

SHEAR BEHAVIOUR OF FRICTIONALLY ANISOTROPIC GEOTECHNICAL INTERFACES: SNAKESKIN-INSPIRED PATTERNS

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Shear Behaviour of Frictionally Anisotropic Geotechnical Interfaces: Snakeskin-Inspired Patterns

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Dedicated to my Family.

CERTIFICATE

This is to certify that the thesis entitled "**SHEAR BEHAVIOUR OF FRICTIONALLY ANISOTROPIC GEOTECHNICAL INTERFACES: SNAKESKIN-INSPIRED PATTERNS**" is being submitted by **Ms Gayathri Venu Latha** in the fulfilment for the award of the degree of **Doctor of Philosophy** to the **Indian Institute of Technology Delhi**. This thesis is the record of the research work entirely carried out by her under my supervision and guidance. The research report and results presented in this thesis have not been submitted, in part or full, to any University or Institute for the award of any degree or diploma.



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ABSTRACT

The interaction of two different types of materials at their interface in a geotechnical engineering structure can be complex and can profoundly influence the efficiency and stability of the system. Gaining an understanding of the frictional behaviour at these interfaces is crucial for the design of safe and efficient structures, as well as for optimising the properties of interface materials in practical applications. Recent advancements in bio-inspired geotechnics have shown promise in developing innovative engineering surfaces for various geotechnical applications. Of particular interest is the distinctive direction-dependent frictional characteristics, termed frictional anisotropy, of the ventral scale patterns of the snakeskin.

This thesis aims to investigate the shear behaviour of the snakeskin-inspired surfaces that can exhibit optimal frictional characteristics required in geotechnical applications. For this purpose, ventral scale morphologies of different snakes were studied, and three model organisms, namely Viper Snake (VS), Eastern Kingsnake (EK) and Sand Boa (SB), that move over different terrains and exhibit different locomotion techniques were selected. The selected scale patterns were idealised from a geotechnical engineering perspective, and continuum surfaces with the selected patterns were 3D printed using a Fused Filament Fabrication (FFF) 3D printer. A systematic investigation of the interface shear behaviour of the developed snakeskin-inspired continuum surfaces with different geomaterials, including sands of different shape characteristics, clay and Plaster of Paris (PoP), was undertaken. To this end, a versatile interface shear test apparatus was developed to understand the interface shear behaviour accurately.

The interface shear tests on the sands of different shapes (angular sand and rounded glass beads) revealed that the snakeskin-inspired patterns exhibit significantly different behaviour than the unpatterned surface and a prominent frictional anisotropy between the cranial (scales oriented towards the head of the snakes) and the caudal (scales oriented towards the tail of the snakes) directions of shearing. It was also observed that the frictional anisotropy and the efficiency of the snakeskin-inspired patterns depend on the morphology of the scale patterns, namely, the height and the shape of the patterns and the shape of the sand particles. The SB patterns mobilised larger frictional resistances and frictional anisotropy, followed by EK and VS.

The shapes of the different snakeskin-inspired patterns were further adopted for ribbed 3D printed continuum surfaces to exclusively understand their effect on the complex interactions at the interface, and their shear behaviour was tested with sand and clay soils. The results of the tests show that the shape of the snakeskin-inspired ribs is also an influential parameter in mobilising their frictional anisotropy with soils and that they generate considerable inhomogeneous deformation at both sand and clay interfaces. Both snakeskin-inspired scale asperities and the ribs mobilise interface friction resistances greater than the shear strength of the sands in the cranial direction, whereas the clay-ribbed interfaces exhibited higher interface shear resistance than the shear strength of the clay in the cranial and caudal directions due to the complex interactions at the interface. It was also revealed that the snakeskin-inspired patterns perform better for applications involving low normal stresses.

The concept of the frictionally anisotropic behaviour of the snakeskin-inspired patterns with a solid or continuum geomaterial (PoP) was explored for the first time through interface shear tests. The results indicated that the frictional anisotropy of the snakeskin-inspired patterns is in-

deed mobilised by solid or continuum materials, which can be attributed to the more wearing of the PoP surfaces in the cranial direction than the caudal directions. The frictional anisotropy of the snakeskin-inspired patterns was found to be dependent on the scale angle of the patterns and showed an increase upto a critical scale angle of 14.5° , which was followed by a decreasing frictional anisotropy with an increase in the scale angle. Based on the encouraging results from the interface shear tests, Split Sets with snakeskin-inspired surface patterns were 3D printed to explore their application for frictionally anisotropic friction bolts. The insertion and pull-out model tests on the snakeskin-inspired Split Sets with PoP blocks also bring out a frictional anisotropy of the patterns, which follow a bilinear relationship with scale angle, with the least occurring at 16° .

