Numerical and experimental assessment of steering forces during horizontal penetration in sand – a validation of a bio-inspired optimal tip shape.

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ABSTRACT

The exploration, characterisation, and monitoring of the subsurface is relevant to a wide range of applications, from environmental monitoring and in-situ characterisation to infrastructure construction (e.g., directional drilling and tunnelling) and resource withdrawal. Bio-inspiration offers promising solutions to overcome two of the most important challenges in the development of autonomous subsurface exploration probes: exploration range (related to drag forces) and steerability (i.e., ability to control direction of movement). The work uses a previously proposed bio-inspired intruder shape to study the relationship between tip orientation and the resulting forces (lateral and vertical); and explores the idea that these forces can be used to steer the probe, i.e., control the direction of motion of the probe as it advances. Numerical results with the discrete element method and experimental results with a large-scale test bed show a direct relation between tip orientation and the steering (lift and lateral) forces – supporting the case for steering systems based on intruder tip rotation. In the results, lateral and vertical forces also show a strong relation with tip orientation, however, for the tip shape tested, the vertical forces are limited to the neutral to upwards range (i.e., towards the free surface). Experimental results evidence the significant effect of intruder deformation (bending) and/or path deviation in the penetration forces acting on the intruder.

Keywords: Bio-inspiration; experimental testing; burrowing; granular media.

1. Introduction

The development of self-burrowing devices for underground exploration will enable autonomous geotechnical in-situ characterisation, more efficient exploration of hazardous or difficult access locations, and cost-effective tillage and construction of underground infrastructure. Two of the most significant challenges in the development of subsurface exploration methods are exploration range and steerability. Reducing the drag forces that oppose intruder movement has the potential to lower the energy consumption during burrowing – increasing exploration range. Similarly, reducing the

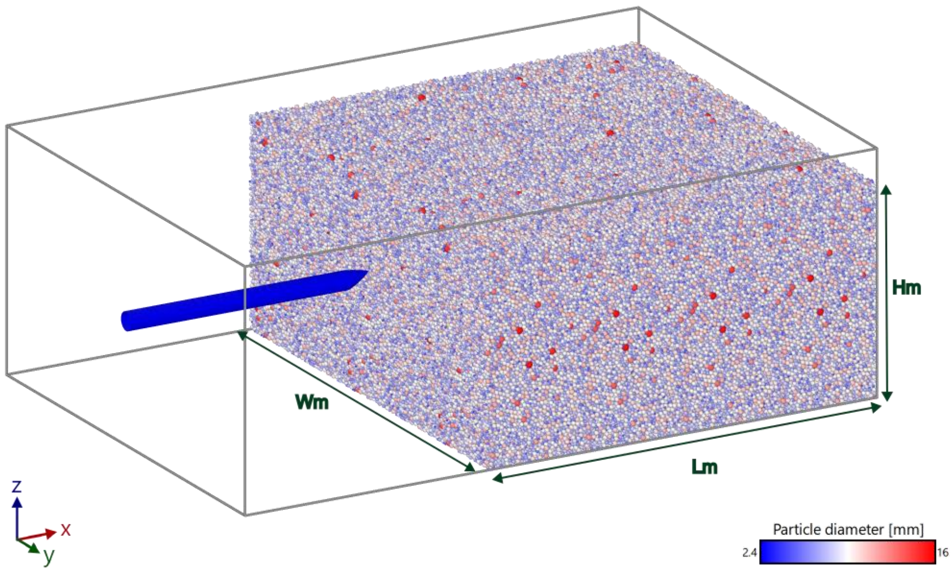

Figure 1. Representative DEM model with a tip orientation of 90º

'granular lift' forces that develop in the vertical direction, can improve the steerability, i.e., the ability to maintain and change the course of underground intruders.

Horizontal burrowing methods under development have proposed different strategies to overcome these challenges, including: constrained penetration with rig bound penetrometers (Broere and Van Tol 2001; Wei, Tumay, and Abu-Farsakh 2005), bio-inspired peristalsis (Borela et al. 2021; Das et al. 2023), anchor-push mechanisms (Zhang et al. 2023; Tao, Huang, and Tang 2020), and intruder/tip rotation (Jung et al. 2017; Tang, Zhong, and Tao 2024).

