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DEVELOPMENT AND EXPERIMENTAL EVALUATION OF BIO-INSPIRED PILE SURFACE ASPERITIES FOR ENHANCED LOAD TRANSFER IN SANDY SOILS

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In sandy soils, skin resistance efficiency is critical, as it governs load capacity, settlement, and foundation cost. This study investigates pile foundations with directional surface asperities embedded in uniform sand to clarify the limited knowledge of how asperity orientation (cranial vs. caudal), geometric ratio (L / H), and pile diameter affect axial load transfer. Experimental tests were conducted on steel piles with diameters of 10, 12, and 15.85 mm under smooth, cranial, and caudal conditions with L / H ratios of 20, 26.67, and 33.33. Axial compression tests following ASTM D1143-20 in controlled dry sand provided ultimate load and shaft resistance data, validated by one-way ANOVA. The results show that cranial asperities consistently outperformed other surfaces, with the Cr L / H 20 configuration on the 15.85 mm pile reaching 0.368 kN, a 392.51% increase over smooth piles, while caudal asperities achieved only 134.30%. Cranial asperities also mobilized shaft resistance more uniformly along the pile, reducing end-bearing reliance. This performance is explained by stronger passive interaction at the pile-soil interface, which raises normal stress and friction mobilization. The distinctive feature of this research is the identification of the L / H ratio as a measurable design parameter, with L / H = 20 found to be optimal, in contrast to previous studies that described roughness only qualitatively. The findings demonstrate practical potential for applying cranial asperity designs in pile foundations for light- to medium-scale infrastructure on sandy soils, such as bridges, wharves, and transmission towers, enabling shorter or fewer piles without compromising safety while improving cost efficiency and geotechnical performance

Keywords: axial load capacity, caudal asperity, cranial asperity, experimental validation, L / H ratio

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1. Introduction

In recent decades, advances in bio-inspired engineering have opened new opportunities in the development of underground structural technologies. One of the most notable breakthroughs is the use of surface textures that mimic natural morphologies, such as those found on snake scales, to generate anisotropic friction at the soil-structure interface. This directional frictional interaction offers significant potential to enhance load transfer efficiency in foundation systems, particularly in sandy soils, where shaft resistance plays a critical role in pile performance.

Numerous studies have demonstrated that texture orientation has a strong influence on frictional behavior. Cranial orientation (opposing the shear direction) consistently produces higher interface friction compared to caudal orientation [1]. Moreover, geometric motifs such as sawtooth and serpentine patterns have been shown to either reverse or amplify frictional responses, depending on the loading direction and surface orientation [2]. Accordingly, strategically oriented surface designs are crucial in determining the efficiency of axial load transfer in pile foundations [3].

However, while small-scale interface shear tests are widely reported [4], model-scale axial loading tests on textured piles remain scarce. To date, no systematic approach has evaluated the combined influence of asperity orientation, length-to-height (L / H) ratio, and pile diameter on shaft resistance characteristics. This leaves a critical research gap that must be addressed to ensure the reliability of directionally textured design concepts under field conditions.

Beyond design aspects, experimental success is also highly dependent on controlled testing conditions [5]. One crucial factor is particle gradation in granular soils, as it governs dilation behavior [6] and load transfer pathways [7]. The application of appropriate statistical analysis is therefore essential to validate findings and minimize reliance on empirical approaches that lack universality.

Within the global demand for cost-efficient and sustainable infrastructure, optimizing pile design through surface engineering becomes increasingly relevant. By enhancing skin resistance through directional texturing, material and energy consumption can be reduced, while prolonging structural service life, especially under repeated loading conditions. Therefore, further exploration of directionally textured pile surfaces is vital to advancing more efficient, adaptive, and environmentally friendly foundation systems.

2. Literature review and problem statement

The development of efficient and sustainable deep foundations remains a persistent challenge in geotechnical engineering. In sandy soils, pile performance is predominantly governed by skin resistance rather than end bearing, as the interaction between pile surface and soil controls settlement, overall capacity, and long-term reliability. Even relatively small improvements in skin resistance mobilization may result in significant reductions in pile length and number, offering substantial economic and environmental benefits [8]. Early laboratory studies emphasized the role of pile surface roughness, demonstrating that it can increase the interface friction angle by up to 50% in uniform sand. These findings highlighted the contribution of surface microgeometry in enhancing load-transfer efficiency, but they were limited to roughened surfaces without considering directional texturing.

Building on this foundation, researchers began exploring bio-inspired textures resembling snake scales [9], which revealed the presence of anisotropic friction at soil-structure interfaces [10, 11]. Experimental observations confirmed that cranial orientation, which opposes the shear direction [12], could mobilize interface shear resistance up to 22 kPa, substantially higher than the 6 kPa observed for caudal orientation [13]. This demonstrated that asperity orientation is a key variable influencing interface behavior, though most of these investigations were confined to tribological-scale tests. Complementary laboratory studies showed that directional textures also enhanced sand dilation, with increases in shear angle of 20% for cranial-smooth, 15% for cranial-caudal, and 10% for caudal-smooth configurations at $L / H = 20$ [14]. While these results emphasized the importance of texture orientation, systematic evaluations of different asperity aspect ratios (L / H) remain absent.