The findings of the study are encouraging for potential applications in geotechnical engineering. The significant data generated in the study to understand the fundamental behaviour of snakeskin-inspired patterns with different geomaterials is a valuable addition to the emerging domain of bio-inspired geotechnics and lays a strong foundation for future studies and research.

सारांश

भू-तकनीकी इंजीनियरिंग संरचना में उनके इंटरफेस पर दो अलग-अलग प्रकार की सामग्रियों की बातचीत जटिल हो सकती है और सिस्टम की दक्षता और स्थिरता को गहराई से प्रभावित कर सकती है। इन इंटरफेस पर घर्षण व्यवहार की समझ हासिल करना सुरक्षित और कुशल संरचनाओं के डिजाइन के साथ-साथ व्यावहारिक अनुप्रयोगों में इंटरफेस सामग्री के गुणों को अनुकूलित करने के लिए महत्वपूर्ण है। जैव-प्रेरित भू-तकनीकी में हालिया प्रगति ने विभिन्न भू-तकनीकी अनुप्रयोगों के लिए नवीन इंजीनियरिंग सतहों को विकसित करने में वादा दिखाया है। विशेष रूप से रुचि विशिष्ट दिशा-निर्भर घर्षण विशेषताओं है, जिसे सांप की खाल के उदर पैमाने पैटर्न के घर्षण अनिसोट्रॉपी कहा जाता है।

इस थीसिस का उद्देश्य सांपकिन से प्रेरित सतहों के कतरनी व्यवहार की जांच करना है जो भू-तकनीकी अनुप्रयोगों में आवश्यक इष्टतम घर्षण विशेषताओं को प्रदर्शित कर सकते हैं। इस उद्देश्य के लिए, विभिन्न सांपों के उदर पैमाने की आकृति विज्ञान का अध्ययन किया गया था, और तीन मॉडल जीव, अर्थात् वाइपर स्नेक (वीएस), पूर्वी किंग्सनेक (ईके) और सैंड बोआ (एसबी), जो विभिन्न इलाकों में चलते हैं और विभिन्न हरकत तकनीकों का प्रदर्शन करते हैं, का चयन किया गया था। चयनित पैमाने के पैटर्न को भू-तकनीकी इंजीनियरिंग परिप्रेक्ष्य से आदर्श बनाया गया था, और चयनित पैटर्न के साथ सातत्य सतहों को फ्यूज्ड फिलामेंट फैब्रिकेशन (एफएफएफ) 3 डी प्रिंटर का उपयोग करके 3 डी मुद्रित किया गया था। विभिन्न आकार की विशेषताओं, मिट्टी और प्लास्टर ऑफ पेरिस (पीओपी) की रेत सहित विभिन्न भू-सामग्रियों के साथ विकसित सांपकिन-प्रेरित सातत्य सतहों के इंटरफेस कतरनी व्यवहार की एक व्यवस्थित जांच की गई थी। यह अंत करने के लिए, एक

बहुमुखी इंटरफ़ेस कतरनी परीक्षण उपकरण इंटरफ़ेस कतरनी व्यवहार को सही ढंग से समझने के लिए विकसित किया गया था।

विभिन्न आकृतियों (कोणीय रेत और गोल कांच के मोती) की रेत पर इंटरफ़ेस कतरनी परीक्षणों से पता चला है कि सांप-प्रेरित पैटर्न अनपैटर्न्ड सतह की तुलना में काफी अलग व्यवहार प्रदर्शित करते हैं और कपाल (सांपों के सिर की ओर उन्मुख तराजू) और दुम (सांपों की पूंछ की ओर उन्मुख तराजू) के बीच एक प्रमुख घर्षण अनिसोट्रॉपी कतरनी की दिशाएं। यह भी देखा गया कि घर्षण अनिसोट्रॉपी और सांप-प्रेरित पैटर्न की दक्षता पैमाने के पैटर्न की आकृति विज्ञान पर निर्भर करती है, अर्थात्, ऊंचाई और पैटर्न का आकार और रेत कणों का आकार। एसबी पैटर्न ने बड़े घर्षण प्रतिरोधों और घर्षण अनिसोट्रॉपी को जुटाया, इसके बाद ईके और वीएस।