This contribution assesses the potential of a burrowing system based on an optimised intruder coupled with a tip rotation system, to tip minimise drag forces, while controlling steering forces during burrowing. This design is motivated by the aforementioned body of research, and on the prevalent steering method in horizontal directional drilling, based on the constant rotation of an asymmetric drill string end (known as bent subs) (Royal, Riggall, and Chapman 2010). We present a numerical and experimental investigation into the relationship between intruder tip orientation, and the resulting penetration forces: drag, lateral and lift, encountered during horizontal penetration in granular media. The intruder tip tested was proposed by (Patino-Ramirez and O'Sullivan 2023) as the optimal trade-off between drag (i.e., penetration force that develops against the direction of movement) and lift (vertical) forces.

Constant velocity tests were carried out using a cylindrical intruder of diameter D_p=40mm (similar to a standard CPT cone) moving horizontally at a depth of 200mm (5·D_p). Three tip orientations were tested (numerically and experimentally) to assess the viability of a steering system based on tip rotation control. Tip orientations are rotations around the axis of the cylindrical probe (x-axis, see Figure 1).

Section 2 of the manuscript details the discrete element model and its results, while Section 3 of the manuscript describes the experimental setup and its results. Lastly, Section 4 summarizes the findings of the study and directions of future work.

2. Discrete element model

2.1. Model description

Discrete element (DEM) simulations were carried out using the granular package of the open-source, molecular dynamics software LAMMPS (Plimpton 1995). A simplified Hertz-Mindlin model was used to model the contact between particles, using mechanical parameters consistent with the properties of quartz (Simmons and Brace 1965) and summarized in **Table 1**. The timestep of the simulations ($1 \cdot 10^{-7} s$) was calculated according to (Otsubo, O'Sullivan, and Shire 2017).

Table 1. Material and contact properties - DEM model

Property	Symbol	Value
Shear Modulus	G	29 GPa
Poisson's ratio	ν	0.2
Particle density	ρ	2670 kg/m^2
Friction coefficient	μ	0.25

The spherical particles in the model are scaled-up from the particle size distribution (PSD) of Toyoura sand, a fine, rounded sand with a mean particle size d_{50} = 0.22 mm, coefficient of curvature C_c = 0.96 and coefficient of uniformity C_u = 1.39; the scaled-up PSD has a d_{50}=7.2mm (scale factor 33). Randomly generated particles are placed and left to settle under gravity (9.81 m/s^2) to form a testbed under geostatic stress conditions, and rigid boundaries. The surface of the testbed is unconstrained to allow free movement of the material.

A cylindrical, horizontal probe with a diameter D_p=40mm enters the domain at a depth H_p = 200mm from the free surface. The probe is modelled as a group of spherical particles arranged to follow the contour of the probe (cylindrical body plus optimal tip), referred as intruder particles herein. The diameter and spacing between particles (measured between particle centers) are 2mm and 1mm respectively. Intruder particles move as a rigid body in the positive x-direction at a speed of 25mm/s over a total distance of 440mm (11 times D_p).

The flow regime of objects moving in granular media is controlled by the Froude number, a dimensionless number that compares the characteristic times of the intruder movement versus the time for a particle to fall back as the intruder moves past (Hilton and Tordesillas 2013). The simulations presented are in the quasi-static regime with Froude numbers $\ll 1$. In this regime, penetration forces are expected to be independent of penetration velocity (Seguin 2022).

Figure 1 shows a representative DEM model indicating the axes and dimensions used. The dimensions of the model are summarized in **Table 2**. Model dimensions were chosen to balance computational cost, while minimizing boundary effects.

