JICE Journal Innovation of Civil Engineering

Vol. 7, No. 1, pp. 114-127
Submit: 11-10-2025 |
Accepted: 08-05-2026 |
Publish: 11-06-2026 |

Enhancing Pile Interface Shear Resistance in Loose Sand Using Tofu Wastewater Biocementation

Dery Maharnindra, Agata Iwan Candra
Program Study of Civil Engineering, Universitas Kadiri, Kediri 64115, Indonesia

e-mail : iwan_candra@unik-kediri.ac.id

ABSTRACT
Loose sandy soils exhibit low relative Density and internal friction angle, rendering them unsuitable for stable foundation support. Meanwhile, tofu wastewater (TW), a byproduct of household-scale tofu industries in Kediri, Indonesia, contains natural urease enzymes and active organic compounds with potential as eco-friendly biocementation agents. This study aims to evaluate the effect of TW treatment on the enhancement of skin resistance (Q_s) and interface shear resistance (δ) of pile foundations in loose sand. The methodology involved TW treatment for 30 days, axial load testing, and analysis based on Meyerhof's bearing capacity theory supported by ANOVA validation. The results indicate a substantial increase in Q_s of 553%, rising from 0.0103 kN to 0.0675 kN after TW treatment. The δ/φ coefficient reached 2.98 at a depth of 0.015 m (D/B=1.5), representing a 156% improvement over untreated sand and indicating enhanced mobilization of pile–soil interface friction. ANOVA confirmed the improvement was statistically significant ($p<0.05$). A correction factor δ of 2.27–2.56 was proposed to represent TW contribution to interface strength. Utilizing tofu wastewater enhances load transfer efficiency in loose sandy soils. It offers a sustainable alternative, while the corrected δ coefficient refines classical bearing capacity models under biologically improved soil–structure interaction conditions.

Keywords: *Biocementation; Interface Shear Resistance; Loose Sandy; Skin Resistance; Soil Improvement; Tofu Wastewater (TW).*

1. Introduction

Loose sandy soils are classified as geotechnical materials with mechanical properties that are generally unfavorable for maintaining structural stability [1]. These soils typically exhibit a low relative density less than 35%, a small internal friction angle (φ) less than 28° [2], and high permeability on the order of 10^{-3} cm/s [3]. Such conditions accelerate water infiltration into soil pores [4], which, in turn, increases pore water pressure [5] and reduces shear strength and overall soil stability [6]. Consequently, structures founded on loose sand are prone to excessive settlement and potential shear failure due to the absence of natural cohesion between particles [7], [8].

Kediri City in East Java is known as a major hub for small-scale household tofu production, generating approximately 75–100 liters of tofu wastewater (TW) per production unit per day [9]. This wastewater contains elevated levels of biological oxygen demand (BOD) and chemical oxygen demand (COD), posing a significant risk to environmental quality if discharged untreated [10], [11]. However, TW also contains naturally occurring urease enzymes and active organic compounds derived from the soybean soaking process, which exhibit potential as interparticle binding agents in granular soils [12]. This dual characteristic offers a promising opportunity to utilize TW as a simple, eco-friendly biostabilization agent that simultaneously mitigates environmental pollution and enhances the mechanical performance of loose sand.

Numerous studies have demonstrated that the Enzyme-Induced Carbonate Precipitation (EICP) technique consistently enhances the mechanical properties of granular soils by inducing calcium carbonate ($CaCO_3$) precipitation, which acts as a binding agent between sand particles [13]. In one study, the unconfined compressive strength (UCS) of initially cohesionless sand increased

Vol. 7, No. 1, pp. 114-127
Submit: 11-10-2025 |
Accepted: 08-05-2026 |
Publish: 11-06-2026 |

dramatically from 0 kPa to 2300 kPa after EICP treatment, indicating the method's high effectiveness even in soils with no initial compressive strength [14]. In another case, UCS improved from 25.5 kPa to 507.7 kPa, representing an increase of approximately 1890.98%, demonstrating that naturally derived urease can produce substantial soil strengthening [15]. Even in soils with an initial UCS of 622 kPa, EICP treatment elevated the strength to 3395 kPa, confirming that the method remains effective when applied to materials with already moderate to high mechanical strength [16].

Soybean-based urease has also been shown to enhance interparticle contact quality and increase internal adhesion forces by up to 72.6%, primarily due to calcium carbonate ($CaCO_3$) precipitates forming on grain surfaces [17]. The active organic content increased by 616%, while porosity decreased from 37.15% to 30%, indicating a densification process and partial filling of intergranular voids due to mineral cementation [18]. At the macroscopic scale, laboratory testing revealed a strength improvement from 21.3 kPa to 785.1 kPa. In comparison, field tests showed an increase from 70 kPa to 956 kPa, confirming a mechanical transition of the treated soil from non-cohesive to semi-cohesive behavior [19]. The urease activity not only enhanced the bulk strength of the soil mass but also altered the soil–structure interaction characteristics, as reflected by an increase in elastic modulus (E) from 0 to 1.69 MPa [20] and the development of a stronger soil crust, with improvements reaching up to 1150% [21]. The formation of $CaCO_3$ crystals also contributed to increased shear strength and internal friction angle, with overall strength gains ranging from 1.24 to 1.88 times across various soil types [22]. However, previous studies have primarily focused on the improvement of bulk soil properties such as compressive strength and stiffness, while the quantitative effect of biologically induced interface modification on the soil–pile shear resistance coefficient (δ) remains poorly understood.

Improvements in soil mechanical properties induced by Enzyme-Induced Carbonate Precipitation (EICP) must be further evaluated in terms of foundation performance, particularly the ultimate bearing capacity of pile foundations [23]. According to Meyerhof's bearing capacity theory (1976), the ultimate bearing capacity of a pile foundation comprises two main components: point resistance (Q_p) and skin resistance (Q_s). The Q_s The component is strongly influenced by the coefficient of lateral earth pressure (K) and the interface shear resistance (δ) at the pile-soil interface[8]. The parameter δ represents the intensity of shear interaction at the soil–pile interface and plays a direct role in the efficiency of axial load transfer along the pile shaft; therefore, an increase in δ leads to a greater contribution of Qs to the bearing capacity.

