Bioinspired Horizontal Self-Burrowing Robot

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ABSTRACT

Many organisms adopt well-evolved strategies and traits to facilitate burrowing/penetration in soils. Example features include the "dual-anchor" strategy used by razor clams and rotational drilling adopted by scarab beetle larva and some seed awns. Overall, underground burrowing requires overcoming resistances to advance forward and forming anchorage to prevent slip backward. Inspired by the aforementioned self-burrowing features, we designed a modular horizontal burrowing robot that features an extensible body and a rotatable tip. The robot was buried 7 cm below the surface of a bed of glass beads, and burrowed by cyclically alternating extension/retraction of the body segment, facilitated by the rotation of the tip. The burrowing performance of the designed robot was evaluated under different tip designs and control strategies. Insights into the general principles of burrowing in granular media were discussed by comparing to swimming in low Reynolds number fluids.

INTRODUCTION

Moving in soil can be increasingly hard with depth. This is mainly due to the intrinsic gravitational field, which leads to an increasing effective stress and soil shear strength with depth. Nonetheless, many burrowing organisms live underground and are capable of propelling themselves through soil using well-evolved locomotion strategies. Typical examples include the "dual-anchor" strategy used by bivalve clams (Trueman 1967), the peristalsis implemented by many polychaeta worms (Dorgan 2015), and body undulation employed by snakes and sandfish lizards (Maladen et al. 2011; Sharpe et al. 2015). Even in the kingdom of plants, strategies exists to facilitate the growth of roots and germinations. Plant roots penetrate soils by growing in the longitudinal and radial directions alternatively (Abdalla et al. 1969); some wheat seeds are covered with humidity-sensitive awns, and bury themselves into soil by winding and unwinding of the awns cyclically (Elbaum et al. 2007). These organisms are useful biological models for a burrowing robot that can move in soil automatically.

The motility of burrowing organism is typically enabled by internal forces and body deformations. On one hand, organisms coordinate the movement of different body parts to promote generations of anchorage and thrust to resist backward slip and facilitate forward advancement. On the other hand, organisms manipulate the surrounding soil by changing the shape of different body parts to improve the effectiveness and efficiency of the locomotion. Similar to the soil-structure interaction problems in geotechnical engineering, underground locomotion in nature is fundamentally a soil-organism interaction problem. It is therefore expected that the effectiveness and efficiency of underground locomotion are related to the implemented burrowing kinematics and the properties of surrounding soil.

Recently, many biological burrowing mechanisms have been translated to robotic design principles and several bio-inspired robots have been reported (Huang and Tao 2021; Naclerio et al. 2018; Ortiz et al. 2019; Pitcher and Gao 2015; Sadeghi et al. 2014; Tao et al. 2020; Winter et al. 2014). In this study, a simple burrowing robot is designed and able to move horizontally in a glass bead pool. A series of burrowing tests are then performed to preliminarily evaluate the burrowing performance of the robot under different conditions. Results from this study have implications for the future development of an innovative self-burrowing robot that can burrowing in multiple directions and used for geotechnical subsurface investigation, underground contamination detection, and precision agriculture etc.