Table 2. DEM model dimensions

Dimension	Symbol	Value	Normalized value (by D_p)
Intruder diameter	D_p	40 mm	1
Mean particle diameter	d_{50}	7.2 mm	1/5
Model width	W_m	520 mm	13
Model Length	L_m	720 mm	18
Model Height	H_m	420 mm	10.5
Intruder depth	H_p	200 mm	5

2.2. Numerical results

Discrete element method (DEM) simulations are performed, measuring the penetration forces exerted on the intruder for tip orientation angles: 0º, 45º and 90º. Figure 3 shows the intruder tip at the orientations tested; different orientations are rigid body rotations around the axis of the cylindrical body of the intruder (parallel to the x-axis) in the counterclockwise direction.

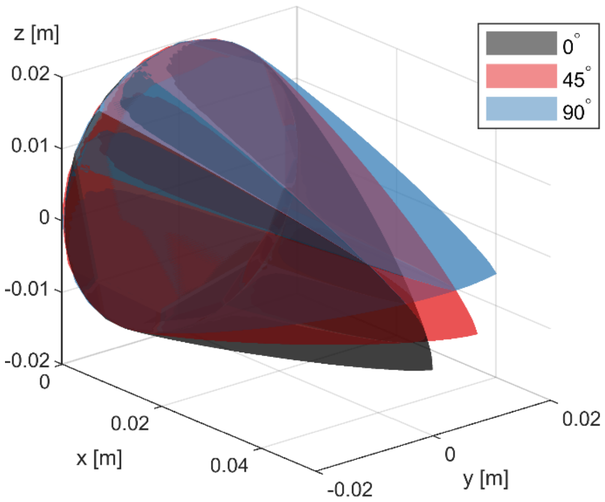

Figure 3. Intruder tip at the different orientations tested

The forces acting on the tip of the intruder in the x, y and z directions are referred to herein as the drag, lateral, and lift forces (respectively). Figure 2 shows the evolution of the penetration forces as a function of the penetration distance X_p (normalised by the diameter of the probe). Drag forces increase slightly with the angle of tip orientation, with the 90º orientation exhibiting an average drag force that is 11% higher than that of the original tip orientation (0º).

Amongst the three forces, the lateral forces show the largest variation, increasing significantly with orientation angle and reaching a maximum for the 90º orientation. Expectedly, the direction of the lift force ranges from (nearly) neutral, for the original tip, to a comparatively

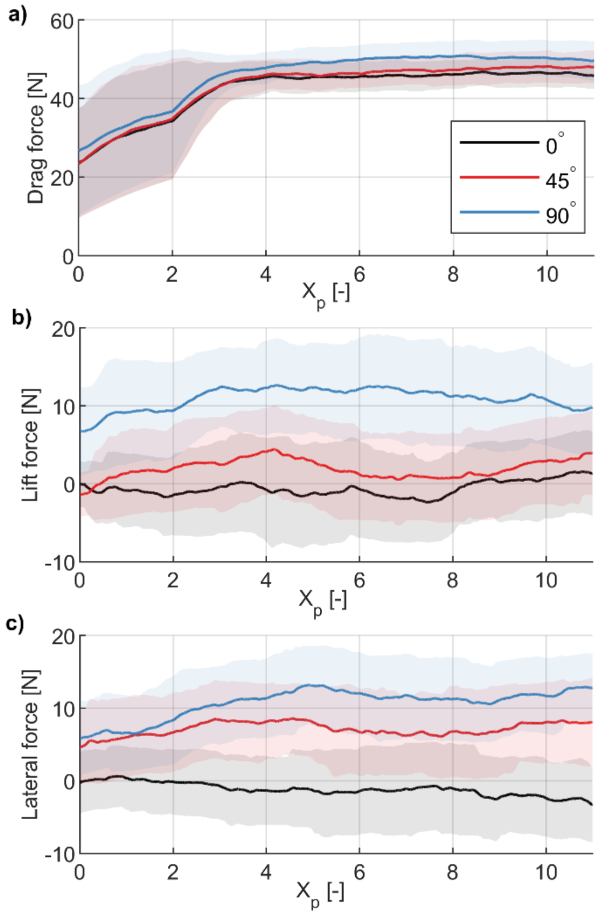

Figure 2. Penetration forces from DEM simulations

strong force that would steer the intruder towards the free surface. For the 90º orientation, the magnitude of the lateral and lift forces is similar – future studies with tip orientations over 90º will test if lateral forces continue to increase.