In practice, δ is commonly expressed as a fraction of the soil internal friction angle (φ) and is influenced by soil type, pile material, surface roughness, and installation method. Previous studies have reported that the δ/φ ratio increases from 0.7 to 1.2 with increasing normalized roughness (Rn) from 0.01 to 0.06 in uniform sands [24], and up to 0.85 in certain fine sandy conditions [25], while typical δ/φ ranges are 0.6–0.8 for steel, 0.7–0.9 for timber, and 0.8–1.0 for concrete piles [26]. Consistent with these observations, experimental studies have demonstrated that EICP treatments significantly enhance pile shaft resistance (Q_s), particularly at shallow depths, due to $CaCO_3$ precipitation that increases interface roughness and the effective pile diameter, indicating that the improvement in bearing capacity is primarily controlled by soil–pile shear interaction mechanisms [23]. Nevertheless, despite the well-established influence of pile material and surface roughness on δ, the effect of biochemically induced interface modification, specifically the role of urease activity in EICP on the quantitative enhancement of δ remains insufficiently understood, thereby defining a clear research gap that warrants further investigation (Table 1).

Table 1. State-of-the-Art Review of Experimental Methods and Evaluated EICP Studies

References	Author	Method			Result					
		Urease (Soy-Bean)	Cementation	Incubation	UCS	Increase Qs	δ	coeff. δ	coeff. δ Correction	ANOVA Validation
[14]	Almajed et al. (2020)	✔	✔	✔	✔					
[15]	Pratama et al. (2024)	✔	✔	✔	✔					

Vol. 7, No. 1, pp. 114-127
Submit: 11-10-2025 |
Accepted: 08-05-2026 |
Publish: 11-06-2026 |

References	Author	Method			Result					
		Urease (Soy-Bean)	Cementation	Incubation	UCS	Increase Qs	δ	coeff. δ	coeff. δ Correction	ANOVA Validation
[16]	M. H. Baziar (2021)	✓	✓	✓	✓					
[10]	S. Shu (2022)	✓	✓	✓	✓					
[18]	Z. Sun et al. (2024)	✓	✓	✓	✓					
[19]	L. Miao (2024)	✓	✓		✓					
[22]	A. Chandra (2021)	✓	✓	✓	✓					
[23]	Hai Lin (2021)	✓	✓	✓		✓				
-	This Study	✓		✓		✓	✓	✓	✓	✓

This study proposes a practical, simplified approach that directly utilizes tofu wastewater (TW) as a natural urease source, without the addition of external chemical reagents. The objective of this research is to evaluate the effect of TW treatment on the enhancement of soil–pile interface shear resistance (δ) and the resulting skin resistance (Q_s) in loose sandy soils through enzyme-induced biocarbonate precipitation and particle aggregation around the pile surface. The study further examines the influence of embedment depth (*D*) and the depth diameter ratio (*D/B*) on variations in δ and Q_s. Based on the experimental results, a correction factor for δ is proposed to provide a more realistic representation of soil–pile interaction under biologically improved conditions. Unlike previous EICP studies that primarily focused on improving bulk soil strength, this study explicitly quantifies the enhancement of soil–pile interface behavior induced by TW treatment. It demonstrates its role in improving the prediction of pile skin resistance in biologically stabilized sandy soils, thereby supporting more efficient and sustainable foundation design in loose sand.

2. Materials and Methods

2.1. Soil Characteristics

The sand used in this study (Figures 1 and 2) was collected from natural alluvial deposits of the Brantas River in the Mojoroto area, Kediri City, Indonesia. This location was selected due to the prevalence of residential buildings and public infrastructure founded on sandy soils along the riverbanks, which are known to exhibit low bearing capacity and high settlement potential. Sampling was performed in a limited, non-protected sedimentation zone, using a small volume specifically intended for laboratory testing, in accordance with environmental sustainability principles and without exploitative activity. Before testing, the sand was oven-dried at 105°C for 24 hours to remove residual moisture content. All geotechnical tests, including physical and mechanical characterizations, were carried out in accordance with American Society for Testing and Materials (ASTM) standards to ensure consistent, accurate, and repeatable results under controlled laboratory conditions. The soil properties obtained from these tests are summarized in Table 2. This study was conducted at the Civil Engineering Laboratory of Kadiri University, Indonesia, in May 2025.

Figure 1. Saturated sand condition (moisture content: 28%).

Figure 2. Dried sand condition (moisture content: 0%).

JICE Journal Innovation of Civil Engineering
Vol. 7, No. 1, pp. 114-127
Submit: 11-10-2025 |
Accepted: 08-05-2026 |
Publish: 11-06-2026 |

Table 2. Summary of geotechnical properties of tested sand used in the laboratory model, and the soil type is SP (Sand, Poorly Graded).

Properties	Value
Water content (%)	28
Relative Density (%)	25
Moist unit weight (γ_{sat}) [kN/m³]	16.38
Dry unit weight (γ_d) [kN/m³]	14.22
Coefficient of curvature C_c	1.21
Uniformity coefficient C_u	2.93
Average particle size D50 [mm]	0.37
Void ratio (e)	0.83
Maximum void ratio (e_{max})	0.94
Minimum void ratio (e_{min})	0.47
Porosity (%)	45
Specific Gravity (G_s)	2.65
Friction angle φ [°]	27.02

2.2. Sample Conditioning

This study applied two treatment conditions in loose sand: untreated sand (control) and sand treated with tofu wastewater (TW) to evaluate the influence of natural biocementation on soil mechanical behavior. The TW used in this study was obtained from soybean soaking water generated during traditional tofu production in Kediri City, East Java, Indonesia. The tofu wastewater (TW) was prepared by soaking approximately 322 g of soybeans in 1 L of water for 5 hours, allowing soluble organic compounds and naturally occurring urease enzymes to diffuse into the aqueous phase. The resulting solution contained approximately 322 g/L of soybean-derived organic material, which acts as a precursor medium for carbonate precipitation during soil treatment (Figure 3). No external chemicals or microbial cultures were introduced, thereby preserving the wastewater's native biochemical composition.

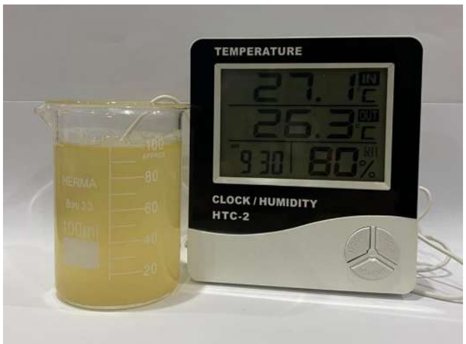

Figure 3. Tofu Wastewater (TW) obtained from soybean soaking water used in tofu production, maintained at room temperature (27° C) and relative humidity of 80%.