Numerical studies using the Discrete Element Method (DEM) provided further mechanistic insights. Results indicated that asperities with smaller L / H ratios improve particle interlocking and yield a more uniform stress distribution. For instance, cranial orientation at $L / H = 4.16$ mobilized shaft resistance up to 3.7 kN, whereas caudal orientation at $L / H = 6.25$ achieved only 2.0 kN [15]. However, numerical models remain limited in replicating in-situ boundary conditions, highlighting the need for experimental validation [16]. At the model pile scale, tests demonstrated that directional textures can significantly increase shaft resistance, with improvements of up to 780% for cranial and 340% for caudal orientations compared with smooth piles [17]. Despite these remarkable gains, existing studies have not simultaneously addressed the combined influence of asperity orientation, L / H ratio, and pile diameter.

Field-scale investigations reinforced the importance of scale effects, reporting that a 0.30 m diameter pile could sustain nearly twice the skin resistance of a 0.20 m diameter pile. These results suggest that pile diameter strongly influences mobilization of skin resistance, particularly when combined with surface texturing, yet the relationship between these parameters has never been comprehensively analyzed [18]. Moreover, granular soil characteristics such as particle gradation are known to affect dilation and stress transfer pathways, underscoring the necessity of carefully controlling and reporting soil conditions in experimental programs [19]. From a methodological perspective, recent studies stressed the importance of statistical validation to ensure the reliability of results. Statistical analysis confirmed the highly significant effect of cranial orientation on shaft resistance, thus reinforcing the urgency of incorporating quantitative validation in pile design [20].

In summary, the literature demonstrates the potential of directional surface texturing to enhance pile performance; however, existing research remains fragmented. Although roughness, orientation, and dilation have been independently studied, there is no systematic investigation of the combined effects of asperity orientation, aspect ratio (L / H), and pile diameter on axial load-transfer efficiency. Addressing these gaps is essential in the context of the growing demand for cost-effective and sustainable infrastructure. By optimizing pile design through bio-inspired surface engineering, it is possible to reduce material consumption and energy usage while extending the foundation's service life under repeated loading. These considerations clearly establish the necessity of further research into directionally textured piles in sandy soils. To address these limitations, it was proposed to use of a classical mathematical model to define shaft resistance [21]

$$Q_S = K \cdot \sigma'_v \cdot \tan\delta \cdot \pi \cdot B \cdot D, \tag{1}$$

where Q_S – the total shaft resistance; K – the lateral earth pressure coefficient; σ'_v is the effective vertical stress; δ – the interface friction angle; πBD represents the pile-soil contact area. This equation serves as the basis for extracting the dimensionless parameter L / H, which is used to characterize the geometric profile of surface asperities.

The ratio L / H is adopted as a non-dimensional variable, following the principles of similarity theory, which allows results obtained at the model scale to be reasonably generalized to field conditions [22]. In this way, the experimental framework adheres to geometric similarity, ensuring that the derived conclusions are valid beyond laboratory setups.

Accordingly, several aspects remain unresolved. The differences between cranial and caudal asperity orientations in axial load transfer are not yet well documented. The optimum L / H ratio capable of efficiently mobilizing shaft capacity is also not clearly defined. Furthermore, the interaction between pile diameter and directionally textured asperities in enhancing overall bearing capacity remains poorly understood. These knowledge gaps arise from technical limitations in full-scale testing, the high cost of field experiments, and methodological challenges in maintaining asperity orientation during pile installation.

3. The aim and objectives of the study

The study aims to develop directionally textured pile surface asperities (cranial and caudal) with varying geometric ratios (L / H) and pile diameters, to enhance the efficiency of axial load transfer in sandy soils.

To achieve this aim, the following specific aims are established:

– to evaluate the maximum axial load capacity and load transfer behavior of piles with cranial asperities at varying L / H ratios and diameters;

– to evaluate the maximum axial load capacity and load transfer behavior of piles with caudal asperities at varying L / H ratios and diameters;

– to identify the optimal asperity configuration ($L / H = 20$) for cranial and caudal orientations in large-diameter piles;

– to statistically analyze the influence of asperity orientation on axial load transfer using one-way ANOVA.

