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Interface Friction Response between Snakeskin-Inspired Surfaces and Jumunjin Sand under Repetitive Loading

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ABSTRACT: Understanding the anisotropic friction behavior at soil-structure interfaces is critical for designing efficient geotechnical systems. This study investigates the interface shear characteristics of bio-inspired surfaces modeled after snake ventral scales under repetitive loading conditions. A series of direct shear tests are conducted with textured surfaces subjected to constant vertical stress and two shearing directions: cranial (against the scales) and caudal (along the scales). The results demonstrate that the cranial shearing consistently yields higher shear resistance compared to caudal shearing regardless of initial shearing direction. Additionally, the scale geometry plays a critical role in controlling the frictional response; surfaces with higher scales height and shorter scale lengths exhibited enhanced normalized interface friction angles across all cycles. Over multiple cycles, the difference in normalized interface friction angles between cranial and caudal shearing directions diminished and converged after a certain number of cycles. This research provides valuable insights into the influence of repetitive loading and bio-inspired surface geometry on frictional anisotropy, offering guidance for the development of advanced soil-structure interface designs.

KEYWORDS: Anisotropic behavior, soil-structure interfaces, repetitive shearing, scale geometry, directional frictional resistance.

1 INTRODUCTION

Recent research has highlighted the exceptional frictional properties of snakeskin and their potential for developing textured surfaces that exhibit directional frictional behavior. Snakes' ventral scales show a reduction in friction during forward movement (caudal direction) and an increase in friction during backward movement (cranial direction). Inspired by this unique behavior, multiple studies have sought to replicate snakeskin's surface patterns to enhance frictional anisotropy in soil-structure interactions for use in a range of geotechnical engineering applications (Hazel et al. 1999; Martinez et al. 2019).

Studies have identified several factors influencing the frictional behavior between surfaces and soil, such as the direction of shearing, surface roughness, soil density, and soil composition. Specifically, cranial shearing typically results in higher frictional resistance at the interface between bio-inspired surfaces and soil, as compared to caudal shearing. Asymmetric bio-inspired piles demonstrate variations in shaft capacity depending on the load direction during installation and pullout. The piles experience higher skin friction under tensile pullout forces than during compression when installed using jacking methods (O'Hara & Martinez 2020; Kim et al. 2024).

Previous research has focused on the interface behavior of bio-inspired piles and sand under constant normal stiffness (CNS) conditions. However, CNS conditions lead to a reduction in vertical stress, which produces different behavior compared to constant normal load (CNL) conditions. Additionally, most of these studies have examined one-way shear loading, and therefore, there remains a gap in understanding how snakeskin-inspired surfaces perform under repetitive shear stress, an area not yet fully explored.

This study performs a series of repetitive direct shear tests using snakeskin-inspired surfaces, applying a constant vertical stress of 100 kPa and two-way shear directions. The results are analyzed to quantify the influence of repeated shearing cycles on frictional anisotropy and the interfacial shear response. The findings of this research are presented with an emphasis on the variation in interfacial friction angles in relation to scale geometry ratios (H/L) under different shearing cycles.

2 MATERIAL AND EXPERIMENTAL METHDOS

2.1 *Properties of snakeskin-inspired plate and sand*

In this experiment, seven 3D-printed snakeskin-inspired surfaces made from polycarbonate material, are used. Each surface consists of a central textured segment measuring 72 mm, with untextured portions (45 mm) on both sides to maintain adequate distance from the shear box sidewalls (for more details refer to Lee et al. 2023; Nawaz et al. 2024). The geometric properties of these surfaces are summarized in Table 1.

For the tests, Jumunjin standard sand is used, which is a poorly graded, sub-rounded silica sand (SiO_2 = 88.21%), a specific gravity (G_s) of 2.62, median grain size (D_{50}) of 0.58 mm, a coefficient of uniformity (C_U) of 1.46, a coefficient of curvature (C_C) of 0.93, a maximum void ratio (e_{max}) of 0.92, and a minimum void ratio (e_{min}) of 0.62.

Table 1. Geometry of snakeskin-inspired plate.