Before specimen preparation, the sand was oven-dried to remove residual moisture. The dried sand was then placed into rigid test boxes measuring 400 × 260 × 200 mm using the air pluviation method [27], ensuring relatively uniform grain distribution and simulating natural sediment

Vol. 7, No. 1, pp. 114-127
Submit: 11-10-2025 |
Accepted: 08-05-2026 |
Publish: 11-06-2026 |

deposition conditions. For treated specimens, TW was mixed with sand to achieve an initial moisture content of 28%, identical to that of the control specimens prepared with water. Mixing was performed manually until a homogeneous soil matrix was achieved, ensuring uniform liquid distribution throughout the sand mass. After preparation, all specimens were incubated for 30 days under laboratory conditions to allow natural biochemical reactions within the TW to occur. During this stage, organic compounds and naturally occurring urease activity promoted carbonate precipitation within the pore spaces, gradually forming bonding bridges between sand particles. This process potentially enhanced mechanical interaction between the soil matrix and the pile surface, thereby contributing to improvements in soil–pile interface shear resistance.

All specimens were incubated for 30 days at room temperature (27°C) under open-air conditions to simulate natural field conditions and facilitate urea hydrolysis, with calcium carbonate ($CaCO_3$) precipitating between sand particles. This incubation stage played a critical role in preserving the enzymatic activity of the natural urease and enabling the formation of interparticle bonds that contribute to soil structure enhancement, increased stiffness, and the potential improvement of interface shear resistance (δ) between the soil and pile surface. Chemical analysis indicated that the pH of the TW solution was 5.51, while that of the control water was 6.88, confirming that the mildly acidic condition of TW remains within the optimal range for sustaining natural enzymatic activity.

2.3. Testing Procedure

Pile installation tests were conducted to quantitatively evaluate the effect of tofu wastewater (TW) treatment on bearing capacity and soil-pile shear interaction in loose sandy soils. All tests were performed using a fully automated axial loading apparatus, equipped with a real-time data acquisition system for precise recording of load and deformation responses (Figure 4). The test media were prepared in two separate boxes: one containing untreated sand (control) and the other containing TW-treated sand. In each box, a steel model pile with a diameter of 10 mm was vertically installed to a depth of 0.1 m, with a controlled penetration rate of 0.01 mm/s. This setup yielded a length-to-diameter (*L/D*) ratio of 20 and a length-to-box-width (*L/B*) ratio of 26-40, both of which exceed the standard minimum thresholds required to eliminate boundary effects from the container walls [28].

Figure 4. Automatic axial loading apparatus with real-time data (AIC Innovation) [29].

Vol. 7, No. 1, pp. 114-127
Submit: 11-10-2025 |
Accepted: 08-05-2026 |
Publish: 11-06-2026 |

After reaching the designated embedment depth, axial loading was applied incrementally until the condition approached the ultimate limit state to determine the pile's ultimate bearing capacity (Q_u). Following the installation, the point resistance (Q_p) was calculated theoretically based on the bearing capacity theory proposed by Meyerhof, using the following approach:

$$Q_p = \sigma`. N_q . A_b \tag{1}$$

where σ′ is the effective stress, N_q is the point bearing capacity factor, and A_b is the pile point surface area. The skin resistance (Q_s) was obtained experimentally by subtracting the theoretical point resistance (Q_p) from the measured ultimate bearing capacity (Q_u), using the following Equation:

$$Q_s = Q_u - Q_p \tag{2}$$

where, determining the experimental value of skin resistance (Q_s), the interface shear resistance (δ) between the pile surface and the soil can be derived using the skin friction equation, as follows:

$$Q_s = K . \sigma'. tan\ \delta . A_s \tag{3}$$

$$\delta = tan^{-1}\left(\frac{Q_s}{K .\ \sigma'. A_s}\right) \tag{4}$$

where K is the coefficient of lateral earth pressure, with K = 1 as suggested by Meyerhof (1951), and A_s is the shaft surface area in contact with the surrounding soil [8].

This study aims to evaluate the effect of tofu wastewater (TW) treatment on the enhancement of interface shear resistance (δ) and skin resistance (Q_s) of pile foundations embedded in loose sand. The evaluation was conducted by analyzing the relationship between depth (*D*) and the *D/B* ratio in relation to changes in δ and Q_s to identify the underlying shear-interaction mechanisms induced by the natural biocementation process. Furthermore, the study introduces a correction factor for δ within Meyerhof's (1976) bearing capacity formulation, accounting for the specific influence of TW treatment on improving load-transfer efficiency along the pile shaft.

2.4. Statistical Validation

To ensure the statistical reliability of the experimental results, a one-way analysis of variance (ANOVA single factor) was conducted to compare the effects of tofu wastewater (TW) treatment against the control condition on two key parameters: skin resistance (Q_s) and interface shear resistance (δ). The test was performed at a 95% confidence level ($\alpha = 0.05$) to determine whether the observed increases in soil–pile interaction were statistically significant [30]. The results confirmed that the improvements in Q_s and δ were not attributed to random variation, but rather to the direct effects of natural biocementation processes triggered by urease enzyme activity and active organic compounds present in TW.

3. Results and Discussions

3.1. Significant and Early Improvement of Skin Resistance (Q_s)

The skin resistance (Q_s) results presented in Figure 5, calculated using Equations (1) and (2), indicate a substantial improvement following treatment with soybean-derived urease. Under initial soil conditions (Initial Soil), the maximum Q_s value reached only 0.0103 kN at a *D/B* ratio of 10. In contrast, for the treated soil (Soil-TW), Q_s increased significantly to 0.0675 kN at the same depth, representing an enhancement of over 553%. Remarkably, even at a very shallow *D/B* ratio of 0.5 (equivalent to a depth of 0.005 m), Soil-TW already recorded a Q_s value of 0.0075 kN, which exceeds the maximum value observed in the initial soil. These findings suggest that biomineralization processes associated with $CaCO_3$ precipitation were active even at shallow depths, contributing to the early development of stronger particle contacts within the soil matrix [19].