4. Materials and methods

The object of this study is to investigate the axial load transfer behavior of steel model piles with varying surface textures and L / H ratios embedded in dry, uniformly compacted sandy soil. The central hypothesis is that cranially oriented asperities with lower L / H ratios significantly enhance shaft resistance and ultimate axial load capacity compared to smooth and caudal oriented pile configurations. The experimental setup assumes a homogeneous, dry soil medium and that axial load is transferred primarily through shaft friction under monotonic vertical loading. To ensure experimental control, several simplifications were adopted, including the exclusion of pore water pressure effects, time-dependent soil behavior, and lateral or cyclic loading conditions. These assumptions are acceptable within the scope of this study, which focuses on understanding fundamental load transfer mechanisms under idealized conditions.

This study follows the conventional static load testing procedure outlined in ASTM D1143/D1143M-20, which serves as the classical framework for evaluating the axial bearing capacity of deep foundation piles in uniform sand. The experimental setup replicates standard boundary conditions, including pile embedment depth, loading sequence, and sand compaction, ensuring methodological consistency with widely accepted geotechnical testing practices.

However, unlike traditional approaches that typically employ smooth-surfaced piles, this study enhances the classical design by introducing two additional variables: the directional orientation of surface asperities (cranial and caudal) and the dimensionless geometric ratio (L / H) as novel design parameters. These additions are not intended to replace the classical method, but rather to extend and enrich it, enabling a deeper understanding of soil pile interaction, particularly in the context of bioinspired directional surface engineering.

This study is designed to evaluate the influence of pile surface asperity orientation (cranial and caudal), geometric ratio (L / H), and pile diameter on skin resistance in uniform sand. Theoretically, the initial calculations refer to pile bearing capacity equations in sandy soils, emphasizing the contribution of shear angle in mobilizing skin capacity. After the sand medium is treated with asperity geometry, the approach shifts to an evaluation based on mobilized cohesion governed by interlocking mechanisms. Accordingly, the research method integrates a simple analytical framework with experimental verification under controlled laboratory conditions.

Steel piles were fabricated in three diameter variations (B), with surface conditions consisting of three types: smooth, cranial asperities, and caudal asperities. The asperity variations were arranged in terms of length (L) and height (H). The dimensional details of the asperities are presented in Table 1, while the pile models are illustrated in Fig. 1. Smooth piles were employed as the reference (control).

The tests were conducted using an axial loading system equipped with a stepper motor actuator controlled by an Arduino R4 WiFi, operating at a constant penetration rate of 0.1 mm/s. The applied load was recorded using an S-type load cell (Zemic H3), while axial displacement was measured with a linear potentiometer. Data were acquired in real-time through the MS Excel Data Streamer. The schematic of the testing system is shown in Fig. 2. A test box with dimensions of 420 × 420 × 470 mm was employed as the testing medium. Sand placement was carried out using the water pluviation method until the target relative density was achieved. The sand used in this study was Brantas River sand, classified according to its geotechnical properties as summarized in Table 2.

Tests were carried out on all pile configurations. Each steel pile model was driven into the sand to a depth of 240 mm. Following installation, axial loading was applied incrementally using a loading machine, as illustrated in Fig. 2. Loading was continued until either the maximum load was reached or the settlement corresponded to twice 15% of the pile diameter, in accordance with ASTM D1143-20. To ensure load alignment and minimize unwanted side friction, the system was equipped with a spherical bearing, as shown in Fig. 3. Each pile configuration was tested at least twice to ensure data consistency. All load-settlement data were recorded automatically.

Table 1

Asperity profile details of the pile foundation

Factor	Smooth	Cranial caudal L / H 20	Cranial caudal L / H 26.67	Cranial caudal L / H 33.33
B 10 (mm)	10	10	10	10
B 12 (mm)	12	12	12	12
B 15.85 (mm)	15.85	15.85	15.85	15.85
L (mm)	–	6	6	6
H (mm)	–	0.3	0.3	0.3

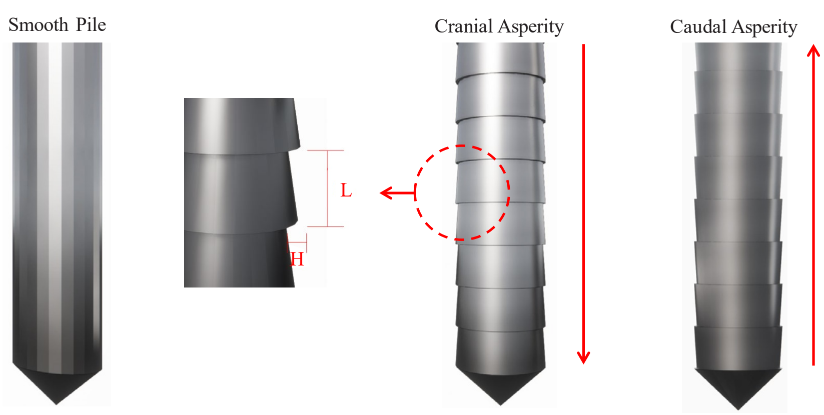


Fig. 1. Asperity details of pile foundation (AIC innovation)