METHODOLOGY

Burrowing Robot. Purcell (1977) demonstrated that net translation only occurs when organisms implement a non-reciprocal or asymmetric kinematics to swim in very viscous Newtonian fluids. A reciprocal kinematics means the body shape changes in a way that is symmetrical in time. This demonstration has been termed as the "scallop theorem": if a scallop opens and closes its shell (1-DOF motion) in a low-Reynolds number fluids, the kinematics is reciprocal and the scallop will return to its original location after a cycle of motion. Burrowing in dry granular media is to some extent analogous to swimming in low-Reynold number fluids, as both are inertialess and dominated by drags (Hosoi and Goldman 2015; Maladen et al. 2009). Nonetheless, burrowing in dry granular media is different from the low Reynold's swimming, as the soil medium is highly dissipated and subjected to the gravitational field. It has been confirmed that net translations can be achieved by breaking the symmetry in kinematics or boundary conditions in granular media (Maladen et al. 2011; Tao et al. 2020). For example, a cylindrical linear actuator can only generate a reciprocal extension-contraction motion. If the cylindrical linear actuator is placed horizontally in dry sand or on the surface of a desk, the kinematics or boundary conditions are both symmetric, and thus the actuator is not expected to move horizontally, according to the scallop theorem; nonetheless, if the linear actuator is placed vertically in dry sand, the reciprocal motion will drive the actuator out of the sand due to the asymmetric soil stress and boundary conditions (Tao et al. 2019; Tao et al. 2020). Hence, to enable horizontal burrowing, one must introduce symmetry-breaking features. A potential way to achieve asymmetry is by leveraging rotational motion. It has been found that rotation reduced penetration resistance (Tang et al. 2020; Tang and Tao 2021). By coordinating rotational motion and linear motion, it is possible to break the symmetry of kinematics.

In this study, we propose a burrowing robot that consists of two major segments: an anterior rotatable tip, and an extensible body which involves an anterior segment and a posterior segment, as shown in Figure 1(b). A corrugated soft tube made of DragonSkin-10 is used to cover the connection between the anterior and posterior segments, avoiding the invasion of glass beads during burrowing processes. The rotation of the anterior tip is enabled by a gear motor in the anterior segment, while the extension-contraction of the body is controlled using a micro linear actuator in the posterior segment (Figure 1(a)).

Experimental Setup. A simple testing setup is designed to evaluate the burrowing performance of the robot in a pool of glass beads (Figure 1c). The testing setup consists of a glass bead container (dimension: 39cm * 15 cm * 13cm), and a T-slot framed track that is seated above the container and aligned along the longitudinal direction of the container. During the tests, the robot is buried horizontally in glass beads at a depth of 7 cm, with its longitudinal direction aligned in parallel with the sidewalls of the container. A steel mast is fixed at the posterior segment of the robot, and aligned along a direction perpendicular to the bottom of the container. The top end of the steel mast extends beyond the T-slot framed track, which limits the movement of the mast to the longitudinal direction of the container. The real-time position of the posterior segment, and potential inclination of the robot during the tests are monitored via tracking two markers on the steel mast using a camera (marker B locates 16.8 cm above the posterior segment surface; marker A locates 11.8 cm above the posterior segment surface). The obtained videos are then processed using the open-source computer-vision library OpenCV (Bradski and Kaehler 2000), and an optical flow algorithm based on the Lucas-Kanade method (Lucas and Kanade 1981) is used to extract the trajectories of the two markers located on the mast from the video. Inclination of the mast in the vertical plane during robot burrowing is defined as the angle between the axial direction of the mast and the ground surface, and estimated based on the extracted locations of these two markers. The burrowing characteristics of the robot is then inferred based on the moving characteristics of marker A and the associated inclination of the steel mast in this study.

