Enhancing Pile Group Pullout Resistance Using Cutback Asphalt under Inclined Loading Conditions

Wisam Adil Aljuboori
Department of Civil Engineering, College of Engineering, University of Baghdad, Iraq
w.shakir1001@coeng.uobaghdad.edu.iq (corresponding author)

Aamal A. H. Al-Saidi
Department of Civil Engineering, College of Engineering, University of Baghdad, Iraq
dr.aamal.al-saidi@coeng.uobaghdad.edu.iq

Received: 29 April 2025 | Revised: 1 June 2025 | Accepted: 14 June 2025

 DOI: https://doi.org/10.48084/etasr.11802

ABSTRACT

The stability and performance of pile foundations under inclined pullout loads are critical factors in geotechnical engineering, particularly in sandy soils with weak shear strength. This study examines the load-displacement behavior of double and triple long pile groups subjected to inclined pullout forces at 0°, 30°, 45°, 60°, and 90° before and after soil improvement with cutback MC-30 asphalt. The experiment included preparing natural and asphalt-treated sandy soil samples and conducting pullout tests to evaluate the load resistance and displacement characteristics. Additionally, numerical simulations were conducted to validate and support the experimental findings. The soil behavior is assumed to be based on an elastic-perfectly plastic constitutive relation using the non-associated Mohr–Coulomb criterion, which is commonly used to analyze the pile behavior. The results revealed significant improvements in the pullout capacity and displacement reduction after asphalt treatment. For double piles under vertical load-displacement behavior, the maximum increase in the pullout load was 406.8% at 30°, with a 51.85% reduction in displacement. Under horizontal loading conditions, the maximum load improvement was 469% at 30°, with a 59.96% reduction in displacement. For triple piles, the vertical load-displacement behavior showed a maximum load increase of 288% at 0°, with a 10% reduction in displacement. Meanwhile, under horizontal load-displacement conditions, the highest improvement was observed at 30°, with a 453.52% increase in load and a 32.8% reduction in displacement.

Keywords-piles; soil improvement; inclined load; pullout; analysis approach

I. INTRODUCTION

Pile foundations are used for buildings on loose soils, such as bridges and marine structures, where the surface is too weak to support the imposed loads [1, 2]. Pile foundations are designed as groups of square or rectangular columns made from wood, concrete, and steel. Each material offers distinct advantages based on specific project requirements [1, 3]. Piles can be categorized by their fundamental design purpose: end-bearing, friction, or a combination of the two. Alternatively, they can be classified by their construction technique, including displacement (driven) or replacement (bored) methods [4]. Pile groups connected by a cap are important for transferring structural loads to the earth, especially in challenging environments, such as offshore platforms [5, 6]. These groups offer a high load-bearing capacity, minimal settlement, and enhanced stability, making them ideal for water-based constructions [6, 7]. However, determining the load-bearing capacity is difficult due to overlapping soil strains when piles are closely spaced, which reduces the overall efficiency [8-10]. A thorough study must consider all forces (uplift, lateral, compressive, etc.), using advanced analytical techniques and numerical modeling to ensure the safety and reliability of the pile foundations [11]. The ability of piles to resist the lateral forces depends on the soil conditions and pile type. These tests evaluate how well piles resist the withdrawal forces applied in different directions, helping engineers design more efficient foundations [12]. This study uses a small-scale physical model to examine the pullout capacity of grouped piles under vertical and inclined static loads. The experimental setup comprises a steel soil tank, a robust steel loading frame, and an electrical hydraulic jack capable of applying loads at varying angles (0°, 30°, 45°, 60°, and 90°). The displacement measurements are precisely recorded using two Linear Variable Differential Transformers (LVDTs). Sandy soils present challenges for pile foundations due to their relatively low shear strength and limited cohesion [13]. Several soil improvement techniques, such as compaction, grouting, and the use of stabilizing agents, are used to enhance the performance of the piles in sandy soils [14-17]. This research aims to evaluate the pullout resistance of pile groups embedded in improved sandy soils and asphalt-improved soils under vertical and inclined static load conditions. Authors in [18] examined the pullout capacity of suction piles under unicentric inclined loads and showed that the capacity increases as the morning position moves down the suction pile, especially when the morning pile position is greater than 50% of the pile length. Authors in [19] showed the numerical response of battered piles subjected to inclined loads using the FLAC3D code. The load inclination reduces the pile's pullout capability, especially at low load inclination values with respect to the pile's axis. When the load inclination surpasses 10° with respect to the pile's axis, the impact of the contact state at the soil–pile interface can be disregarded.

II. MATERIALS AND METHODOLOGY

A. Materials Used

In this study, a variety of materials were used in the experimental process, including sandy soil, cutback asphalt, steel piles, and asphalt grouting material. A detailed description of each material, its source, and its properties is provided below:

1) Sandy Soil

- The sandy soil sample was collected from Karbala, Iraq, for laboratory analysis.
- According to the Unified Soil Classification System (USCS), the material in question is categorized as Poorly Graded Sand (PS). The grain size distribution was subsequently analyzed in accordance with the provisions set forth in ASTM D2487-2011, as shown in Figure 1.