Case	Scale geometry [mm]		Scale ratio, H/L [-]
	Length, L	Height, H	
#1	6	0.3	0.05
#2	12	0.3	0.025
#3	18	0.3	0.017
#4	24	0.3	0.0125
#5	12	0.1	0.008
#6	12	0.45	0.0375
#7	12	0.72	0.06
Smooth	-	-	-

2.2 *Modified interface direct shear test*

The Direct Shear (DS) test apparatus is commonly used to estimate the shear parameters of soil. However, traditional systems have several limitations, such as the rotation of the upper shearing box and tilting of the upper loading plate, both of which can hinder accurate measurement of shear response. To overcome these challenges, several modifications have been introduced to the conventional DS setup, particularly for testing soil-structure interactions with surfaces inspired by snakeskin.

In the conventional DS system, normal stress is applied via a vertical loading rod attached to a steel ball and vertical loading plate. In contrast, the updated design utilizes a loading plate securely fixed to a vertical loading frame, which replaces the earlier mechanism, providing greater stability and accuracy in applying normal stress.

For the loading system, a constant vertical stress is maintained using an air cylinder, ensuring a consistent application of load. Additionally, the system uses a shear motor to precisely control the shear strain, enhancing the accuracy of the shear response measurements.

To ensure smooth and frictionless movement of the shear box, a linear motion (LM) guide has been incorporated into the design. This guide guarantees the seamless movement of the bottom shear box, which is firmly attached to an outer moving box. The snakeskin-inspired surface is mounted on the lower shear box, allowing for effective interface testing between the surface and soil.

Finally, the sensor system is equipped with dedicated load cells to measure both vertical and horizontal loads. Additionally, two LVDT sensors are used to accurately measure both horizontal and vertical displacements, ensuring precise data collection during the testing process.

2.3 *Experimental program*

A series of 14 repetitive interface direct shear (DS) tests are performed on seven snakeskin-inspired surfaces under a constant normal load (CNL), corresponding to a vertical stress of 100 kPa, with testing conducted in both two-way shearing directions for a total of 20 cycles. Each complete cycle involves two shearing sequences: (1) cranial to caudal test, where the first half of the cycle applies cranial shearing followed by caudal shearing in the second half, and (2) caudal to cranial test, where caudal shearing is applied during the first half and cranial shearing during the second half of the cycle.

To achieve a relative density (D_r) of 40%, sand is air-pluviated onto the textured surface (snakeskin-inspired) within the shear box. The specimen is then sheared until a 5 mm displacement is reached, with a constant shear rate of 1 mm/min. The data sampling rate is set to 1 Hz, and the data is automatically recorded and stored using a data logger, while LabView software is employed for continuous monitoring of the testing process. The shear stress is calculated by dividing the recorded shear force by the cross-sectional area of the specimen.

3 RESUTLS

Figure 1 presents the interface frictional behavior under 20 shearing cycles at a vertical stress of 100 kPa. The bio-inspired surface, characterized by a scale length (L) of 24 mm and a scale height (H) of 0.3 mm, is tested to evaluate the shear resistance under different initial shearing directions. Note that the stress ratio is defined as the shear stress divided by the vertical stress, and the horizontal displacement is normalized by the total length of the asperity plate (= 72 mm). During the cranial first half of the shearing, the normalized shear stress increased sharply with the shearing cycles, while the shear strength slightly decreased in the caudal second direction. In contrast, when the first shear direction is caudal, the shear stress increased gradually over the cycles, and in the cranial second direction, the shear strength is higher than in the caudal first direction. These results highlight the anisotropic characteristic of snakeskin-inspired surfaces, with shear strength varying depending on the loading direction.

Figure 2 shows the variation in normalized shear stress with respect to scale height (H) under a constant vertical stress and scale length (L = 12 mm). The repeated normalized shear stress exhibits notable variations depending on the initial shear direction and the scale height (H). Specifically, under the cranial first shearing, higher scale heights result in larger initial normalized shear stress, with little change observed over the repeated cycles. In the subsequent caudal shearing, the normalized shear stress remains lower than shear stress of the first cranial direction throughout the cycles, and the effect of scale height is minimal. Conversely, when the initial shear direction is caudal, the shear stress shows similar values across scale height and cycles, whereas in the cranial second shearing, significant differences are observed according to both the scale height and the number of repeated cycles.

Figure 3 illustrates the change in normalized shear stress as a function of scale length (L), while the scale height is kept constant at 0.3 mm. In the snakeskin-inspired plate, the total asperity length is fixed at 72 mm, so as the scale length increases, the number of asperity decreases. Regardless of the initial shear direction, smaller scale lengths mobilize the higher initial normalized shear stress. These observations can be attributed to the fact that an increased scale height or a shorter scale length results in greater surface roughness, which subsequently promotes the formation of larger passive wedges, as reported by Martinez et al (2019).