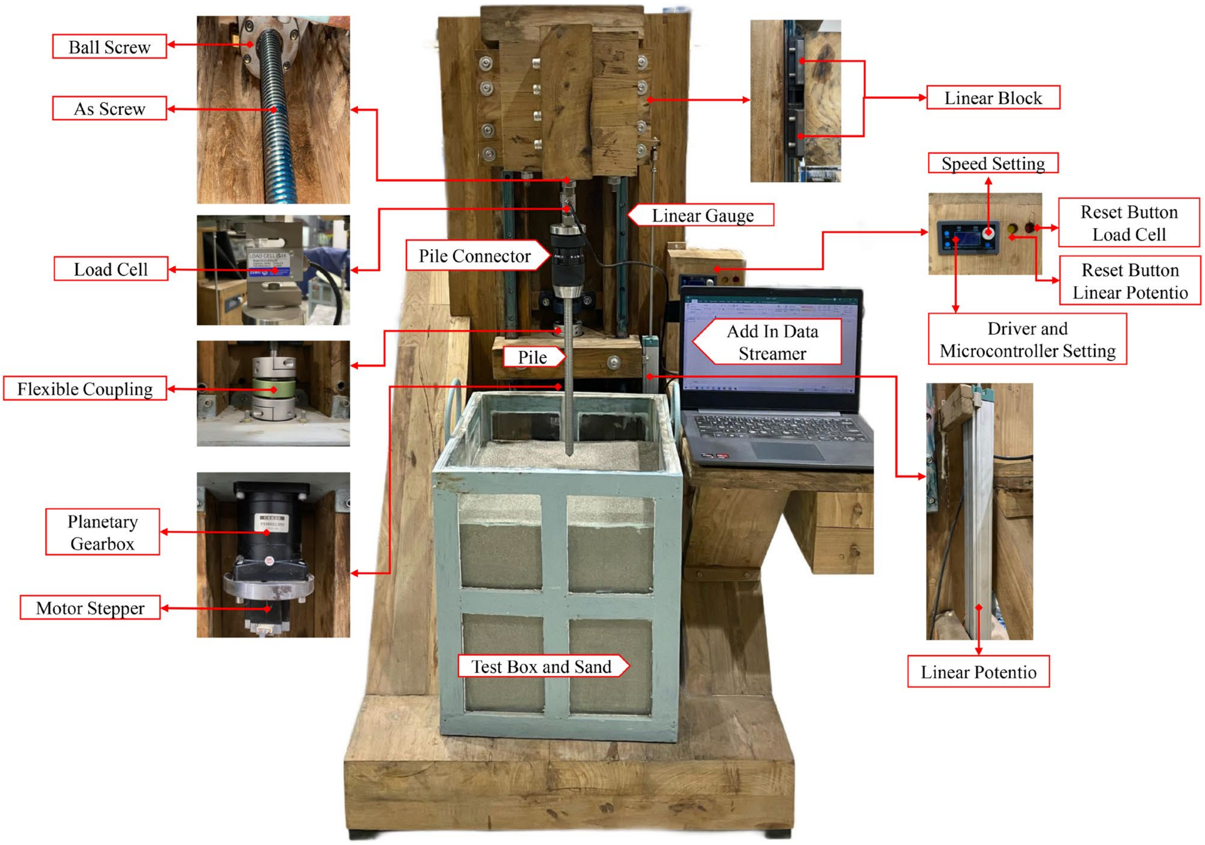
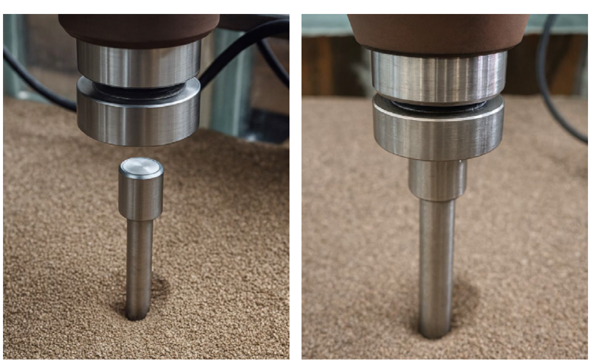


Fig. 2. Pile driving test equipment setup (AIC innovation)

Table 2

Properties of Brantas sand

Properties	Value
Sand type	SP
Dr (%)	70
Dry unit weight (γ_t) [kN/m^3]	16.69
Coefficient of curvature *Cc*	0.96
Uniformity coefficient *Cu*	3.42
Average particle size D_{50} [mm]	0.40
Void ratio (e)	0.71
Maximum void ratio $e_{\max}$	0.91
Minimum void ratio $e_{\min}$	0.62
Porosity (%)	38.24
Specific gravity (G_s)	2.76
Friction angle φ [°]	30



a *b*

Fig. 3. Axial load test setup: *a* – spherical bearing detail; *b* – incremental axial loading process

To validate the effects of the research parameters, the test data were analyzed using one-way ANOVA with statistical software. This analysis was conducted to assess the significance of differences among asperity orientation, L/H ratio, and pile diameter, with a significance level of $\alpha = 0.05$.

