Penetration Forces of a Rotating Helical Penetrator in Granular Media: Experiments and Insights into the Design of a Burrowing Robot

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ABSTRACT

It has been observed that some organisms such as *Erodium* seeds, snakes, and sandfish skink can bury themselves in the ground effectively and efficiently. These self-burial behaviors are achieved by one or multiple modes of locomotion including rotation, twisting, and undulation of an asymmetric body. To better understand the fundamental mechanism of these biological burrowing strategies, a series of upward and downward rotational penetration tests were conducted to evaluate the effects of rotational motion, asymmetric shape, and different properties of granular media on the penetration resistance using a robotic arm and 3D printed motorized penetrators. The results confirm that the downward penetration force decreases with the increase of rotational speed and that it further decreases if the penetrator is of a helical shape, highlighting the effects of asymmetric kinematics. It can be concluded that the penetration resistance of a helical penetrator depends on the rotational direction. For a right-handed helical penetrator, clockwise rotation resulted in significantly lower penetration force than counterclockwise rotation and required lower torque, although both reduced penetration force compared to non-rotational penetration. It was found that by coordinating the motions of the helical body, the penetration forces, and anchorage forces can be tuned to achieve self-burrowing.

INTRODUCTION

Moving into the soil is challenging due to the intrinsic gravitational field, which causes effective stress and soil shear strength to increase with depth. However, many burrowing species live underground and have well-developed movement strategies. The movement mechanism into the soil relies upon the properties of the medium and size of organisms(Dorgan 2015).

For example, a sand-swimming lizard, an undulatory sandfish as shown in Fig. 1 (b) can swim within granular media (Maladen et al. 2011). Earthworms and mole cricket can dig up the soil in front of them and pull it back so they can go forward (Moon et al. 2013). Bivalves can burrow themselves into the sediment using the two-anchor process (Koller-Hodac et al. 2010). The Atlantic razor clam (*Ensis directus*) can burrow into the soil by contracting its valves, which causes the surrounding soil to fluidize and reduces burrowing drag (Dorsch and Winter 2015). *Erodium seeds* as shown in Fig. 1 (a) have two categories, an autochory type that can fly the seeds away from the plant and a self-burial strategy of the seeds. These two movements are possible due to hygroscopic tissues, that produce passive movement changing the hydration of the cell walls. However, to facilitate the self-burial process each seed contains a unique dispersal unit (the awn) that responds to changes in environmental humidity by changing its shape: the awn is helical when dry and linear when wet (Pandolfi et al. 2012). *Erodium seeds* move across the surface and into the ground thanks to coiling and uncoiling motor action caused by the day-night humidity cycle (Elbaum et al. 2007; Stamp 1984). These species can be used as biological models for a burrowing robot that can automatically travel through soil.

Internal forces and body twists allow burrowing organisms to move. However, organisms coordinate the movement of several body parts to improve generations of anchoring and propulsion, allowing them to resist backward slip and march forward. Similarly, organisms alter the morphology of numerous body parts to improve locomotor efficacy and efficiency. Underground locomotion in nature is essentially a problem of soil-organism interaction, similar to the challenges of soil-structure interaction in geotechnical engineering (Huang and Tao 2022). In this study, motivated by a biological burrowing mechanism of *Erodium seeds* and *sandfish skink* a series of downward rotational burrowing tests are performed to preliminarily evaluate the burrowing performance of helical penetrator under different conditions. Propulsive force is induced along the axis of the rotating helical penetrator which facilitates symmetry breakdown and reduces anisotropic frictional forces (Texier et al. 2017). The findings of these experiments have implications for the future creation of a unique self-burrowing two-auger robot that can burrow in different directions and can be used for geotechnical site investigation, underground sensing, precision agriculture, and other applications.

(a) (b)

Fig. 1. Bio-inspired models from nature: (a) *Erodium seeds awn*; (b) *sandfish skink* (Fig. 1 (a): Image courtesy of the Attribution-Share Alike 4.0 International; Fig. 1 (b): Image courtesy from through the sandglass magazine)

METHODOLOGY

It has been proven that breaking kinematic symmetry or granular media boundary conditions can result in net translations (Maladen et al. 2011; Tao et al. 2020). It has been found that rotation reduces penetration resistance (Tang et al. 2020; Tang and Julian Tao 2021). By coordinating rotational motion and asymmetry shape it is possible to break the symmetry of kinematics of soil.