विभिन्न सांपकिन-प्रेरित पैटर्न के आकार को आगे 3 डी प्रिंटेड सातत्य सतहों के लिए अपनाया गया था ताकि इंटरफ़ेस पर जटिल इंटरैक्शन पर उनके प्रभाव को विशेष रूप से समझा जा सके, और उनके कतरनी व्यवहार का परीक्षण रेत और मिट्टी की मिट्टी के साथ किया गया था। परीक्षणों के परिणाम बताते हैं कि सांपकिन से प्रेरित पसलियों का आकार भी मिट्टी के साथ उनके घर्षण अनिसोट्रॉपी को जुटाने में एक प्रभावशाली पैरामीटर है और वे रेत और मिट्टी दोनों इंटरफ़ेस पर काफी अमानवीय विरूपण उत्पन्न करते हैं। सांप-प्रेरित स्केल एस्पेरिटीज और पसलियां दोनों कपाल दिशा में रेत की कतरनी ताकत से अधिक इंटरफ़ेस घर्षण प्रतिरोध को जुटाते हैं, जबकि मिट्टी-रिब्ड इंटरफ़ेस ने इंटरफ़ेस पर जटिल बातचीत के कारण कपाल और दुम दिशाओं में मिट्टी की कतरनी ताकत की तुलना में उच्च इंटरफ़ेस कतरनी प्रतिरोध का प्रदर्शन किया। यह भी पता चला कि सांपकिन से प्रेरित पैटर्न कम सामान्य तनाव वाले अनुप्रयोगों के लिए बेहतर प्रदर्शन करते हैं।

एक ठोस या सातत्य भू-सामग्री (पीओपी) के साथ सांप-प्रेरित पैटर्न के घर्षण रूप से अनिसोट्रोपिक व्यवहार की अवधारणा को पहली बार इंटरफ़ेस कतरनी परीक्षणों के माध्यम से खोजा गया था। परिणामों ने संकेत दिया कि सांप-प्रेरित पैटर्न की घर्षण अनिसोट्रॉपी वास्तव में ठोस या सातत्य सामग्री द्वारा जुटाई जाती है, जिसे दुम दिशाओं की तुलना में कपाल दिशा में पीओपी सतहों के अधिक पहनने के लिए जिम्मेदार ठहराया जा सकता है। सांप-प्रेरित पैटर्न की घर्षण अनिसोट्रॉपी को पैटर्न के पैमाने कोण पर निर्भर पाया गया और 14.5 डिग्री के महत्वपूर्ण पैमाने के कोण तक वृद्धि देखी गई, जिसके बाद स्केल कोण में वृद्धि के साथ घटती घर्षण अनिसोट्रॉपी हुई। इंटरफ़ेस कतरनी परीक्षणों से उत्साहजनक परिणामों के आधार पर, सांपकिन से प्रेरित सतह पैटर्न के साथ स्प्लिट सेट 3 डी मुद्रित किए गए थे ताकि घर्षण रूप से अनिसोट्रोपिक घर्षण बोल्ट के लिए उनके आवेदन का पता लगाया जा सके। पीओपी ब्लॉकों के साथ सांपकिन-प्रेरित स्प्लिट सेट पर सम्मिलन और पुल-आउट मॉडल परीक्षण भी पैटर्न के एक घर्षण अनिसोट्रॉपी को सामने लाते हैं, जो स्केल कोण के साथ एक बिलिनियर संबंध का पालन करते हैं, जिसमें कम से कम 16 डिग्री होता है।

अध्ययन के निष्कर्ष भू-तकनीकी इंजीनियरिंग में संभावित अनुप्रयोगों के लिए उत्साहजनक हैं। विभिन्न भू-सामग्रियों के साथ सांप-प्रेरित पैटर्न के मौलिक व्यवहार को समझने के लिए अध्ययन में उत्पन्न महत्वपूर्ण डेटा जैव-प्रेरित भू-तकनीकों के उभरते डोमेन के लिए एक मूल्यवान अतिरिक्त है और भविष्य के अध्ययन और अनुसंधान के लिए एक मजबूत आधार रखता है।

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LIST OF SYMBOLS AND NOTATIONS

R	roundness of soil particle
S_{wl}	sphericity of soil particle
e_{max}	maximum void ratio of soil
e_{min}	minimum void ratio of soil
γ_{max}	maximum dry unit weight of soil
γ_{min}	minimum dry unit weight of soil
W_p	width of patterns
L_p	profile length of patterns
L_i	length of interaction
IL_R	interaction length ratio
R_{micro}	micro-roughness of the continuum surfaces
R_{max}	maximum surface roughness of the continuum surfaces
R_n	normalised roughness of the continuum surfaces
τ	shear stress
σ	normal stress
ϕ_f, ϕ_p	friction angle of soil at failure or peak
D_{50}	mean diameter of the soil particle
δ_f, δ_p	interface friction angle at failure or peak

ψ	dilation angle
E	efficiency/efficiency parameter
VD	vertical displacement
V	coefficient of variation
X_m	mean of the data
σ_m	standard deviation of the data
τ_{pi}	peak interface shear stress
τ_{ps}	peak shear stress of soil
τ_{ri}	residual interface shear stress
a_p, b_p	power curve coefficients at peak shear
a_r, b_r	power curve coefficients at residual shear stage
S_n	normalised strain softening
F_s	interface shear load
F_n	applied normal load
I_t	total interaction
I_n	normalised interaction
n_s	number of scales