Vol. 7, No. 1, pp. 114-127
Submit: 11-10-2025 |
Accepted: 08-05-2026 |
Publish: 11-06-2026 |

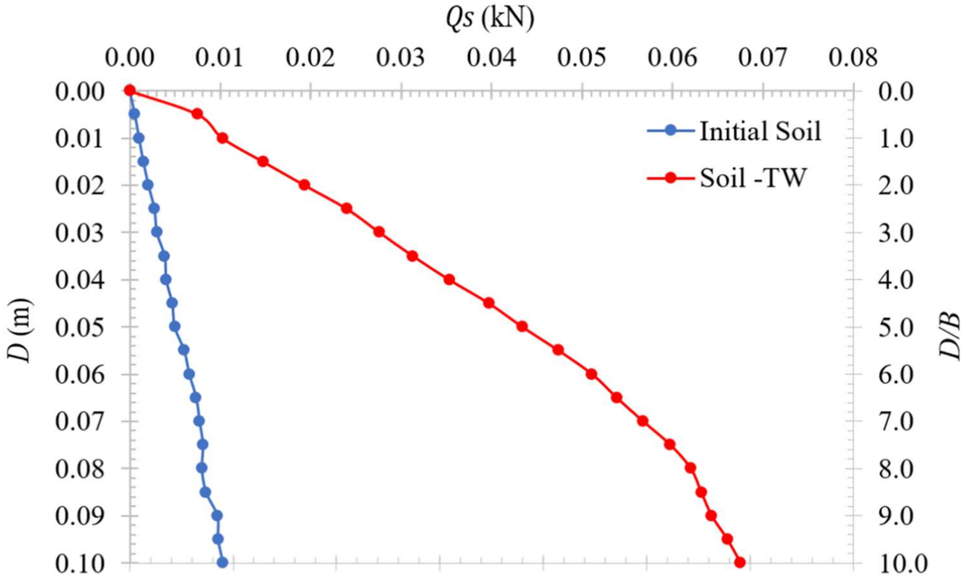

Figure 5. Skin resistance (Q_S) distribution with respect to depth and *D/B* (depth and diameter ratio) in initial and treated soil (Soil–TW)

The consistent and gradual distribution of skin friction suggests a mechanical transformation of the treated soil, from a non-cohesive material to a semi-cohesive matrix which significantly enhances soil–structure interaction [20]. This aligns with previous studies that reported up to 72.6% improvement in interparticle adhesion due to $CaCO_3$ deposition induced by soybean-based urease [17]. However, in the present study, the reinforcement effect was not only more pronounced but also observed at shallower depths, suggesting that the proposed treatment has strong potential as an environmentally sustainable ground improvement technique for foundations in granular soils.

3.2. Interface Shear Resistance (δ) Enhancement Using Tofu Wastewater

The results of the interface shear resistance (δ) test, presented in Figure 6 and calculated using Equation (4), demonstrate a significant increase following treatment with soybean-derived urease. Under initial soil conditions (Initial Soil), δ ranged from 31° to 34°, indicating relatively low internal friction at the soil–structure interface.

After treatment (Soil–TW), δ increased sharply, reaching 83.79° at a depth of 0.005 m (*D/B* = 0.5), and remained consistently high up to a depth of 0.1 m (*D/B* = 10). This stable vertical distribution of elevated δ values indicates the formation of a stiffer, more cohesive contact interface that extends uniformly throughout the soil column, even at shallow depths.

These findings are consistent with previous studies reporting enhanced shear strength in sandy soils treated with soybean-based urease, including up to a 72.6% increase in interface shear resistance due to improved microscale bonding within the contact zone [17]. In addition, previous studies have reported that higher concentrations of active organic compounds can lead to higher internal friction angles and reduced effective soil porosity. [18]. Accordingly, the observed improvement in δ for the TW-treated soil (Soil–TW) reinforces the conclusion that tofu wastewater (TW) effectively strengthens soil–structure interaction by modifying the physical properties of the soil surrounding the pile, resulting in a stronger, more stable shear response compared to untreated soil.

Vol. 7, No. 1, pp. 114-127
Submit: 11-10-2025 |
Accepted: 08-05-2026 |
Publish: 11-06-2026 |
JICE Journal Innovation of Civil Engineering

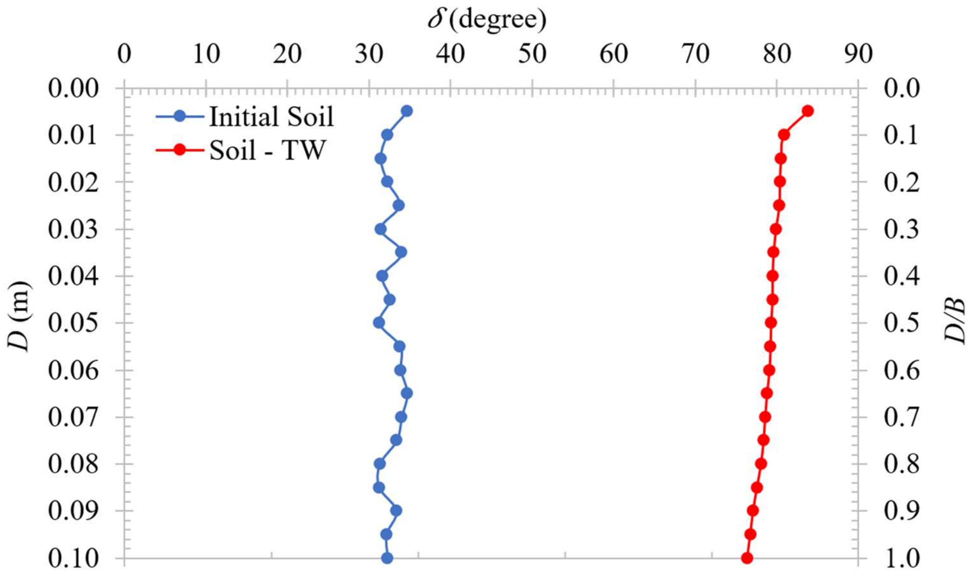

Figure 6. Distribution of interface shear resistance (δ) with depth and *D/B* (depth and diameter ratio) in initial and treated soil (Soil–TW).

3.3. Distribution of Interface Shear Resistance Coefficient (δ/φ)

Figure 7 illustrates the relationship between the interface shear resistance coefficient (*Coef.* $\delta = \delta/\varphi$), depth (*D*), and the *D/B* ratio for both the untreated soil (Initial Soil) and TW-treated soil (Soil–TW). The trend observed in the coefficient closely mirrors that of the interface shear resistance (δ) presented in Figure 6, as the coefficient is derived by comparing δ to the constant internal friction angle (φ) of the tested soil, which remained fixed at 27°. Therefore, any variation in Coef. δ reflects only the improvement in δ as a result of TW treatment. The distribution of Coef. δ with depth demonstrates a substantial increase due to the soil improvement induced by tofu wastewater. In the Initial Soil condition, Coef. δ ranged only from 1.16 to 1.28, whereas after TW treatment, the values increased sharply to 2.83–3.10. This significant rise was observed even at a shallow *D/B* ratio of 1.5, representing a 156% improvement compared with untreated sand and indicating enhanced mobilization of pile–soil interface friction