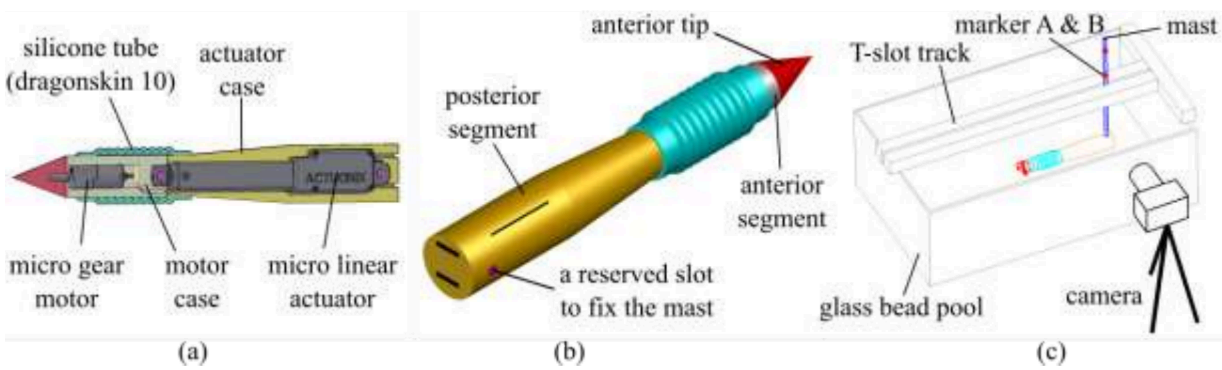

Figure 1. Illustration of the burrowing robot and the testing setup

Testing scenarios. In this preliminary study, we focus on evaluating the dependency of the burrowing performance of the robot on several factors: extension rate of the linear actuator, overburden pressure of the glass beads, tip rotation, and cross-sectional shape of the anterior segment. A naming strategy is used as following: FE/SE --- Fast/Slow extension; FC --- Fast contraction; TR/NR --- With/Without tip rotation; NP/OP --- With/Without overburden pressure; RD/SQ --- Round/Squared cross-sectional shape of anterior tip part (Figure 2); and H --- Horizontal burrowing. For each test, a constant amount of glass beads is pluviated into the container; the granular packing condition is roughly consistent throughout all the tests by maintaining a consistent initial surface level (10 cm from the bottom of the container). During the tests, the robot burrows by extending and contracting the linear actuator periodically. The anterior tip rotates during the extension stage only in the TR series; while no tip rotation occurs during the contraction stage for all the tests considered. The overburden pressure effect is considered by placing only a square metal plate on a local surface area right above the anterior segment and tip. Movement of the linear actuator and the gear motor are controlled using a microcontroller (Arduino Mega). In total, 5 tests are conducted, as summarized in Table 1. The 'FE-FC-TR-H-NP-RD' case serves as a reference case.

Table 1. Naming strategy used for the robot burrowing tests.

#	Actuator extension	Actuator contraction	Tip rotation	Burrowing direction	Overburden pressure	Cross section	Test label
1	FE	FC	TR	H	NP	RD	FE-FC-TR-H-NP-RD
2	FE	FC	TR	H	OP	RD	FE-FC-TR-H-OP-RD
3	SE	FC	TR	H	NP	RD	SE-FC-TR-H-NP-RD
4	FE	FC	NR	H	NP	RD	FE-FC-NR-H-NP-RD
5	FE	FC	NR	H	NP	SQ	FE-FC-NR-H-NP-SQ

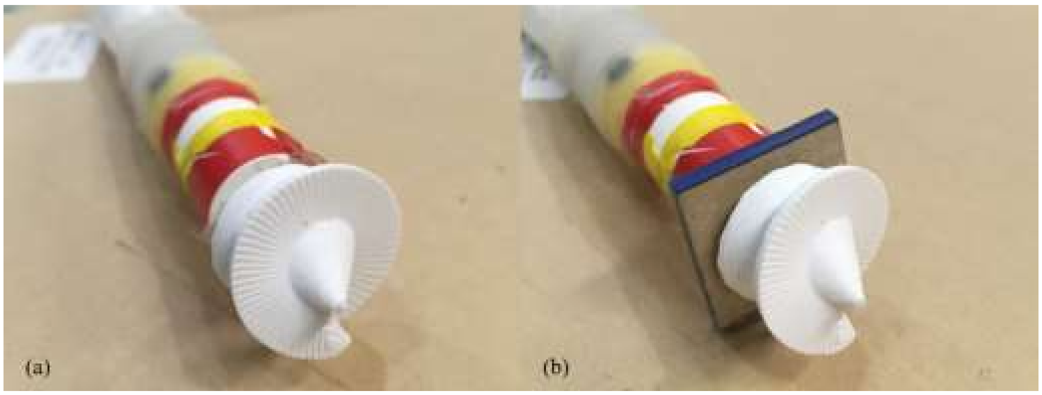

Figure 2. Cross sections of the anterior tip part considered in this study. (a) Round cross section; (b) squared cross section.