5. Results of the study on the effect of pile surface asperity orientation and geometry on axial load capacity and shaft friction

5. 1. Maximum load capacity and load transfer in piles with cranial asperities

The test results presented in Fig. 4 highlight two key aspects: the load-settlement relationship and the distribution of load transfer along the pile depth. Fig. 4, *a* shows the maximum load at a vertical displacement equal to 15% of the pile diameter. For the 10 mm diameter smooth pile, the maximum load was 0.025 kN. The application of cranial asperities with an L/H ratio of 20 increased this value to 0.059 kN. At L/H ratios of 26.67 and 33.33, the maximum loads were 0.048 kN and 0.037 kN, respectively. For the 12 mm diameter pile, the maximum load increased from 0.046 kN (smooth pile) to 0.114 kN at $L/H = 20$, 0.095 kN at $L/H = 26.67$, and 0.071 kN at $L/H = 33.33$. In the case of the 15.85 mm diameter pile, the maximum load rose from 0.075 kN (no asperities) to 0.175 kN at $L/H = 20$, then decreased to 0.150 kN at $L/H = 26.67$ and 0.100 kN at $L/H = 33.33$. The maximum recorded vertical settlements during testing were 1.5 mm for the 10 mm pile, 1.8 mm for the 12 mm pile, and 2.4 mm for the 15.85 mm pile. The results indicate that larger pile diameters are associated with greater final settlements.

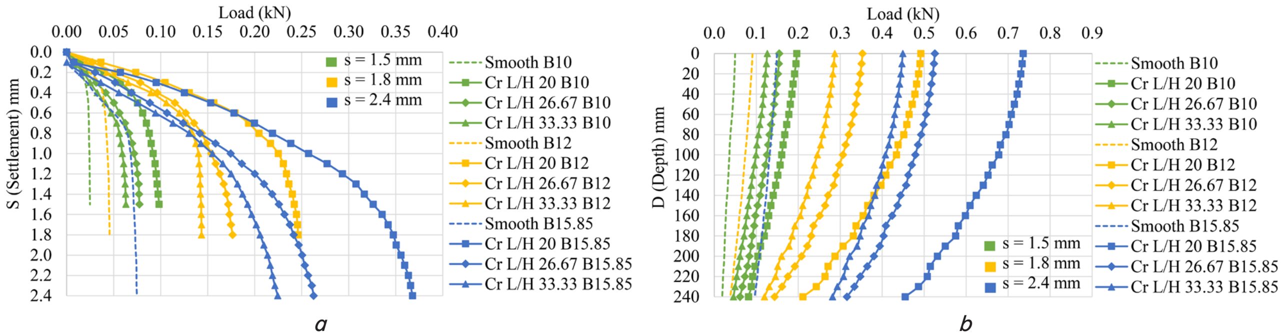


Fig. 4. Test results for cranial and smooth piles:
a — load and settlement relationship; *b* — load and penetration depth relationship

The load distribution with depth in the graph shown in Fig. 4, *b* indicates that for the Cr *L* / *H* 20 configuration, the initial load at a depth of 0 mm was recorded as 0.23 kN for B10, 0.42 kN for B12, and 0.736 kN for B15.85. The residual load transferred to the pile base at 240 mm depth was 0.00 kN for both B10 and B12, and 0.455 kN for B15.85. The difference between the initial and final loads reflects the amount of load transferred along the shaft: 0.23 kN (B10), 0.42 kN (B12), and 0.281 kN (B15.85), which corresponds to transfer rates of 0.00096 kN/mm, 0.00175 kN/mm, and 0.00117 kN/mm relative to the embedded length. Across all pile diameters, the Cr *L* / *H* 20 configuration consistently exhibited the highest load capacity and the most effective load transfer values, with a more uniform distribution along the shaft.

5. 2. Maximum load capacity and load transfer in piles with caudal asperities

The caudal asperity configuration was also tested using identical pile diameters and *L* / *H* ratios, as illustrated in Fig. 5. For the 10 mm diameter pile, the maximum load increased from 0.025 kN (smooth pile) to 0.059 kN at *L* / *H* = 20, 0.048 kN at *L* / *H* = 26.67, and 0.037 kN at *L* / *H* = 33.33. For the 12 mm diameter pile, the load capacity increased from 0.046 kN to 0.114 kN at *L* / *H* = 20, followed by 0.095 kN at *L* / *H* = 26.67, and 0.071 kN at *L* / *H* = 33.33. The 15.85 mm diameter pile recorded maximum loads of 0.175 kN at *L* / *H* = 20, 0.150 kN at *L* / *H* = 26.67, and 0.100 kN at *L* / *H* = 33.33.