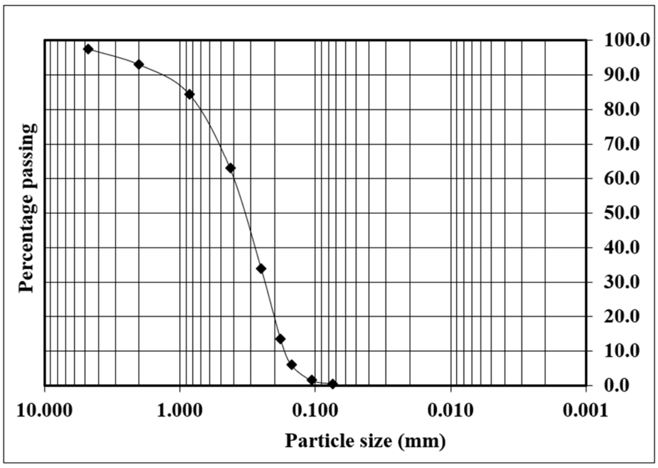

Fig. 1. Grain size distribution.

2) Cutback Asphalt (MC30)

MC30 cutback asphalt was purchased from the local market for improving the sandy soil properties, as depicted in Table I.

3) Steel Piles

- The steel piles were produced in a local facility, according to specifications that were determined through analytical laboratory testing.
- The structure is composed of hollow steel pipes. The diameter of the object is 22 mm and the length of the object is 400 mm. The pile cap was composed of 3-mm-thick steel plates. The piles were arranged in a triangular pattern, with spacing equivalent to 90 mm (more than three times the pile diameter).

TABLE I. CUTBACK PROPERTIES

Chemical properties	Results
Viscosity centistokes at 50 °C	45
Lower limit of flash point °C	38
Water %	0.2
Distilled volume from total distilled to 225 °C Upper limit	25
Distilled volume from total distilled to 260 °C Upper limit	60
Distilled volume from total distilled to 315 °C Upper limit	80
Remaining distillation at 360 °C%	50
Permeability at 25 °C	180
Drawability at 25 ° C/cm	100
Solubility%	99

B. Experimental Procedure

A small-scale physical model was used to simulate the behavior of a pile group under pullout loads in improved sandy soil. The model was designed to replicate real pile behavior in soil, using geometric scaling principles to ensure proper proportions. The steel piles were placed within a steel testing tank, which had dimensions of 0.7 m × 0.7 m × 0.8 m, providing a suitable testing environment. The sandy soil was subjected to a 48-h air-drying process to reduce the potential impact of residual moisture on the test outcomes. The soil was then divided into six equal layers, with each layer measuring 10 cm in thickness, and was placed into the designated test tank through the usage of the raining system to ensure a uniform density distribution. The cutback asphalt was subjected to rigorous testing to ascertain its optimal mix ratio. Preliminary tests indicated that a 2.25% asphalt content provided the highest shear resistance, thus making it the selected percentage for the experiment. The asphalt was injected into the soil using a custom-designed injection system that was built in the laboratory. Subsequent to the injection, the soil was permitted to rest for 24 h to allow the asphalt to stabilize and interact with the soil particles prior to testing. The steel piles were installed in accordance with a predetermined geometric arrangement, and a spirit level was used to verify that all piles were perfectly vertical. A hydraulic jack was mounted above the piles to apply a gradual pullout force. A load cell was connected between the jack and the piles to measure the applied force and convert it into digital data. LVDTs were used to assess the pile displacement during the pullout test. These sensors were mounted on top of the piles and connected to a data logger, which stored all digital readings for subsequent analysis. The test was conducted until the occurrence of pile failure or the attainment of the maximum allowable pullout force. Following the completion of the tests, the recorded data from the data logger were extracted and analyzed using Excel. A comparative analysis was conducted to assess the variation in the pullout resistance between untreated and asphalt-improved soil specimens and examine the influence of the load angle on the pile behavior.

C. Numerical Analysis

A soil model was developed using PLAXIS, a geotechnical engineering finite element program, to examine the resistance of the pile group pullout under inclined loading conditions. The research studied the group behavior in piles under various loading orientations, including vertical angles (0°, 30°, 45°, and 60°) and horizontal angles (90°, 30°, 45°, and 60°). The efficacy of the soil treatment in enhancing the pullout strength was assessed by conducting a comparative analysis of sandy soil samples before and after the implementation of asphalt improvements. The soil behavior is hypothesized to be governed by an elastic perfectly-plastic constitutive relation based on the non-associated Mohr–Coulomb criterion.