Applications that require steering in the negative z-direction (i.e., moving the intruder deeper into the soil) may require a different tip shape and/or a different steering system that does not rely on rotation alone.

3. Experimental campaign

3.1. Experimental setup

The testbed used for the experimental validation consists of a polypropylene box holding a sand specimen of the dimensions summarized in Table 3 and shown in Figure 4. The material used is Fuse sand 80/20, a fine, angular, and uniform sand with a median particle size (d_{50}) of 0.4mm. The sand specimens are prepared with dry pluviation, using the moving pluviometer described in (Patino-Ramirez et al. 2024); a constant pluviation height of 200mm yielded an average unit weight of 16.7 kN/m3, corresponding to a relative density of 74%. Prior to every test, the testbed was emptied and a new specimen pluviated; the variation in relative density among specimens was <5%.

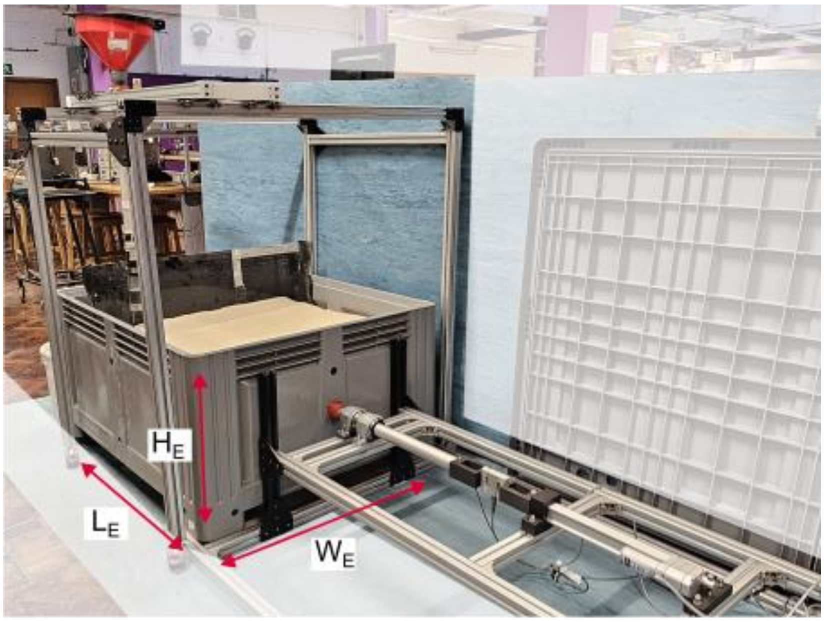

Figure 4. Experimental setup

Table 3. Experimental setup dimensions

Dimension	Symbol	Value	Normalized value (by D_p)
Intruder diameter	D_p	40 mm	1
Mean particle diameter	d_{50}	0.4 mm	1/100
Model width	W_E	1000 mm	25
Model Length	L_E	920 mm	23
Model Height	H_E	470 mm	11.75
Intruder depth	H_{DE}	200 mm	5

The intruder consists of an aluminium pipe with a 40mm diameter, attached to a 3D printed tip following the same geometry described in the numerical modelling section. The movement of the intruder was constrained to the horizontal direction with two linear bearings, while a linear actuator pushed the intruder into the testbed at a speed of 4mm/s over a total stroke of 300mm. The forces acting on the tip of the probe were measured using a 6-axis force sensor (reference Nano25 – ATI industrial automation) attached to the tip and placed inside the hollow body of the intruder. Tip orientations were manually set prior to pluviation and fixed for the entire duration of the test.

3.2. Experimental results

Ther experimental campaign seeks to validate the results from the numerical simulations, while also capturing the complexities associated with physical testing. Three different probe orientations were tested: 0º, 45º and 90º. The penetration forces (drag, lateral and vertical) as a function of intruder penetration are summarized in Figure 5. Interestingly, the drag forces decrease for the 45º and 90º orientation angles, being about 19% lower than that of the 0º orientation.