The load distribution along depth for the Cl *L* / *H* 20 configuration showed initial head loads of 0.20 kN for B10, 0.35 kN for B12, and 0.350 kN for B15.85. Fig. 5, *b* shows that the residual loads at the pile base (depth 240 mm) were 0.00 kN for both B10 and B12, and 0.148 kN for B15.85. Accordingly, the effective load transferred along the shaft was 0.20 kN (B10), 0.35 kN (B12), and 0.202 kN (B15.85). The corresponding unit load transfer for B15.85 was 0.00084 kN/mm.

5. 3. Maximum asperity configuration for cranial and caudal orientation on B15.85 pile (*L* / *H* = 20)

The Cr *L* / *H* 20 and Cl *L* / *H* 20 configurations on the 15.85 mm diameter pile were directly compared to evaluate the maximum performance of each asperity orientation. In the load-settlement graph (Fig. 6,), the cranial configuration recorded a maximum load of 0.368 kN with a final settlement of 2.4 mm. In comparison, the caudal configuration reached a maximum load of 0.175 kN at the same displacement. In contrast, the smooth pile recorded a maximum load of 0.075 kN. Compared to the smooth pile, the cranial asperity configuration (Cr *L* / *H* 20) exhibited a 392.51% increase in maximum load capacity, whereas the caudal configuration (Cl *L* / *H* 20) showed an enhancement of 134.30%.

The shaft load transfer recorded for the Cr *L* / *H* 20 configuration was 0.281 kN, while the Cl *L* / *H* 20 configuration transferred 0.202 kN. The smooth pile transferred only 0.087 kN. The corresponding unit load transfer values were 0.00117 kN/mm for the cranial asperity, 0.00084 kN/mm for the caudal asperity, and 0.00036 kN/mm for the smooth pile. As shown in the load-depth distribution graph (Fig. 6, *b*), the cranial configuration demonstrated the highest efficiency in mobilizing and transferring load along the pile shaft surface compared to the other configurations.

5. 4. Statistical analysis of the effect of caudal and cranial asperities

To statistically validate the observed differences in load transfer performance, an ANOVA test was conducted to evaluate the effects of caudal and cranial asperities compared to the smooth pile. The results are summarized in Table 3.

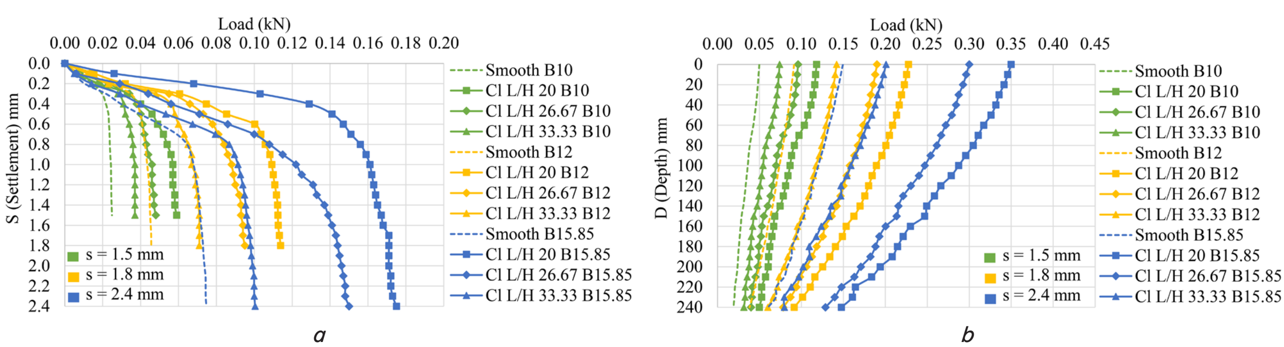


Fig. 5. Test results for caudal and smooth piles:
a — load and settlement relationship; *b* — load and penetration depth relationship