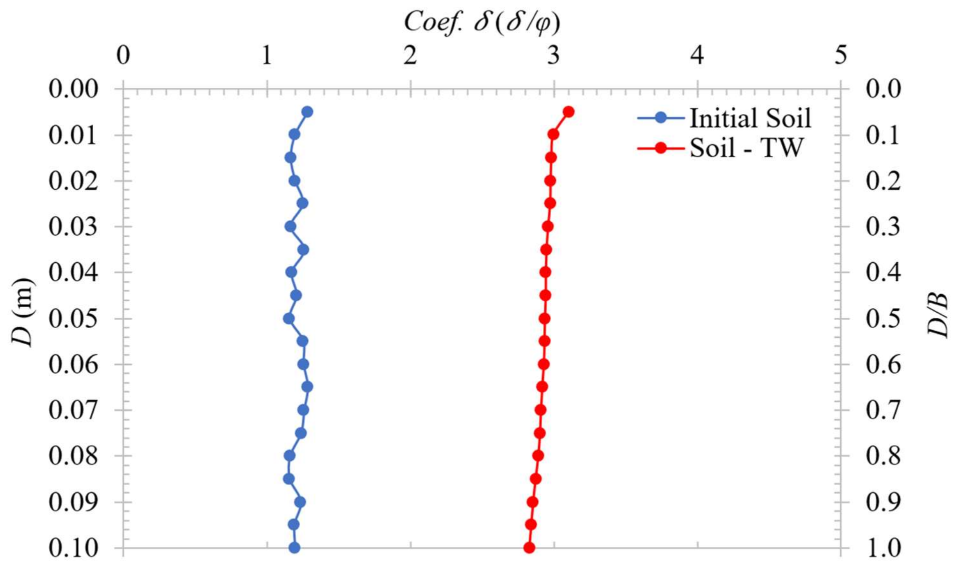

Figure 7. Distribution of interface shear resistance coefficient (δ/φ) with depth and *D/B* (depth and diameter ratio) in initial and treated soil (Soil–TW).

JICE Journal Innovation of Civil Engineering
Vol. 7, No. 1, pp. 114-127
Submit: 11-10-2025 |
Accepted: 08-05-2026 |
Publish: 11-06-2026 |

This improvement is consistent with previous studies reporting a reduction in soil porosity due to $CaCO_3$ infill within interparticle voids, which increases interface shear resistance [18]. Additionally, other studies have shown that the formation of a mineral-induced soil crust significantly enhances soil surface strength, reinforcing the soil–structure contact zone [21]. These results further support the notion that urease-based treatment can transform soil mechanical behavior from non-cohesive to semi-cohesive, producing a stiffer, more shear-resistant interface capable of efficient load transfer [19]. The observed increase in Coef. δ for the TW-treated soil confirms the success of this method in consistently and sustainably improving the mechanical characteristics of the contact zone, even at very shallow depths.

3.4. Statistical Evaluation on Skin Resistance (Q_S) and Interface Shear Resistance Coefficient

The difference in interface shear resistance coefficient (*Δ Coef. δ*) shown in Figure 8 reveals that treatment with tofu wastewater (TW) produced a consistent and significant improvement across all depths. The values of *Δ Coef. δ* ranged from 1.62 to 1.82, corresponding to a relative increase of 127% to 156%. The highest *Δ Coef. δ* was recorded at a depth of 0.015 m, indicating that the earliest and most pronounced strengthening effect occurred in the shallow zone.

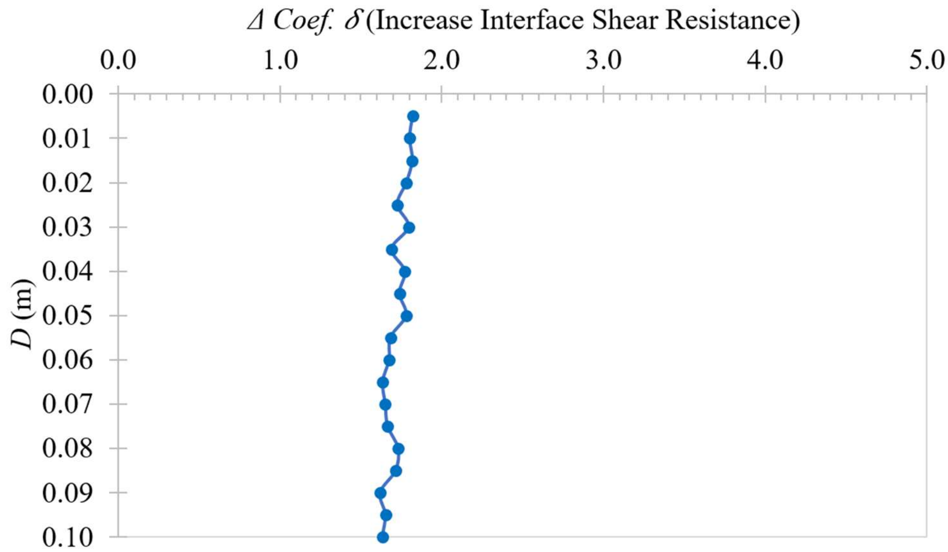

Figure 8. Distribution of interface shear resistance coefficient increase (*Δ coef. δ*) with depth due to soybean wastewater treatment.

The results of the one-way ANOVA test presented in Table 3 indicate that the TW-treated soil had a highly significant effect on the mechanical parameters of the soil, specifically on skin friction (Q_S) and the interface shear resistance coefficient (δ/φ). The F-value for Q_S, recorded at 54.55, far exceeds the critical F-value of 4.08, confirming that the observed increase in Q_S is statistically significant and not due to random variation. This outcome confirms that the TW treatment produced a statistically significant reinforcement effect on the soil–pile interface.

Table 3. One-Way ANOVA results for skin resistance (Q_S) and interface shear resistance coefficient (δ/φ).

Parameters	F	P-value	F crit
Skin Resistance (Q_S)	54.55	5.47×10^{-9}	4.08
Coefficient δ (δ/φ)	10295.65	7.16×10^{-48}	4.10

The exceptionally high F-value for the interface shear resistance coefficient (δ/φ), 10295.65, indicates that the treatment exerted a highly dominant and consistent effect on the soil–structure interface strength. The substantial increase in δ/φ serves as a critical indicator of improved load-

Vol. 7, No. 1, pp. 114-127
Submit: 11-10-2025 |
Accepted: 08-05-2026 |
Publish: 11-06-2026 |

transfer efficiency across the interface, particularly relevant for shallow foundations, geosynthetic reinforcement systems, and other soil-structure interaction elements. These findings support those reporting that mineral precipitation during the EICP process significantly alters the mechanical behavior of granular soils, transforming them from non-cohesive to more cohesive and shear-resistant materials [19]. With p-values well below 0.05 for both parameters, the statistical validation confirms that EICP utilizing tofu wastewater is not only technically efficient but also statistically effective in enhancing the mechanical performance of treated soils.