RESULTS

Burrowing Characteristics. Figure 3 illustrates the moving characteristics of marker A in the reference case. In general, the robot moves forward in the glass beads by alternating body extension with tip rotation and body contraction without tip rotation; the resulting horizontal displacement of marker A increases during the first 70s, and then decreases until the end of the test. For each burrowing cycle, marker A slips backward during robot extension, and advances forward during robot contraction; the net advancement in the forward direction over one cycle is a stride length, as indicated in the inset of Figure 3(a). We also observed that the steel mast inclines backward as the robot moves forward (Figure 4(b)), caused by the uplifting of the anterior tip. The inclination of the mast is responsible for the decreasing horizontal displacement of marker A.

Effects of Extension Rate and Overburden Pressure. Figure 4 presents the influence of the robot extension rate and the overburden pressure on the moving characteristics of marker A. By using a slower robot extension rate ('SE-FC-TR-H-NP-RD' case) or applying overburden pressures ('FE-FC-TR-H-OP-RD' case) on the glass beads surface, marker A moves further than the reference case, as indicated in Figure 4(a). Under these conditions, both the advancement and slip are enhanced. Since the enhancement of the advancement is much more significant than that of the slip, the net effect is an increase of the stride length per cycle, as indicated in Figure 4(c). Moreover, smaller inclinations and slower growth rates of inclination are observed in both cases, especially in the overburden case. A lower inclination during horizontal burrowing of the robot on one hand facilitates the formation of a firm anchor to promote forward advancement of marker A during body contraction; on the other hand, it minimizes the influence of backward inclination on the net horizontal displacement of marker A.

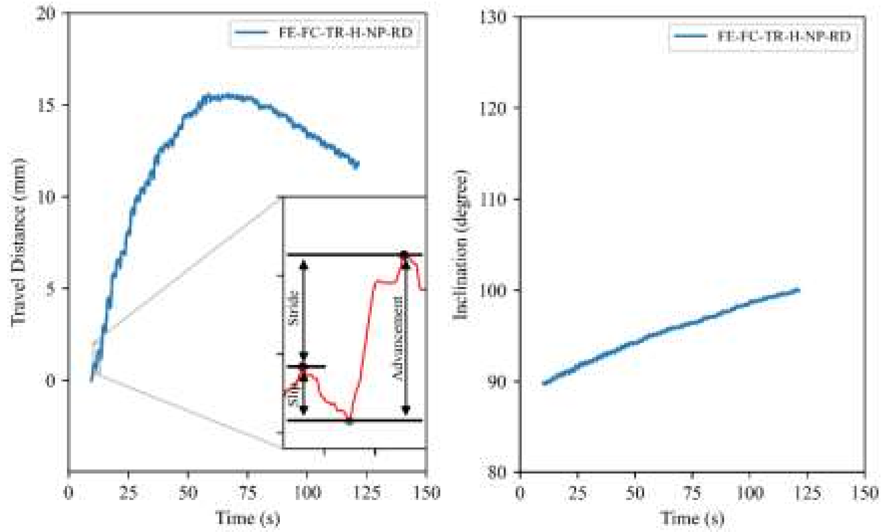

Figure 3. Moving characteristics of marker A in the reference case. (a) burrowing curve of marker A; (b) inclination of the mast