The shear stress under various scale geometry shape is significantly affected with repeated shearing cycles. Figure 4 compare the changes in normalized friction angle based on the scale height. The normalized friction angle is calculated by dividing the interface friction angle between the plate and the soil by the internal friction angle of the soil (= 38°). In all cases, the normalized friction angle gradually increases as the scale height increased. Notably, regardless of the shear sequence, the normalized interface angle is higher under the cranial shear conditions compared to the caudal shear conditions. In addition, the normalized interface angle generated from the cranial

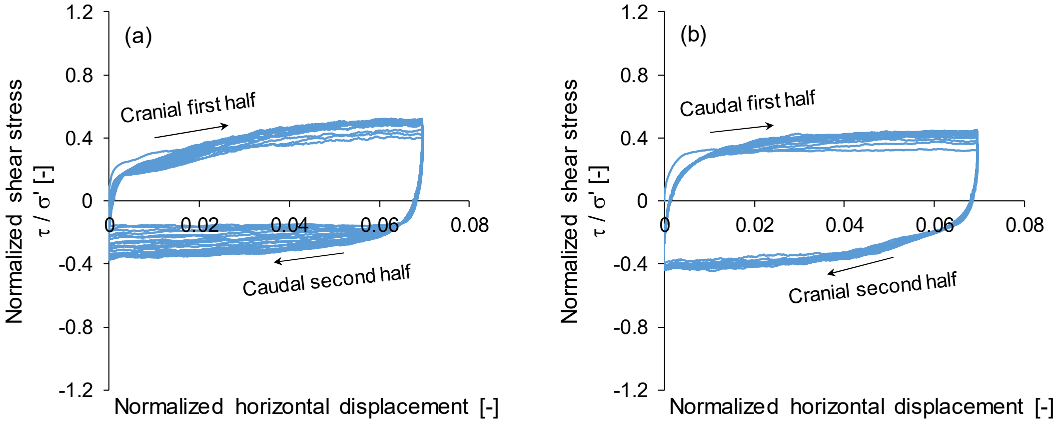

Figure 1. Response of normalized shear stress at repetitive loading cycles under a vertical stress of 100 kPa (L = 24 mm and H = 0.3 mm).

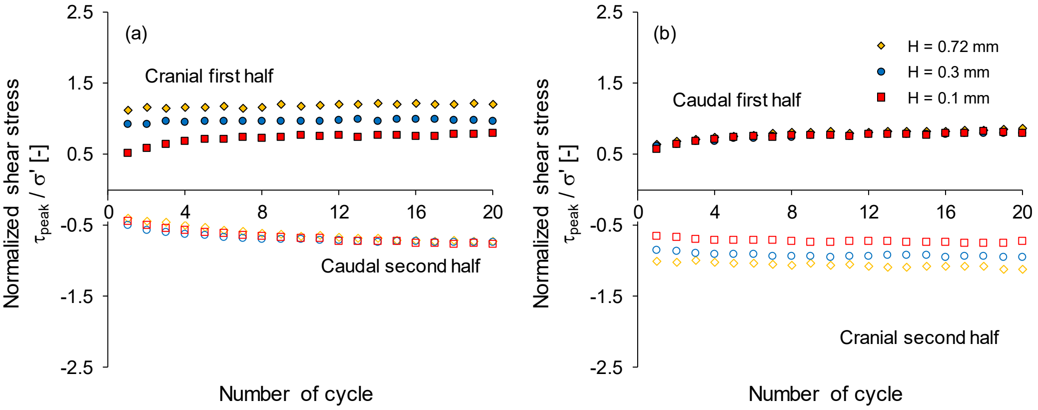

Figure 2. Evolution of normalized shear stress according to scale height (scale length L is fixed as 12 mm).