Additional evidence of structural modification is reflected in the evolution of soil unit weight during the incubation period. Both untreated and TW-treated soils exhibited a gradual decrease in unit weight with increasing incubation time. Initially, both samples showed identical values of 18.06 kN/m^3, which decreased to 16.13 kN/m^3 in the untreated soil and 16.37 kN/m^3 in the TW-treated soil after 33 days of incubation. Overall, the untreated soil experienced a 10.7% reduction, while the TW-treated soil showed a slightly smaller decrease of 9.4%. This trend suggests that incubation influenced particle arrangement and void distribution within the soil matrix. In untreated soil, the larger reduction may reflect particle rearrangement and moisture redistribution during incubation. In contrast, the relatively smaller decrease observed in TW-treated soil may indicate partial stabilization of the soil structure, which is consistent with structural modification mechanisms reported in previous biocementation studies.

Changes in the mechanical interaction between sand particles and the pile surface may explain the significant increase in interface shear resistance observed in the TW-treated soil. In untreated loose sand, shear resistance is primarily governed by frictional contact between particles and the structural surface. However, the presence of urease enzymes, organic compounds, and naturally occurring microorganisms in tofu wastewater may promote biomineralization processes during the incubation period. Microbial metabolism and enzymatic activity can facilitate the formation of carbonate species within the pore fluid. In the presence of available calcium ions, these carbonate species may precipitate as calcium carbonate ($CaCO_3$), forming mineral bridges between sand particles and at the soil–pile interface. This mineral precipitation can modify the contact mechanics, allowing the interface to transition from purely frictional behavior to a partially bonded system. Consequently, both frictional resistance and interparticle bonding contribute to load transfer, thereby increasing the mobilized interface shear resistance.

3.5. Corrected Interface Shear Resistance Coefficient (C^**Coef.* δ) in Treated Soil (Soil–TW)

The corrected values of the interface shear resistance coefficient (C^**Coef.* δ) presented in Figure 9 demonstrate that the improvement in δ resulting from tofu wastewater (TW) treatment remains significant, even after the baseline contribution from the untreated soil has been excluded. The corrected coefficient values ranged from 2.27 to 2.56, indicating that TW treatment directly enhances interface strength. This range remained relatively stable across the entire depth profile, suggesting that the influence of TW was not confined to surface layers but extended uniformly to the maximum test depth of 0.10 m.

Vol. 7, No. 1, pp. 114-127
Submit: 11-10-2025 |
Accepted: 08-05-2026 |
Publish: 11-06-2026 |

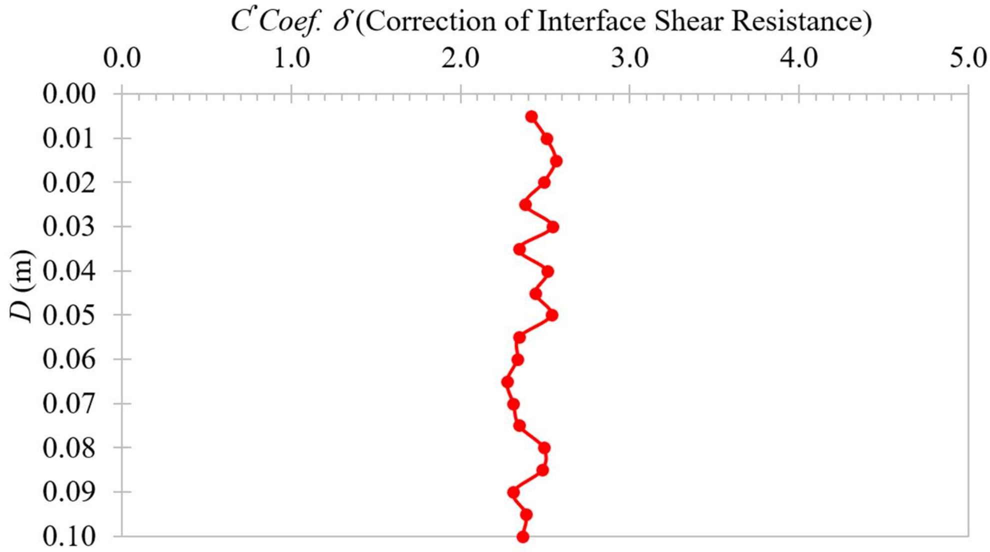

Figure 9. Correction value of the interface shear resistance coefficient (*C̈ Coef. δ*) with depth due to soybean wastewater treatment.

This stable improvement pattern indicates that TW treatment not only enhances shear interaction in the upper soil layers but also increases shear load transfer efficiency along the surfaces of structural elements, such as piles or foundation plates. This results in a mechanical response that is more cohesive and consolidated, in contrast to the original behavior of non-cohesive granular soils. These findings align with those demonstrating that soybean-derived urease treatment effectively reinforces the soil–structure interface by forming $CaCO_3$-based microcrystalline bonds.

Moreover, this discussion reinforces the assertion made in the introduction that the interface shear resistance (δ) is highly dependent on the soil type and the surface characteristics of the structural element. Therefore, the corrected coefficient values are essential for redefining the empirical formulation of δ under biologically stabilized soil conditions. This correction model can be expressed as:

$$\delta_{TW} = \ddot{C}\, tan^{-1}\left(\frac{Q_s}{K\ .\ \sigma'.A_s}\right) \tag{5}$$

where $\ddot{C}$ represents the empirical correction factor for the interface shear resistance (δ), derived from experimental results on soil treated with tofu wastewater (TW). This formulation serves as a critical foundation for designing pile and shallow foundations under in-situ conditions, as it accounts for changes in physical and mechanical properties induced by natural biotreatment. Accordingly, it enables the calculation of a corrected interface shear resistance (δ_{TW}) that is more representative of the behavior of biostabilized granular soils treated with TW.

3.6. Integrative Technical and Environmental Contribution

This research offers a dual benefit by addressing both engineering and environmental concerns in ground improvement. The reuse of Tofu Wastewater (TW), a locally abundant, protein-rich byproduct, demonstrates its viability as a natural source of urease to enhance sand performance with enzyme-induced carbonate precipitation (EICP). The treatment significantly increases the soil-pile interface resistance and promotes semi-cohesive behavior in poorly graded sands. From an engineering perspective, the method offers a scalable solution to improve shallow foundation performance without relying on synthetic chemical stabilizers. The environmental implication is equally significant, as the approach directly reduces the discharge of organic wastewater into ecosystems, offering a closed-loop solution that aligns with sustainable engineering practices. On a theoretical level, the findings support the refinement of interface behavior models under

Vol. 7, No. 1, pp. 114-127
Submit: 11-10-2025 |
Accepted: 08-05-2026 |
Publish: 11-06-2026 |

biochemically modified conditions, and the introduction of a correction factor for the interface shear resistance (δ) provides a basis for adapting classical bearing capacity theories to biocemented soil conditions.