(a) (b) (c)

Fig. 2. Different parts for experiment: (a) Universal Robot (UR16e) connector and DC motor holder; (b) DC motor: (c) Auger (Fig. 2 (a): Autodesk Inventor designed 3D model; Fig. 2 (b): Commercial product from Amazon; Fig. 2 (c): Commercial product from Amazon)

In this study, the penetration forces of a rotating helical penetrator are explored through laboratory tests in granular media. The rotating helical penetrator consists of two major segments: a 12V DC rotational gear motor (Size:136mmx38mm) whose speed range is 50 revolutions per minute (RPM) and a helical auger (size:177.8mmx50.8mm). Ottawa sand F65 (D_{50} = 0.2 mm) and glass beads (D = 3.0 mm) are used as granular media. Two cylindrical buckets with a diameter of 28 cm and a depth of 36 cm are used for sample preparation. The soil sample preparation method is important to conduct any laboratory experimental test. However, to keep the density of the samples accurately and precisely dry pluviation preparation technique is applied (Okamoto and Fityus 2006). According to laboratory measurements, the actual density of granular media is Dr=32.68%. The full experimental set-up consists of a universal robotic arm as shown in Fig. 3 (a), a 3D printed motorized coupler as shown in Fig. 2 (a), a powerful high torque DC motor (Rated torque: 19.5 kg.cm, Rated current: 2.1A, Power: 25W) as shown in Fig. 2 (b), and a helical penetrator as shown in Fig. 2 (c). The rotational penetration tests are conducted with the aid of the UR16e universal robot. The universal robotic arm can measure the penetration force and torque considering real-time feedback from the process during penetration. It includes six-axis force and torque sensor systems that can capture and convert mechanical loads into forces and torques along all axes. The recorded penetration force and torque data from the robotic arm's control box were sent to the local drive using the Real-Time Data Exchange python package. In this experiment, the robotic arm is simply used to move vertically. DC gear motor facilitates rotational penetration in a clockwise and counterclockwise manner considering a right-handed helical penetrator as shown in Fig. 3 (b) and Fig. 3 (c). The rotational movement of the DC gear motor is controlled by an ATmega2560 microcontroller. Arduino ATmega2560 microcontroller can generate PWM signal to facilitate clockwise and counterclockwise rotations (Islam et al. 2018; Prayash et al. 2019; Shaharear et al. 2019). In this study, under different rotational (10 rpm, 30 rpm, 40 rpm, 45 rpm, 50 rpm) and vertical (0.04 m/s, 0.01 m/s, 0.001 m/s) velocities downward penetration tests are conducted. All tests are conducted three times to make sure the experiment data is identical for every test.

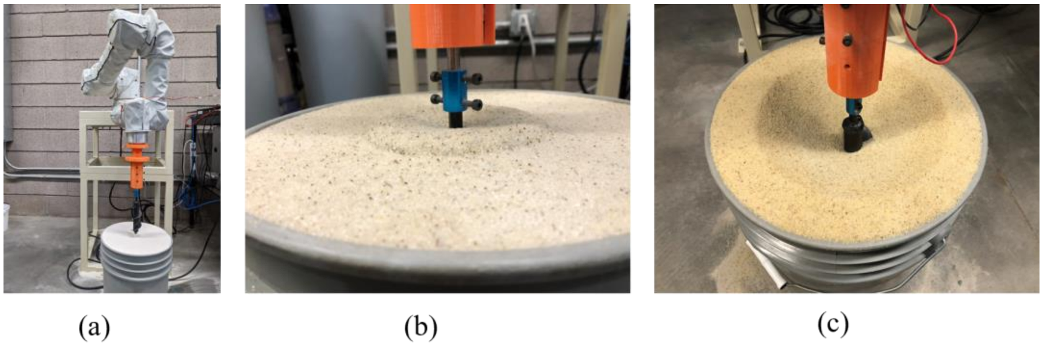

Fig. 3. Testing setup: (a) Full experiment set up with Universal Robot (UR16e) and helical penetrator; (b) Clockwise penetration test: (c) Counterclockwise penetration test.