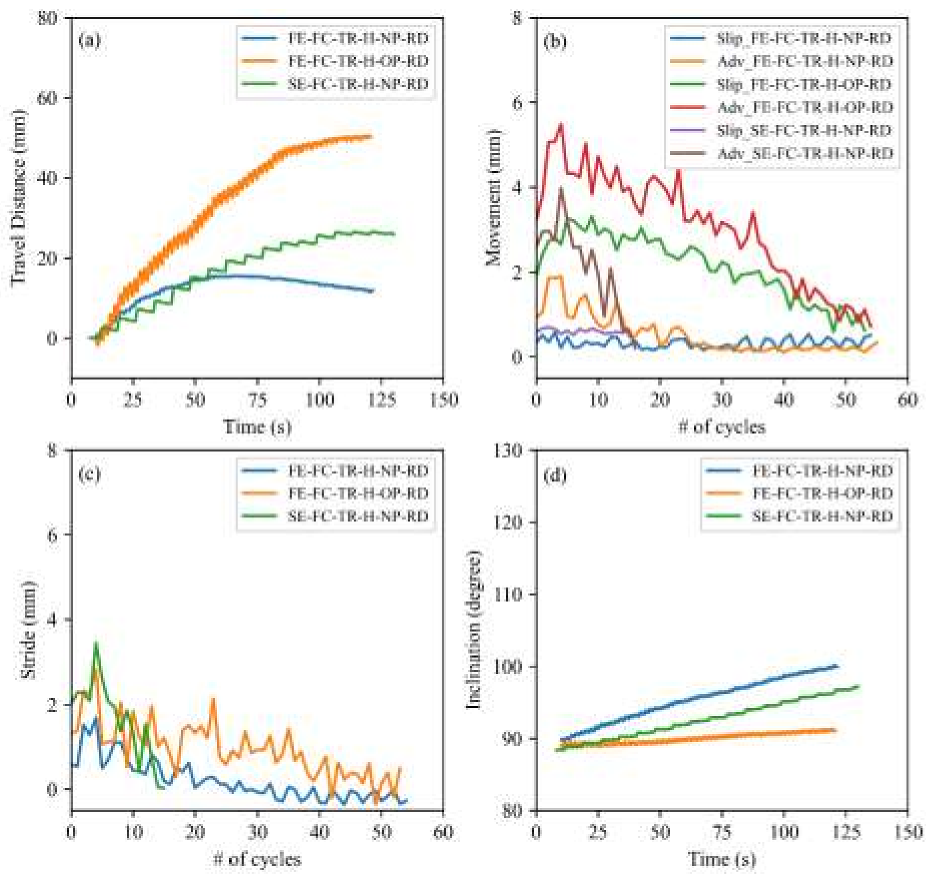

Figure 4. Effect of overburden pressure and body extension rate on the burrowing performance of the robot. (a) moving trajectory of marker A (b) advancement and slip in each burrowing cycle (c) stride length of each burrowing cycle (d) inclination of the mast.

Effects of Tip Rotation and Tip Shape. Figure 5 shows the influence of tip rotation and tip shape on the moving characteristics of marker A. Without tip rotation, the motion of the robot is reciprocal. Based on scallop theorem, there should be no net movement. However, it is observed that marker A in fact moved in 125s without tip rotation, although much less compared to the reference case. This observation implies that scallop theorem cannot be strictly applied to burrowing in granular media. An underlying assumption for the scallop theorem is that the surrounding medium is Newtonian and its properties (e.g., density and viscosity) does not change. However, granular media have memory, and any movements of the burrowing robot within would cause irreversible changes to the stress and packing states of the granular media. This assertion will be further validated in the future work.