3.7. Research Limitations

Despite the favorable outcomes, the study's scope remains confined to controlled laboratory conditions and uniform sandy soils. As such, the mechanical response observed may differ under field conditions where heterogeneous soil profiles, groundwater dynamics, and natural microbial interactions come into play. Although the adopted δ correction model shows high sensitivity to the biocementation effect, it has not yet been calibrated for other soil types or rougher pile interfaces. Furthermore, long-term aspects such as carbonation stability, post-curing strength evolution, and durability under cyclic loading were not investigated in this phase. These limitations suggest that further validation is necessary before the method can be widely applied in practical geotechnical design.

3.8. Recommendations for Future Work

Future studies are encouraged to adopt a multi-scale framework that combines microscopic characterization and macroscopic performance testing. At the microscale, detailed investigations using SEM imaging, XRD analysis, and elemental mapping should be conducted to examine the morphology and spatial distribution of $CaCO_3$ precipitates within the soil matrix. These findings should be correlated with macroscale parameters, such as interface shear resistance, load transfer efficiency, and foundation settlement characteristics, across various loading scenarios. Field-scale testing in different geotechnical environments, particularly with varying relative densities, saturation degrees, and pile surface textures, will also be essential to validate the robustness of the proposed correction model for δ. Ultimately, integrating biochemical, mechanical, and environmental factors into a predictive design framework would expand the utility of TW as a bio-based stabilizing agent for foundation engineering in tropical and subtropical regions.

4. Conclusions

The experimental findings confirmed that applying tofu wastewater (TW) as a natural urease source substantially improved both interface shear resistance (δ) and skin friction capacity (Q_s) in pile foundations installed in loose sand. The biocementation process produced calcium carbonate ($CaCO_3$) precipitates between particles, transforming the soil from non-cohesive to semi-cohesive. The Q_s value increased by more than 553%, and the δ/φ ratio rose by up to 156%, even at shallow depths, confirming the treatment's effectiveness in the upper soil zone. Additionally, the proposed corrected coefficient ($C^{*}Coef.\ \delta$) ranging from 2.27 to 2.56, quantifies the direct impact of TW on interface strength, independent of the initial soil condition. This correction provides a practical modification to classical bearing capacity models to reflect biologically improved soils. Statistical analysis using ANOVA confirmed that all observed mechanical enhancements were statistically significant ($p < 0.05$), verifying that the improvements resulted from biochemical reactions rather than random variation.

Given its technical efficiency and environmental benefit, TW treatment is recommended as a low-cost, sustainable solution for stabilizing granular soils, especially in shallow foundations across tropical regions with high tofu production. This method reduces organic waste while improving soil-structure interaction. Further research should validate the $C^{*}Coef.\ \delta$ under varying soil types and foundation materials. Long-term behavior, especially under cyclic loading, must also be assessed. Full-scale field tests and microstructural analyses, such as SEM and XRD, are essential to better understand $CaCO_3$ bonding mechanisms and their effects on load transfer across the soil–structure interface.

Acknowledgements

The authors gratefully acknowledge the Civil Engineering Laboratory at Universitas Kadiri for providing essential facilities throughout the experimental program. Special thanks are extended to

Vol. 7, No. 1, pp. 114-127
Submit: 11-10-2025 |
Accepted: 08-05-2026 |
Publish: 11-06-2026 |

AIC Innovation, whose generous support in supplying the testing equipment was critical to the successful completion of this research. The authors also wish to express their sincere appreciation to the supervising lecturers for their guidance and constructive feedback during the study. Appreciation is also extended to the reviewers and editors for their valuable insights and contributions.

References

[1] A. Faresghoshooni, S. M. R. Imam, and A. Mahmoodi, "Model Testing on the Effects of Section Geometry and Stiffness on the Cyclic Lateral Behavior of Piles in Loose Sand," *International Journal of Civil Engineering*, vol. 19, no. 5, pp. 563–581, May 2021, doi: 10.1007/s40999-020-00548-x.

[2] Y. Yao, B. Hong, F. Xu, Z. Shao, and S. Huang, "Application and Evaluation of Cone Penetration Testing for Determining Internal Friction Angle in Composite Subgrade Cushion Layer," *Indian Geotechnical Journal*, 2024, doi: 10.1007/s40098-024-01098-y.

[3] S. Hamamoto, Y. Ohko, Y. Ohtake, P. Moldrup, and T. Nishimura, "Water- and air-filled pore networks and transport parameters under drying and wetting processes," *Vadose Zone Journal*, vol. 21, no. 4, Jul. 2022, doi: 10.1002/vzj2.20205.

[4] Z. Yao, Z. Chen, X. Fang, W. Wang, W. Li, and L. Su, "Elastoplastic damage seepage–consolidation coupled model of unsaturated undisturbed loess and its application," *Acta Geotech.*, vol. 15, no. 6, pp. 1637–1653, Jun. 2020, doi: 10.1007/s11440-019-00873-z.

[5] S. G. Goh, H. Rahardjo, and E. C. Leong, "Modification of triaxial apparatus for permeability measurement of unsaturated soils," *Soils and Foundations*, vol. 55, no. 1, pp. 63–73, Feb. 2015, doi: 10.1016/j.sandf.2014.12.005.

[6] K. Tian, A. Yang, K. Nie, H. Zhang, J. Xu, and X. Wang, "Experimental study of steady seepage in unsaturated loess soil," *Acta Geotech.*, vol. 15, no. 9, pp. 2681–2689, Sep. 2020, doi: 10.1007/s11440-020-00948-2.

[7] A. B. Vesic, "Bearing Capacity of Deep Foundations in Sand," 1963.

[8] G. G. Meyerhof, "Bearing Capacity and Settlement of Pile Foundations," *Journal of the Geotechnical Engineering Division*, vol. 3, no. 102, pp. 197–228, Mar. 1976.

[9] D. A. D. Maharani and A. Slamet, "Perencanaan Penyaluran Air Limbah dan Instalasi Pengolahan Air Limbah Sentra Industri Tahu di Kampung Tahu Tinalan, Kota Kediri," *JURNAL TEKNIK ITS*, vol. 13, 2024.