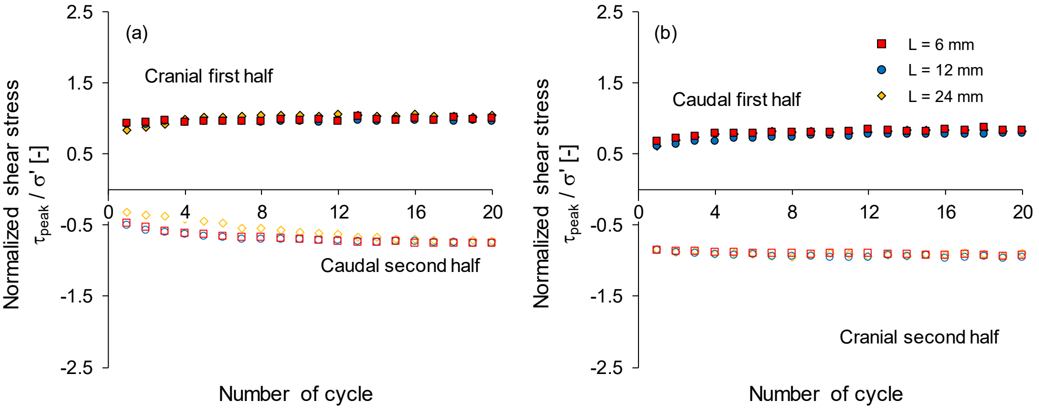

Figure 3. Evolution of normalized shear stress according to scale length (scale height H is fixed as 0.3 mm).

second shearing is always greater than that of the cranial first shearing. The difference in normalized interface angle between the cranial shearing and the caudal shearing gradually decreased as the number of cycles increased.

Figure 5 shows the effects of scale length on the normalized friction angle. As the scale length increases, the normalized friction angle is gradually decreased. Regardless of the shear sequence, the normalized friction angle observed in the cranial shear direction is always higher than that produced in the caudal direction. Additionally, as the number of cycles increases, the difference between the shear directions (cranial vs. caudal) gradually decreases.

4 DISCUSSION

Figure 6 presents the normalized friction angle as a function of the scale ratio (H/L) under different shearing cycles. The graph compares how the normalized friction angle varies with changes in the scale ratio, which is defined as the ratio of scale height (H) to scale length (L). As the scale ratio increases, larger normalized friction angles are observed, indicating increased shear resistance. This highlights the potential of bio-inspired surfaces to optimize load transfer and increase shear strength. Additionally, as the shearing cycles progress, the difference in friction angle based on scale ratio becomes more pronounced. The effect of the loading direction on the normalized friction angle gradually diminishes with increasing cycles, and the difference between cranial and caudal shear directions decreases over time. Notably, the shear stress generated in the cranial shear direction is consistently higher than that in the caudal shear direction, further emphasizing the directional dependence of the shear resistance. These results underscore the significant role of surface geometry in influencing shear strength and the long-term frictional behavior of bio-inspired materials.

5 CONCLUSIONS

In this study, the shear behavior of bio-inspired surfaces based on snakeskin patterns is thoroughly investigated, focusing on their interface frictional properties under repetitive shear cycles. The results reveal several important findings. First, the bio-inspired surfaces consistently demonstrate higher shear resistance compared to smooth surfaces, regardless of the loading direction (cranial to caudal or caudal to cranial). This indicates the potential of snakeskin-inspired textures to enhance shear strength and optimize soil-structure interaction. Additionally, both scale height and scale length significantly influence the shear resistance, with higher scale heights or shorter scale lengths leading to increased shear resistance.

Moreover, the directional dependence of shear resistance is evident, as the cranial shear direction consistently produced higher shear stress than the caudal direction. This highlights the directional frictional anisotropy of the bio-inspired surfaces, with the shear strength being more pronounced in the cranial direction. As the number of shearing cycles increased, the difference in shear stress between the two directions gradually decreased, indicating that repeated shearing cycles lead to a more uniform frictional behavior over time, regardless of the initial loading direction.

The normalized frictional angle is also found to increase with larger scale ratios (H/L). The findings underline the importance of surface texture in improving soil-structure interactions, and by leveraging the unique frictional properties of bio-inspired surfaces, it is possible to optimize load transfer and shear strength in geotechnical applications, such as foundations and piles.