RESULT AND DISCUSSION

Different clockwise and counterclockwise penetration force and torque in Ottawa sand F65 granular media under different rotational and vertical velocities are shown in Fig. 4 and Fig. 5. Penetration force decreases with the increase of rotational speed and it further decreases due to the decrease of vertical velocities during the clockwise penetration test, as shown in Fig. 4 (a). In this preliminary study, from Fig. 4 (a) it is obvious that after 50 rpm-0.04 m/s the granular media is under a critical state and due to further decrement of vertical velocities negative force is found which will be more convenient for burrowing. To get a better understanding of the critical state further investigation will be done. However, penetration torque also decreases concerning increasing rotational speed which is supposed to be not expected.

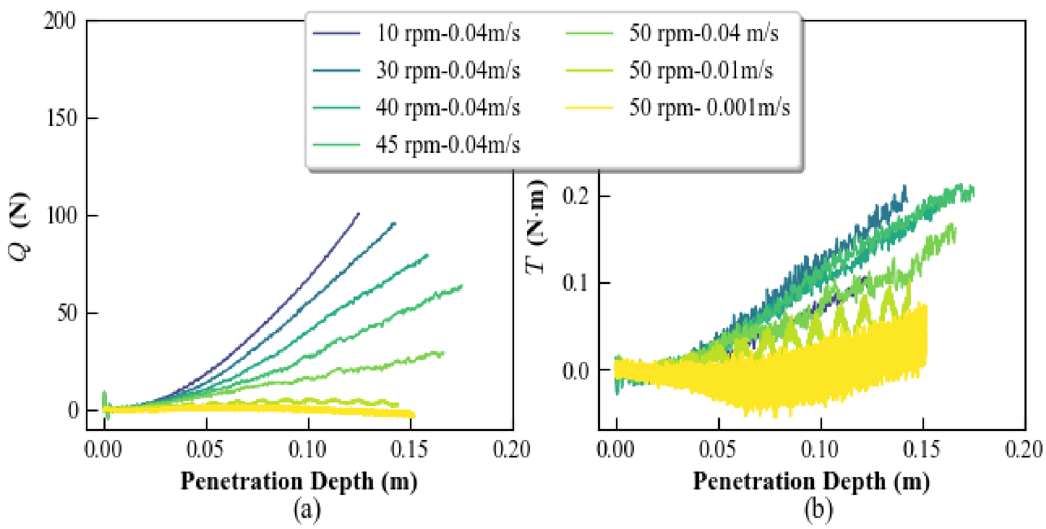

Fig. 4. Clockwise Penetration force and torque for helical penetrator under different rotational velocities in Ottawa sand F65: (a) penetration force (Q); (b) penetration torque (T).