[10] S. Shu, B. Yan, B. Ge, S. Li, and H. Meng, "Factors Affecting Soybean Crude Urease Extraction and Biocementation via Enzyme-Induced Carbonate Precipitation (EICP) for Soil Improvement," *Energies (Basel)*., vol. 15, no. 15, Aug. 2022, doi: 10.3390/en15155566.

[11] S. Li *et al.*, "Evaluation of dust fixation effect of urease-based biological dust suppressant and its field application," *J. Environ. Manage.*, vol. 371, Dec. 2024, doi: 10.1016/j.jenvman.2024.123119.

[12] Y. Qi, Y. Gao, J. He, Y. Zhou, and B. Yan, "Effects of soluble soybean polysaccharides on solidifying aeolian sand by soybean urease-induced carbonate precipitation," *Yantu Gongcheng Xuebao/Chinese Journal of Geotechnical Engineering*, vol. 46, no. 4, pp. 823–832, 2024, doi: 10.11779/CJGE20221554.

[13] I. Ahenkorah, M. M. Rahman, M. R. Karim, and S. Beecham, "Characteristics of MICP and EICP-Treated sands in simple shear conditions: A benchmarking with the critical state of untreated sand," *Geotechnique*, 2023, doi: 10.1680/jgeot.22.00329.

[14] A. Almajed, H. Abbas, M. Arab, A. Alsabhan, W. Hamid, and Y. Al-Salloum, "Enzyme-Induced Carbonate Precipitation (EICP)-Based methods for ecofriendly stabilization of different types of natural sands," *J. Clean. Prod.*, vol. 274, Nov. 2020, doi: 10.1016/j.jclepro.2020.122627.

[15] G. B. S. Pratama *et al.*, "Efficacy of soybean-derived crude extract in enzyme-induced carbonate precipitation as soil-improvement technique," *International Journal of Geo-Engineering*, vol. 15, no. 1, Dec. 2024, doi: 10.1186/s40703-024-00204-6.

Vol. 7, No. 1, pp. 114-127
Submit: 11-10-2025 |
Accepted: 08-05-2026 |
Publish: 11-06-2026 |

[16] M. H. Baziar, M. Sanaie, and O. E. Amirabadi, "Mitigation of Dust Emissions of Silty Sand Induced by Wind Erosion Using Natural Soybean Biomaterial," *International Journal of Civil Engineering*, vol. 19, no. 5, pp. 595–606, May 2021, doi: 10.1007/s40999-020-00587-4.
[17] J. Xu, X. Li, Y. Liu, Z. Li, and S. Wang, "Evaluation of wind erosion resistance of EICP solidified desert sand based on response surface methodology," *Constr. Build. Mater.*, vol. 447, Oct. 2024, doi: 10.1016/j.conbuildmat.2024.138119.
[18] Z. Sun *et al.*, "Study on the Permeability and Mechanical Properties of Sandy Soil Under Carbon Fiber-Based Urease Mineralization," *Sustainable Structures*, vol. 4, no. 1, 2024, doi: 10.54113/j.sust.2024.000040.
[19] L. Miao, H. Wang, X. Sun, L. Wu, and G. Fan, "Effect analysis of biomineralization for solidifying desert sands," *Biogeotechnics*, vol. 2, no. 1, Mar. 2024, doi: 10.1016/j.bgtech.2023.100065.
[20] A. Pirghazani, H. Katebi, H. Samadi Kafil, and A. Fahmi, "Sand Improvement by Surface Percolation Method Using Urease-Containing Substance Extracted from Soybean Seed," *Appl. Environ. Soil Sci.*, vol. 2024, 2024, doi: 10.1155/2024/4134212.
[21] K. Roksana, S. A. Hewage, M. M. Lomboy, C. Tang, W. Xue, and C. Zhu, "Desiccation cracking remediation through enzyme induced calcite precipitation in fine-grained soils under wetting drying cycles," *Biogeotechnics*, vol. 1, no. 4, Dec. 2023, doi: 10.1016/j.bgtech.2023.100049.
[22] A. Chandra and K. Ravi, "Application of Enzyme-Induced Carbonate Precipitation (EICP) to Improve the Shear Strength of Different Type of Soils," in *Lecture Notes in Civil Engineering*, Springer Science and Business Media Deutschland GmbH, 2021, pp. 617–632. doi: 10.1007/978-981-15-6237-2_52.
[23] H. Lin, S. T. O'Donnell, M. T. Suleiman, E. Kavazanjian, and D. G. Brown, "Effects of Enzyme and Microbially Induced Carbonate Precipitation Treatments on the Response of Axially Loaded Pervious Concrete Piles," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 147, no. 8, Aug. 2021, doi: 10.1061/(asce)gt.1943-5606.0002565.
[24] F. Han, E. Ganju, R. Salgado, and M. Prezzi, "Effects of Interface Roughness, Particle Geometry, and Gradation on the Sand-Steel Interface Friction Angle," 2018, doi: 10.1061/(ASCE)GT.1943.
[25] B. M. Lehane, R. J. Jardine, A. J. Bond, and R. Frank, "Mechanisms of shaft friction in sand from instrumented pile tests," *Journal of Geotechnical Engineering*, vol. 119, no. 1, pp. 19–35, 1993, doi: 10.1061/(ASCE)0733-9410(1993)119:1(19).
[26] G. G. Meyerhof, "Some Recent Research on the Bearing Capacity of Foundations," *Canadian Geotechnical Journal*, vol. 1, no. 1, pp. 16–26, Sep. 1963, doi: 10.1139/t63-003.
[27] K. B. O'Hara and A. Martinez, "Load Transfer Directionality of Snakeskin-Inspired Piles during Installation and Pullout in Sands," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 148, no. 12, 2022, doi: 10.1061/(ASCE)GT.1943-5606.0002929.
[28] P. Zhou, F. Dai, B. He, Y. Liu, S. Yang, and M. Wei, "Experimental investigation on the axial static and cyclic response of a single pile in medium-dense sands," *Applied Ocean Research*, vol. 156, Mar. 2025, doi: 10.1016/j.apor.2025.104493.
[29] A. I. Candra, A. Munawir, Y. Zaika, and E. A. Suryo, "Analytical modelling of skin resistance in sandy soils incorporating cranial asperity effects on pile surfaces," *International Journal of Geotechnical Engineering*, vol. 20, no. 1, pp. 16–30, Jan. 2026, doi: 10.1080/19386362.2025.2596749.
[30] I. Khan and R. Umar, "Improving evaluation of groundwater heavy metal(loid)s pollution efficiencies: Insights from novel Shannon entropy-weight and one-way ANOVA analysis," *Groundw. Sustain. Dev.*, vol. 24, Feb. 2024, doi: 10.1016/j.gsd.2023.101052.