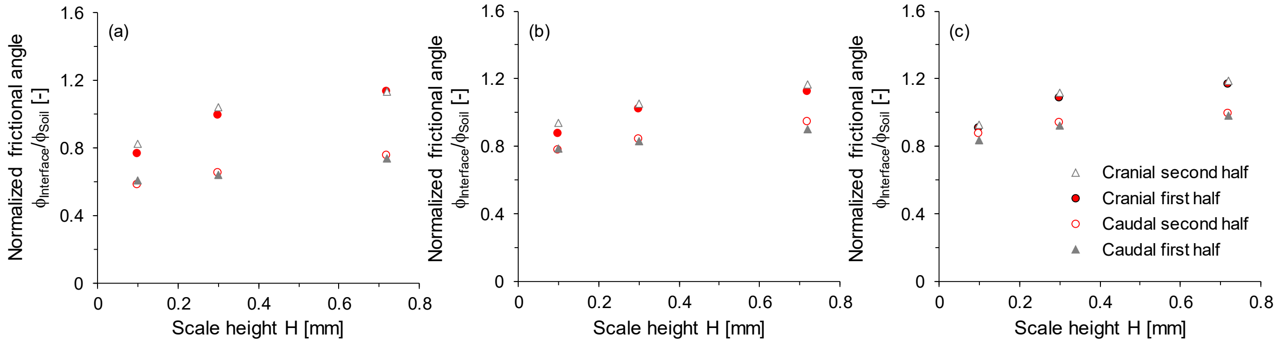

Figure 4. Comparison of normalized frictional angle according to scale height at different shearing cycles: (a) 1st cycle; (b) 10th cycle; (c) 20th cycle.

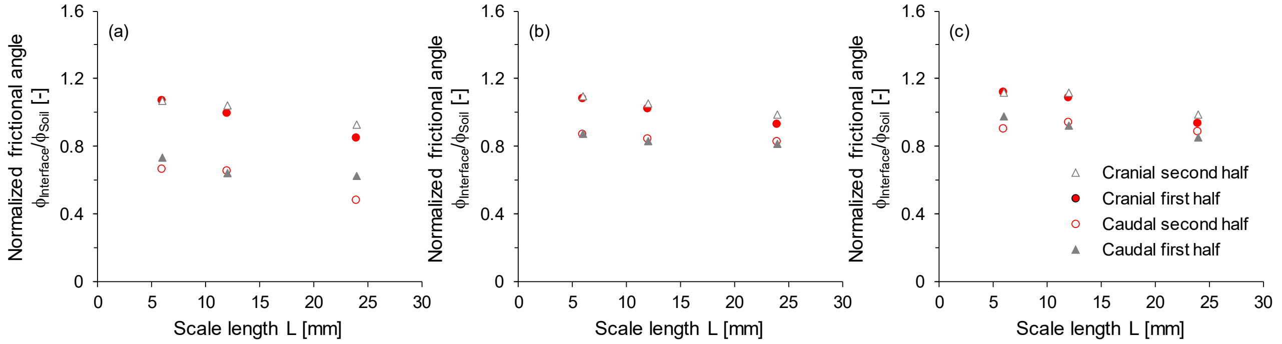

Figure 5. Comparison of normalized frictional angle according to scale length at different shearing cycles: (a) 1st cycle; (b) 10th cycle; (c) 20th cycle.

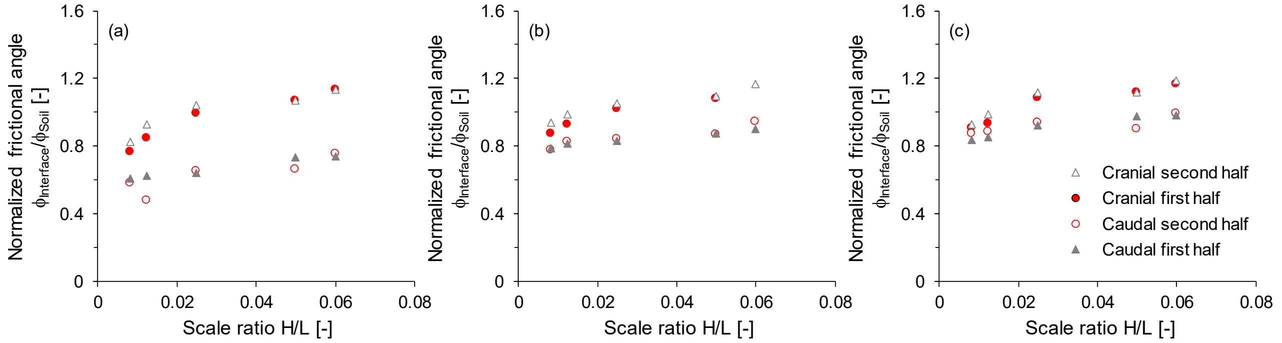

Figure 6. Comparison of normalized friction angle as a function of scale ratio at different shearing cycles: (a) 1st cycle; (b) 10th cycle; (c) 20th cycle.

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