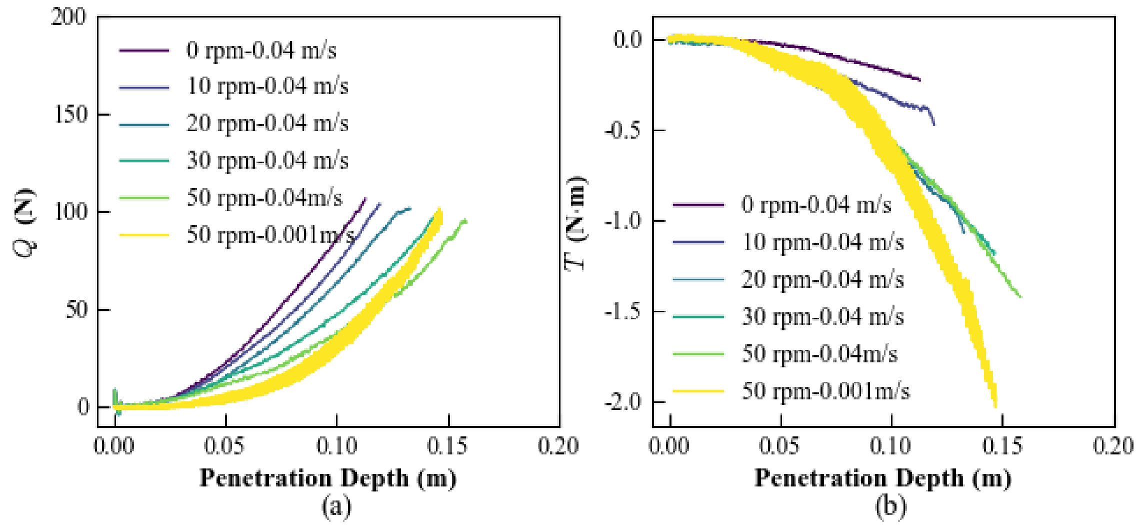

Fig. 5. Counterclockwise Penetration force and torque for helical penetrator under different rotational velocities in Ottawa sand F65: (a) penetration force (Q); (b) penetration torque (T).

This can happen due to the small inclination angle of the helical penetrator. More research is needed to know the actual reason for torque data for the clockwise helical penetrator. The penetration force decreases with the increase of rotational speed during counterclockwise penetration for 0.04 m/s vertical velocities, as shown in Fig. 5 (a) but it further starts increasing for 50 rpm-0.001 m/s state because during counterclockwise penetration particle started to accumulate downward as shown in the Fig. 3 (c) which generate excessive force. However, penetration torque increases with the increase of rotational velocities as shown in the Fig. 5 (b). This observation implies that clockwise penetration is way easier for burrowing sand than counterclockwise penetration.

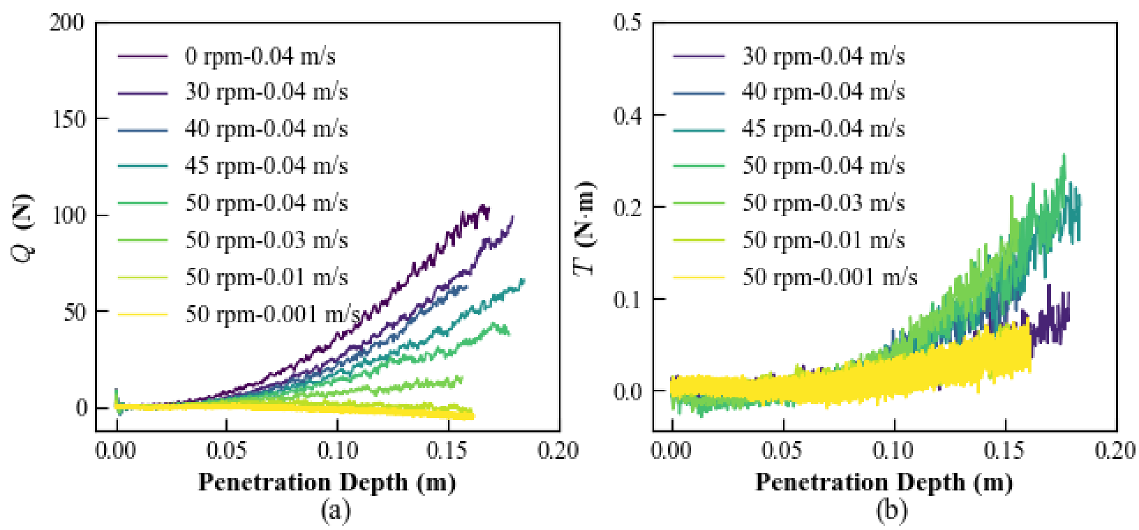

Fig. 6. Clockwise Penetration force and torque for helical penetrator under different rotational velocities in glass beads: (a) penetration force (Q); (b) penetration torque (T).