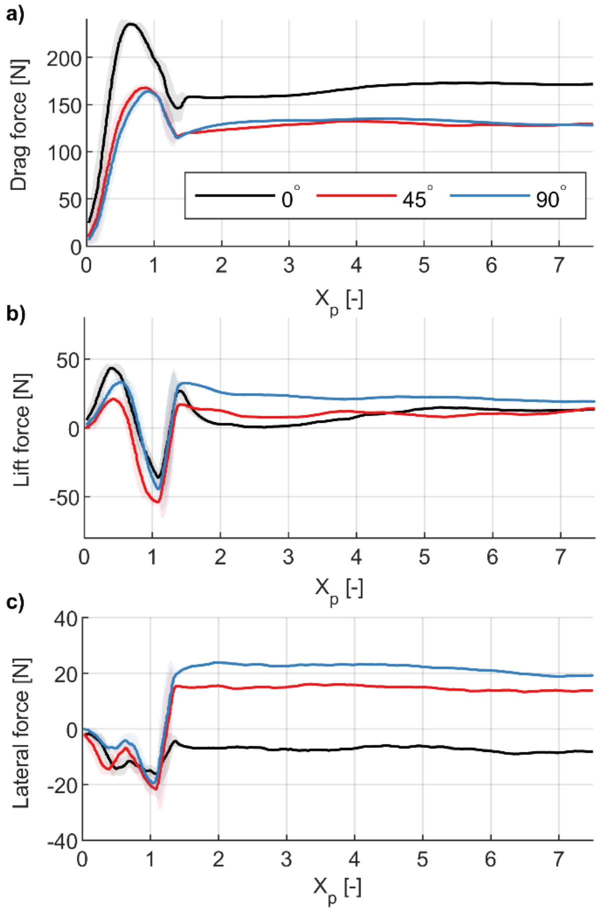

Figure 5. Penetration forces - Experimental tests

Lift forces show a slight increase with tip orientation, while lateral forces significantly increase. Differences in the results from numerical and experimental modelling can be attributed particle size and shape effects, and potential bending of the intruder in the physical experiments, which may affect the trajectory of the intruder, and with it the steering forces.

4. Conclusions

This paper has considered the influence of the orientation of an asymmetrical probe tip on the forces acting on the probes in horizontal penetration of sand. The work contributes to explorations of the potential to develop bioinspired devices to penetrate soil. The key idea explored here is whether the evolution of forces with tip orientation probe can be harnessed to steer the probe, i.e. to control the direction of motion of the advancing probe. The conclusions are informed by data from DEM simulations and 1g physical tests. The main conclusions of this contribution are:

- The geometry of the intruder limits the range of lift forces to the neutral-to-positive range. These data indicate that the capacity to control orientation of the advance or steer the probe by rotating the tip may be limited. However, the strong relationship between orientation and steering forces motivates the use of tip shapes with a different degree of asymmetry, which may expand the range of resulting lift forces.
- Lateral forces can be controlled with an asymmetric tip and a single rotation system. The magnitudes of the resulting lateral forces range between 0 to 50% of the maximum lift force obtained.
- Results show a significant increase in lateral forces with tip orientation, while lift forces show only a slight increase.
- Observed differences between the experimental and numerical results may obey to the effect of intruder deformation and path deviations, which are not captured by the numerical simulations.

Future research will focus on the development of other steering systems that expand the range of achievable lift forces, and intruder designs and experiments that allow and track unconstrained movements in the subsurface.

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References

Borela, R., J. D. Frost, G. Viggiani, and F. Anselmucci. 2021. “Earthworm-Inspired Robotic Locomotion in Sand: An Experimental Study Using x-Ray Tomography.” *Géotechnique Letters* 11 (1): 1–22. https://doi.org/10.1680/jgele.20.00085.

Broere, W, and A F Van Tol. 2001. “Horizontal Cone Penetration Testing in Sand.”