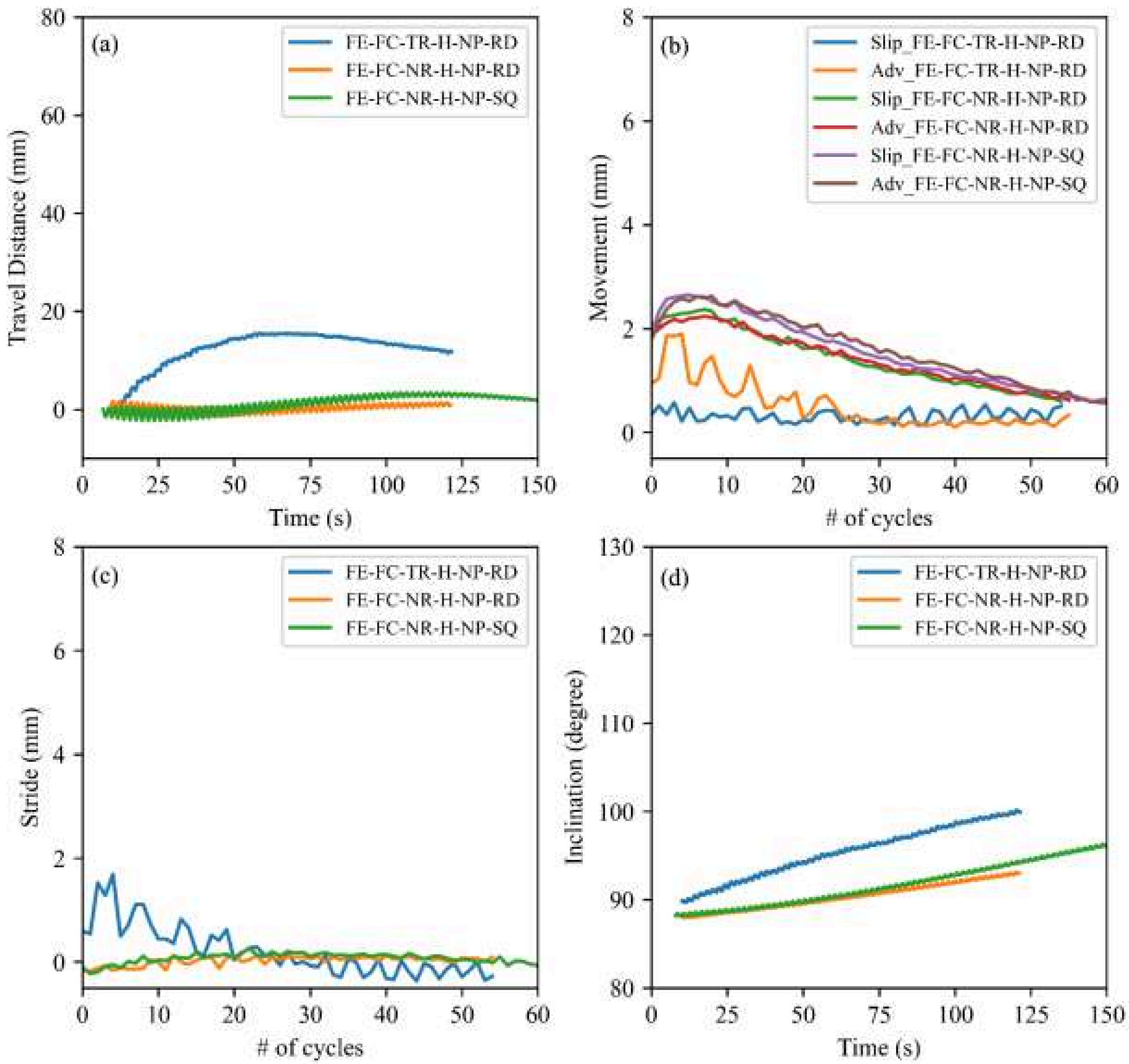

Figure 5. Effect of tip rotation and cross-sectional shape on the burrowing performance of the robot. (a) moving trajectory of marker A (b) advancement and slip in each burrowing cycle (c) stride length of each burrowing cycle (d) inclination of the mast.