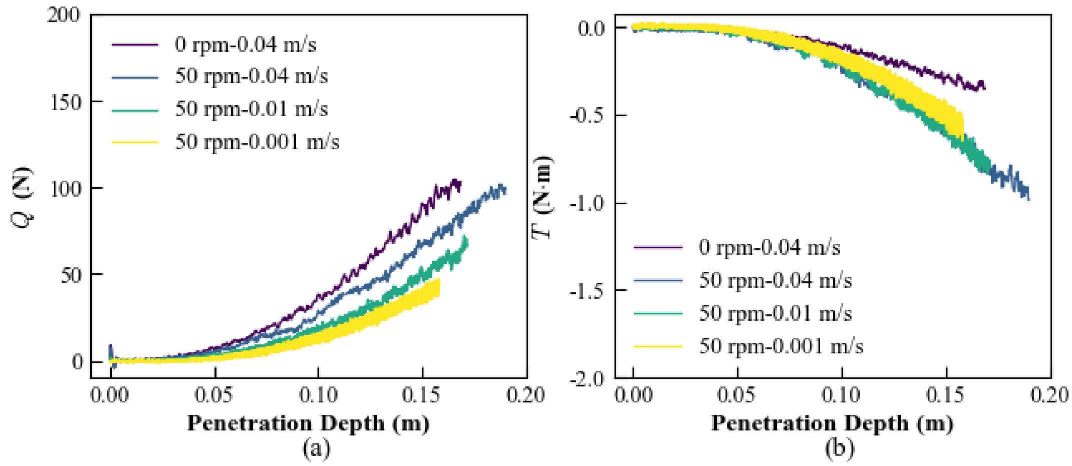

Fig. 7. Counterclockwise Penetration force and torque for helical penetrator under different rotational velocities in glass beads: (a) penetration force (*Q*); (b) penetration torque (*T*).

The penetration force and torque for glass beads under different rotational speeds of helical penetrator are shown in Fig. 6 and Fig. 7. Penetration force decreases for increasing rotational speed and it further decreases for decrements of vertical velocities during clockwise penetration tests as shown in figure Fig. 6 (a). The reason for further decrements is during clockwise penetration particles come out as shown in the Fig. 3 (b). Penetration torque increases for the increment of rotational speed and it decreases due to decrements of vertical velocities for clockwise penetration as shown in Fig. 6 (b). During counterclockwise penetration tests, for glass beads, penetration force and torque do not change that much due to the increment of rotational speeds as shown in Fig. 7. The main reason behind this kind of phenomenon is during counterclockwise penetration particles accumulate downward and sharing blades of helical penetrators get the almost same amount of glass beads particles during penetration.

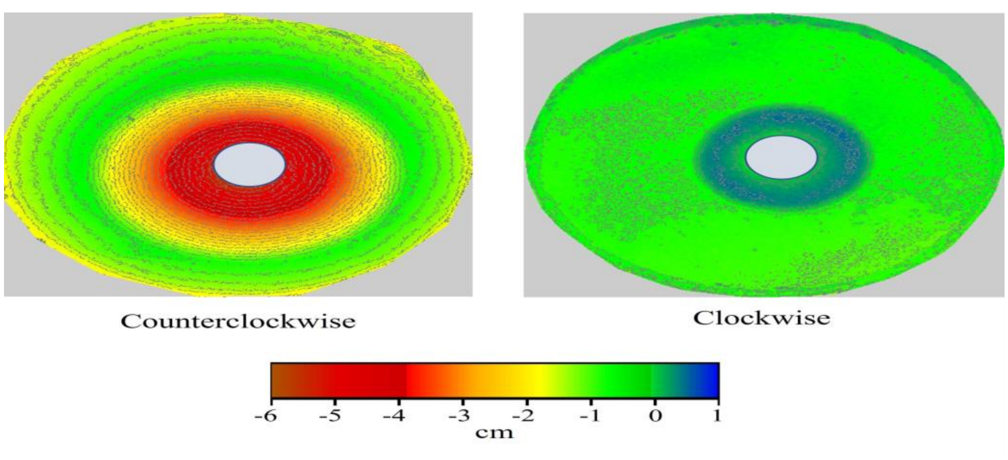

Fig. 8. Surface topography in different penetration manner.

