 50% when compared to direct-push penetration. This in turn reduces the required surface reaction force by the same amount. This behavior, if consistent in larger depths, would significantly lower the required surface anchoring force. This could in turn make subsurface exploration equipment lighter and more versatile. The limiting factor in the bio-inspired approach would be the inflation pressure needed to create the cavity in the ground (1645 psi at 30m in dense sand).

A model for predicting energy consumption in bio-inspired and direct-push penetration was presented. While the bio-inspired penetration is less energy efficient at very shallow depths, as depth increases beyond 1.54 m (in dense sand) or 6.245 m (in loose sand), bio-inspired penetration becomes more energy efficient. Extrapolation of our test results to 30m deep exploration shows that energy consumption could be reduced by 94% when compared to direct-push penetration. The reduction in required surface reaction forces can lead to lighter deployment technologies. It is estimated that CO₂ emissions can be reduced by 99% just by the reduction of mobilized mass in a testing rig.

5 ACKNOWLEDGEMENTS

Support for this research was provided by the New Mexico Space Grant Consortium under NMSGC award (number GR0004899) and by the Engineering Research Center Program of the National Science Foundation under NSF Cooperative Agreement (Number EEC-1449501). Any opinions, findings and conclusions, or recommendations expressed in this material are those of the authors, and do not necessarily reflect those of the NMSGC or NSF.

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The paper was published in the proceedings of the 17th Pan-American Conference on Soil Mechanics and Geotechnical Engineering (XVII PCSMGE) and was edited by Gonzalo Montalva, Daniel Pollak, Claudio Roman and Luis Valenzuela. The conference was held from November 12th to November 16th 2024 in Chile.