Das, Riddhi, Saravana Prashanth Murali Babu, Francesco Visentin, Stefano Palagi, and Barbara Mazzolai. 2023. “An Earthworm-like Modular Soft Robot for Locomotion in Multi-Terrain Environments.” *Scientific Reports 2023 13:1* 13 (1): 1–14. https://doi.org/10.1038/s41598-023-28873-w.

Hilton, J. E., and A. Tordesillas. 2013. “Drag Force on a Spherical Intruder in a Granular Bed at Low Froude Number.” *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics* 88 (6). https://doi.org/10.1103/PhysRevE.88.062203.

Jung, Wonjong, Sung Mok Choi, Wonjung Kim, and Ho Young Kim. 2017. “Reduction of Granular Drag Inspired by Self-Burrowing Rotary Seeds.” *Physics of Fluids* 29 (4). https://doi.org/10.1063/1.4979998/259063.

Otsubo, Masahide, Catherine O’Sullivan, and Tom Shire. 2017. “Empirical Assessment of the Critical Time Increment in Explicit Particulate Discrete Element Method Simulations.” *Computers and Geotechnics* 86 (June): 67–79. https://doi.org/10.1016/J.COMPGEO.2016.12.022.

Patino-Ramirez, F., and C. O’Sullivan. 2023. “Optimal Tip Shape for Minimum Drag and Lift during Horizontal Penetration in Granular Media.” *Acta Geotechnica* 19 (1): 19–38. https://doi.org/10.1007/S11440-023-01887-4/FIGURES/18.

Patino-Ramirez, F., Y. Yong, J. Salomon, A. Holmes, and C. O’Sullivan. 2024. “Drag and Lift Forces during Horizontal Penetration in Granular Media, a Numerical and Experimental Study.” *Manuscript in Preparation*.

Plimpton, Steve. 1995. “Fast Parallel Algorithms for Short-Range Molecular Dynamics.” *Journal of Computational Physics* 117 (1): 1–19. https://doi.org/10.1006/jcph.1995.1039.

Royal, A. C.D., T. J. Riggall, and D. N. Chapman. 2010. “Analysis of Steering in Horizontal Directional Drilling Installations Using Down-Hole Motors.” *Tunnelling and Underground Space Technology* 25 (6): 754–65. https://doi.org/10.1016/J.TUST.2010.06.004.

Seguin, A. 2022. “Forces on an Intruder Combining Translation and Rotation in Granular Media.” *PHYSICAL REVIEW FLUIDS* 7: 34302. https://doi.org/10.1103/PhysRevFluids.7.034302.

Simmons, Gene, and William F Brace. 1965. “Comparison of Static and Dynamic Measurements of Compressibility of Rocks.” *Journal of Geophysical Research* 70 (22): 5649–56.

Tang, Yong, Yi Zhong, and Junliang Tao. 2024. “Bio-Inspired Rotational Penetration and Horizontal Self-Burrowing Soft Robot.” *Acta Geotechnica* 19 (3): 1345–63. https://doi.org/10.1007/S11440-023-02173-Z/TABLES/4.

Tao, Junliang (Julian), Sichuan Huang, and Yong Tang. 2020. “SBOR: A Minimalistic Soft Self-Burrowing-out Robot Inspired by Razor Clams.” *Bioinspiration & Biomimetics* 15 (5): 055003. https://doi.org/10.1088/1748-3190/ab8754.

Wei, Lei, Mehmet T. Tumay, and Murad Y. Abu-Farsakh. 2005. “Field Testing of Inclined Cone Penetration.” *Geotechnical Testing Journal* 28 (1): 31–41. https://doi.org/10.1520/GTJ12541.

Zhang, Ningning, Yuyan Chen, Alejandro Martinez, and Raul Fuentes. 2023. “A Bioinspired Self-Burrowing Probe in Shallow Granular Materials.” *Journal of Geotechnical and Geoenvironmental Engineering* 149 (9): 04023073. https://doi.org/10.1061/JGGEFK.GTENG-11507.