Image processing was performed to reconstruct the experiment scenario and demonstrate the surface topography. About 100 pictures were taken from different angles and orientations for each case, in which the pixel points were processed using the open-access software VisualSFM to reconstruct a 3D structure which consists of plenty of mesh points. Software Cloudcompare was then employed to process and align the dimensions of the mesh points. Fig. 8 shows the surface topography from different rotation manners using the above method.

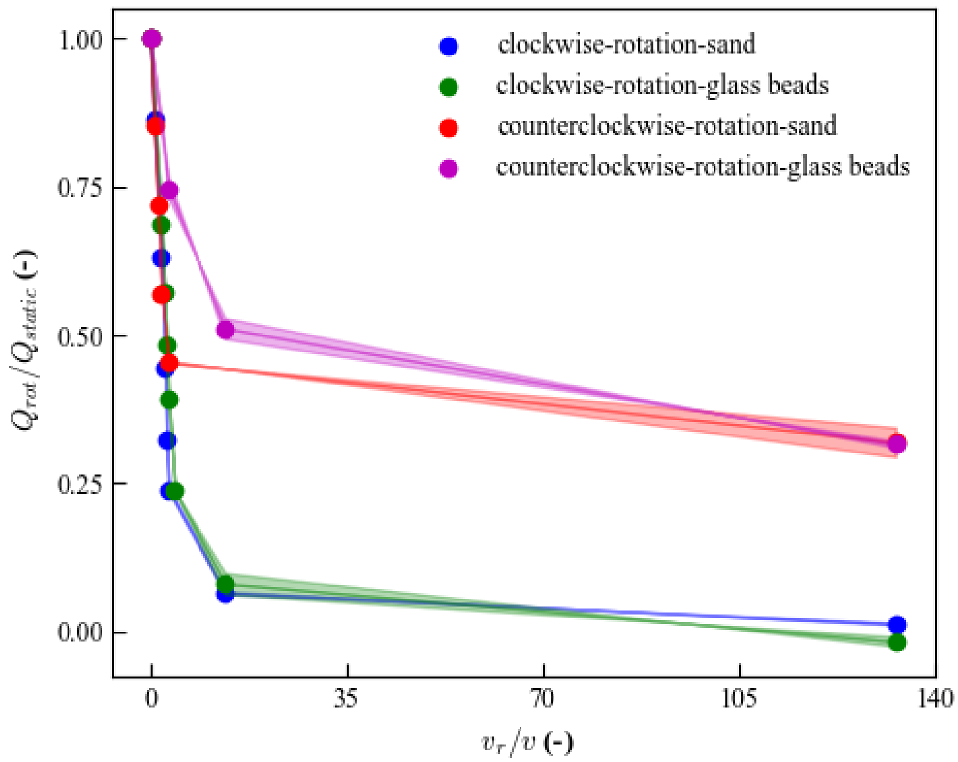

Fig. 9. The normalized penetration force Q_{rot}/Q_{static} for different rotational modes.

The normalized clockwise and counterclockwise penetration force Q_{rot}/Q_{static} under different rotational modes are shown in Fig. 9. It is observed that normalized penetration force decreases with the increase of relative slip velocity. The term relative slip velocity is the ratio between the rotational velocity and the vertical penetration velocity. The result confirms that clockwise rotational penetration forces approach around 1% for relative slip velocity is 133 for Ottawa sand and glass beads. In the counterclockwise state for glass beads and Ottawa sand, penetration force approaches 32% compared with a relative velocity is 133. Based on these observations, the rotational force decrements rate is higher for clockwise penetration compared with counterclockwise penetration.

CONCLUSIONS

In this paper, a series of downward rotational penetration tests are conducted using a helical penetrator to study the effect of penetrator geometry & different granular media. The testing setup consists of a universal robot and a helical motorized penetrator. Highlighting the effect of asymmetric kinematics, this paper shows during clockwise penetration breaking symmetry is much easier than counterclockwise penetration. This study affirms that reducing the anisotropy of friction and symmetry breakdown using the helical shape penetrator determines locomotion in granular media. This result gives us the insight to design a borrowing robot based on the result of the experiment.

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