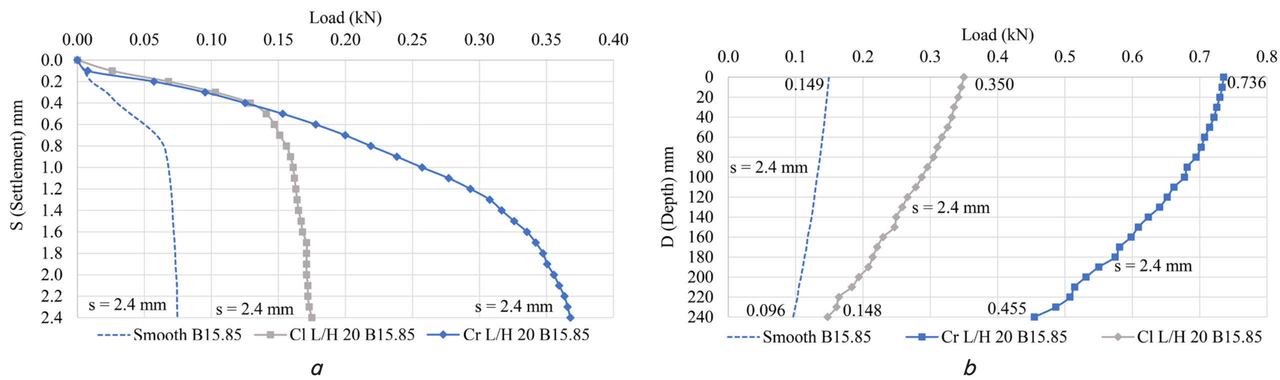


Fig. 6. Maximum test results for B15.85 pile with *L* / *H* = 20:
a — load and settlement relationship; *b* — load and penetration depth relationship

Table 3

ANOVA validation of asperity effects compared to smooth pile B15.85

Pile asperity	F-statistic	P-value
Caudal (*L* / *H* 20)	15.0672	$8.05 \cdot 10^{-4}$
Cranial (*L* / *H* 20)	80.1128	$1.22 \cdot 10^{-11}$

The statistical analysis results show that the caudal asperity configuration with an *L* / *H* ratio of 20 produced an F-value of 15.0672 and a p-value of 0.000805. In comparison, the cranial asperity configuration with the same *L* / *H* ratio yielded an F-value of 80.1128 and a p-value of $1.22 \cdot 10^{-11}$. The complete results of the ANOVA statistical validation for both configurations compared to the smooth pile with a 15.85 mm diameter are presented in Table 3.

6. Discussion on the influence of orientation and geometry of surface asperities on the efficiency of axial load transfer on piles embedded in sand

The results in Fig. 4 clearly demonstrate that the application of cranial asperities with an *L* / *H* ratio of 20 significantly enhances both the load-bearing capacity and axial load transfer efficiency of piles across all diameters [23]. The load-settlement curves reveal peak loads at a vertical displacement equal to 15% of the pile diameter, with the highest values consistently recorded for the *L* / *H* 20 configuration. In contrast, higher *L* / *H* ratios (26.67 and 33.33) indicate a reduction in performance, suggesting that overly spaced asperities reduce interaction efficiency with the surrounding soil [24]. Analysis of load transfer along the pile depth confirms that the 10 mm and 12 mm diameter piles fully mobilized shaft resistance, as no residual load was recorded at the pile base. Conversely, the 15.85 mm pile retained a significant portion of the load at the base, implying partial reliance on end bearing [23]. Additionally, the maximum vertical settlement increased with the pile diameter, reflecting a greater surface area and increased friction mobilization. These findings underscore the importance of optimizing asperity geometry and pile dimensions to achieve efficient load transfer, particularly for light- to medium-scale infrastructure in sandy soils.

The experimental results indicate that cranial asperity orientation consistently enhances the ultimate axial load capacity compared to both caudal orientation and smooth piles. As shown in Fig. 5 and Table 3, the Cr *L* / *H* 20 configuration on a pile with a diameter of 15.85 mm achieved a capacity increase of 392.51% relative to the smooth pile, which is substantially higher than the 134.30% improvement observed for the Cl *L* / *H* 20 configuration. This phenomenon can be attributed to the development of a stronger passive interaction along the pile-soil interface, leading to higher normal stresses and more effective mobilization of interface friction. Such a mechanism aligns with the shear interaction theory at the contact surface [12], which posits that surface orientation opposing the external load direction can enlarge the passive resistance zone.

Furthermore, the load distribution along the pile depth (Fig. 6) demonstrates that the Cr *L* / *H* 20 configuration transferred a load of 0.281 kN, equivalent to 0.00117 kN/mm, which is more uniform compared to the Cl *L* / *H* 20 configuration (0.202 kN or 0.00084 kN/mm) and the smooth pile (0.087 kN or 0.00036 kN/mm). This distribution pattern indicates that cranial asperities not only enhance the ultimate axial load capacity but also sustain continuous load transfer along the pile shaft, thereby reducing reliance on end-bearing resistance. These findings were further validated by a one-way ANOVA analysis, which confirmed that asperity orientation has a statistically significant effect on load capacity ($p < 0.05$), ensuring that the observed improvement is not merely experimental variation but is genuinely governed by asperity geometry. This outcome is consistent with the findings [16], which reported that asperities oriented against the external load accelerate friction mobilization. Also, it aligns with [19], in which it is highlighted that an optimal *L* / *H* ratio enables full mobilization without compromising the effectiveness of the interlocking mechanism.

The originality of this research lies in the use of the asperity *L* / *H* ratio as a design parameter, systematically evaluated with respect to asperity orientation, where the *L* / *H* ratio of 20 was found to provide the optimal condition. This approach differs from previous studies, which generally examined the effect of surface roughness only qualitatively. Through controlled model-scale experiments on uniform dry sand, this research provides quantitative evidence that asperity geometry can serve as a measurable design variable, thereby strengthening its scientific contribution compared to the existing literature.