DISCUSSIONS

Based on the scallop theorem, swimming in low Reynolds Newtonian fluids requires the swimmer to implement an asymmetric motion, which results in anisotropic distribution of drags along the body in each swimming motion. Although the scallop theorem cannot be strictly applied to burrowing in granular media, breaking the symmetry of either kinematics or boundary conditions leads to an anisotropic distribution of soil resistive forces distributed along the robot body in each burrowing cycle, and hence promotes movements of the robot in granular media. In this study, introducing anterior tip rotation into the body extension stage but not into the contraction stage breaks the symmetry: 1) the kinematics is now not reciprocal; 2) the stress boundary conditions are changed due to the rotation. Contribution of this asymmetry to the burrowing can be illustrated by comparing the 'FE-FC-TR-H-NP-RD' case and the 'FE-FC-NR-H-NP-RD' case in Figure 5. Rotation can effectively reduce soil penetration resistance that is typically dependent on the soil shear strength (Tang et al. 2020; Tang and Tao 2021). Thus, it is easier to fail the soil ahead of the tip than the soil around the posterior end during the extension stage. With a constant amount of actuator extension, the forward advancement of the tip is larger than the backward slip of the posterior end, resulting in a net forward movement of the entire robot. The net effect is an increased stride length or burrowing speed, comparing to the burrowing without any tip rotation, as shown in Figure 5a and 5c. Besides, different cross sections (or shapes) of the anterior tip also results in net translation of the robot in granular media, as indicated by the 'FE-FC-NR-H-NP-RD' case and the 'FE-FC-NR-H-NP-SQ' case in Figure 5. This is expected because different shapes between the anterior tip (auger-like) and the posterior end (flat end) also contribute to anisotropic distribution of soil resistance along the robot body by introducing anisotropic disturbances to the surrounding soil.

When there is an overburden pressure applied locally above the anterior segment and tip, the shear strength of the soil around the anterior segment increases. The resulting effect is two-fold: 1) the soil ahead of the anterior tip is harder to penetrate and hence the backward slip of the anterior tip is increased during the extension stage; 2) the anchor formed by the anterior tip is stronger and hence the forward advancement of the posterior end increases during the contraction stage. Moreover, the forward advancement of the posterior end increases more than its backward slip, resulting in a higher stride length and longer travel distance. This can be illustrated by comparing the 'FE-FC-TR-H-NP-RD' and the 'FE-FC-TR-H-OP-RD' cases in Figure 4.

Due to the intrinsic gravitational gradient, as well as the presence of a free boundary on the top, any horizontally moving object would experience a net upward force (Guillard et al. 2014), causing the robot to move upward. As the robot moves further, this upward movement leads to a decrease of the anchorage created by the anterior tip, and consequently a decrease of advancement and stride length. This can be observed through all the cases considered. Also, when there is an overburden pressure applied above the anterior segment, the difference in failure surface and shear strength between the soils on the top and bottom half of the anterior segment becomes smaller, resulting in a smaller uplifting force, and hence smaller inclination during horizontal burrowing process, as shown by the burrowing characteristics of 'FE-FC-TR-H-OP-RD' case in Figure 4. It is worthy to point out that although the posterior end might also experience uplifting during horizontal burrowing, the observed uplifting is much smaller compared with the anterior end, as indicated by the tilting of the mast.

This paper only concerns about how underground self-burrowing can be achieved by breaking symmetry in kinematics and boundary conditions in lab scales. Studies on the detailed mechanisms at multiple scales, and potential scaling effects when applied to engineering practice are still warranted in the future.

CONCLUSION

In this paper, a robot is designed for horizontal burrowing in granular media. The robot consists of an extensible body and a rotatable tip. When the body extension/contraction is properly coordinated with tip rotation, the robot burrows horizontally. Only including tip rotation in the extension stage but not in the contraction stage breaks the symmetry of kinematics and boundary conditions, which facilitates the robot burrowing in granular media. Without tip rotation, the robot still moves, although much less than the case with tip rotation, highlighting the differences between reciprocal motion in granular media and low Reynolds number fluids. It is also observed that the robot moves faster when a slow actuator extension rate or overburden pressure is applied.

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