The findings of this study also provide a strong experimental basis for implementing cranial asperity-based pile surface design in sandy soil conditions. The improvement in ultimate axial load capacity and the efficiency of load distribution along the pile shaft indicate that surface modification with a specific L / H ratio can be utilized to reduce pile length or the number of piles in a foundation group without compromising structural safety. The more uniform load distribution observed in the cranial configuration further contributes to reducing stress concentration at the pile tip. It has the potential to mitigate the risk of local failure, particularly in deep foundations embedded in loose sand. These results may serve as a reference for developing foundation design standards in light to medium-scale infrastructure projects in loose sandy areas, such as short-span bridges, wharf structures, or transmission tower foundations. Accordingly, the application of cranial asperity pile surfaces with an optimal geometric ratio holds promise for being developed into a new technical standard capable of enhancing both cost efficiency and geotechnical performance in engineering practice.

It is worth noting that this study has several limitations. First, the laboratory model employed only pile diameters ranging from 10 to 15.85 mm with an embedment depth of 240 mm, thus requiring further verification before application at full scale. Second, the tests were conducted exclusively on uniformly graded dry sand under static loading, which does not fully represent field conditions involving saturated soils, cohesive materials, or cyclic and dynamic loading. Third, the repeatability of the results is highly dependent on controlling the relative density of sand, a condition that is more difficult to achieve in the field compared to laboratory settings.

Beyond these limitations, certain practical challenges remain. The fabrication of cranial asperities with specific geometric ratios requires high manufacturing precision, which may increase both cost and construction time. Furthermore, the application of this technology to full-scale piles may encounter challenges during casting or installation in the field. To address these issues, the development of alternative fabrication methods, such as the use of prefabricated sleeves or modular formwork techniques, could serve as potential solutions in the future.

For future research, both opportunities and potential difficulties should be considered. From an experimental perspective, full-scale studies in natural soil conditions require substantial costs and complex control of parameters. From a methodological standpoint, numerical model validation requires constitutive soil formulations that can capture the influence of micro-asperities on the local stress field. From the mathematical perspective, analytical or semi-empirical approaches are needed to predict soil-asperity interaction while accounting for scale effects. These challenges not only pose difficulties but also open significant avenues for further investigation, including potential applications in foundations for light- to medium-scale infrastructure constructed in loose sandy soils.

7. Conclusions

1. The results indicate that cranial asperities with an L / H ratio of 20 enhanced the ultimate axial capacity by up to 392.51% compared to the smooth pile. In contrast, caudal asperities achieved only a 134.30% improvement. This highlights the distinct effectiveness of the cranial orientation in mobilizing interface friction more efficiently than the caudal orientation, in contrast to previous studies that evaluated surface roughness without accounting for directional orientation.

2. Controlled axial compression tests on uniform sand confirmed that the L / H ratio significantly influences load transfer efficiency. The Cr $L / H = 20$ configuration produced the most uniform load transfer distribution (0.00117 kN/mm), whereas larger L / H ratios (26.67 and 33.33) exhibited a reduction in capacity. These findings highlight the existence of an optimum condition, which had not previously been quantified, and demonstrate that asperity interlocking is most effective at an intermediate L / H ratio.

3. A comparison of ultimate capacity and shaft resistance distribution revealed that piles with larger diameters ($B = 15.85$ mm) tended to sustain higher loads, with a maximum load of 0.368 kN observed in the Cr $L / H = 20$ configuration. These results indicate that diameter variation plays a significant role in enhancing axial load capacity, particularly when combined with cranial asperity orientation. This finding complements previous studies, which generally examined the influence of diameter or surface roughness separately, without considering the simultaneous interaction between these two factors.

4. Statistical validation using ANOVA analysis demonstrated that asperity orientation had a significant effect on load-bearing capacity ($p < 0.05$). The Cr $L / H = 20$ configuration produced $F = 80.11$ with $p = 1.22 \cdot 10^{-11}$, which is far more significant than the Cl $L / H = 20$ configuration ($F = 15.07$; $p = 8.05 \cdot 10^{-4}$). These results confirm that the increase in capacity is not merely due to experimental variation but is directly governed by asperity geometry. Accordingly, the L / H parameter can be employed as a quantitative design variable, reinforcing the scientific contribution of this study compared to earlier descriptive approaches.

Conflict of interest

The authors declare no conflict of interest.

Financing

This study was conducted without financial support from any public, commercial, or non-profit funding agency.

Data availability

All data used in this study are available in the main text, in both numerical and graphical form.

Use of artificial intelligence

The authors used artificial intelligence technologies within the permissible framework to provide their own verified data, which is described in the research methodology section.

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