III. RESULTS AND DISCUSSION

As shown in Figure 2, the vertical load-displacement behavior for double pile groups is examined under pullout loads inclined at 0°, 30°, 45°, and 60°, with respect to the vertical axis. Both the experimental and numerical results are compared before and after the soil improvement by asphalt. The displacement values are plotted against the applied vertical loads (N), showing clear variations between the untreated and asphalt-treated soil responses. In both the experimental and numerical cases, the asphalt-improved sandy soil consistently exhibited higher load-bearing capacity and reduced displacement compared to the sandy soil. This enhancement is attributed to the asphalt's capacity to augment the soil cohesion, decrease the void ratio, and intensify the friction between the soil and pile surfaces. The numerical curves exhibited a high degree of correlation with the experimental trends, particularly at lower displacement levels. This finding suggests a strong agreement between the numerical model and the experimental data and serves as a testament to the reliability of the numerical model. However, slight deviations are observed at higher loads and displacements. These deviations can be attributed to simplifications in the numerical modeling or experimental variability, such as boundary conditions and pile-soil interface roughness. In summary, the asphalt-treated soil system demonstrated superior performance in comparison to the untreated soil, aligning with the findings reported in [20-22], particularly regarding the strength enhancement and displacement control. For all inclination angles, the asphalt-treated soil exhibited enhanced stiffness and pullout resistance. The most significant enhancement was identified at 30° inclinations, as well as at 0°, 45°, and 60°. While the enhancements were still evident, the inclined nature of the load introduced additional shear components, which led to a slight reduction in the net improvement due to slippage effects. When subjected to vertical loading (0°), the pullout capacity exhibited a 299.3% increase, while the displacement decreased by 48.7%. With an inclination of 30°, the pullout load exhibited a 406.8% enhancement, while the displacement decreased by 51.85%. At an angle of 45°, the pullout capacity exhibited a 247.8% increase, with a 51.61% reduction in displacement. Consequently, at 60°, there was a 216.6% increase in pullout capacity and a 50.0% improvement in displacement. Figure 3 shows the horizontal load-displacement behavior for double pile groups subjected to pullout loads at various inclinations (30°, 45°, 60°, and 90° relative to the vertical axis), along with both the experimental and numerical results before and after the asphalt soil improvement.

(a)

(b)

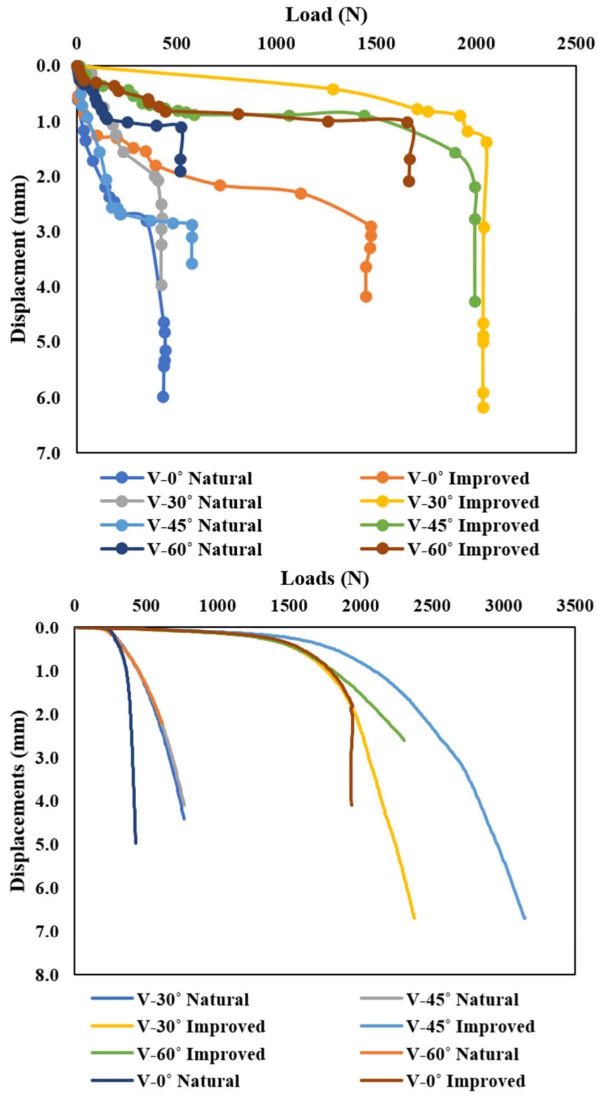

Fig. 2. Comparison of (a) experimental and (b) numerical vertical load-displacement curves for a double pile group subjected to pullout loading, before and after asphalt soil improvement.

The most significant enhancement in the pullout capacity was observed at 30°, with an increase of 469%, followed by 45° (426.3%), 60° (262.3%), and 90° (99.4%). With respect to the lateral displacement, the most significant reduction was observed at 30°, where the displacement decreased by 59.96%, while the reductions for 45°, 60°, and 90° were 27 and the respective values were determined to be 6%, 21.75%, and 0.18%. The findings indicate the substantial impact of the asphalt on enhancing the shear resistance, stiffness, and overall stability of the soil–pile interaction under inclined horizontal pullout forces. Despite the fact that all inclinations exhibited performance gains, the 30° inclination was identified as the most effective angle in terms of load improvement and displacement reduction. This finding provides critical insights into design considerations based on target performance criteria [20-23]. This consistency lends support to the applicability of asphalt stabilization in enhancing the pullout behavior under complex loading conditions.

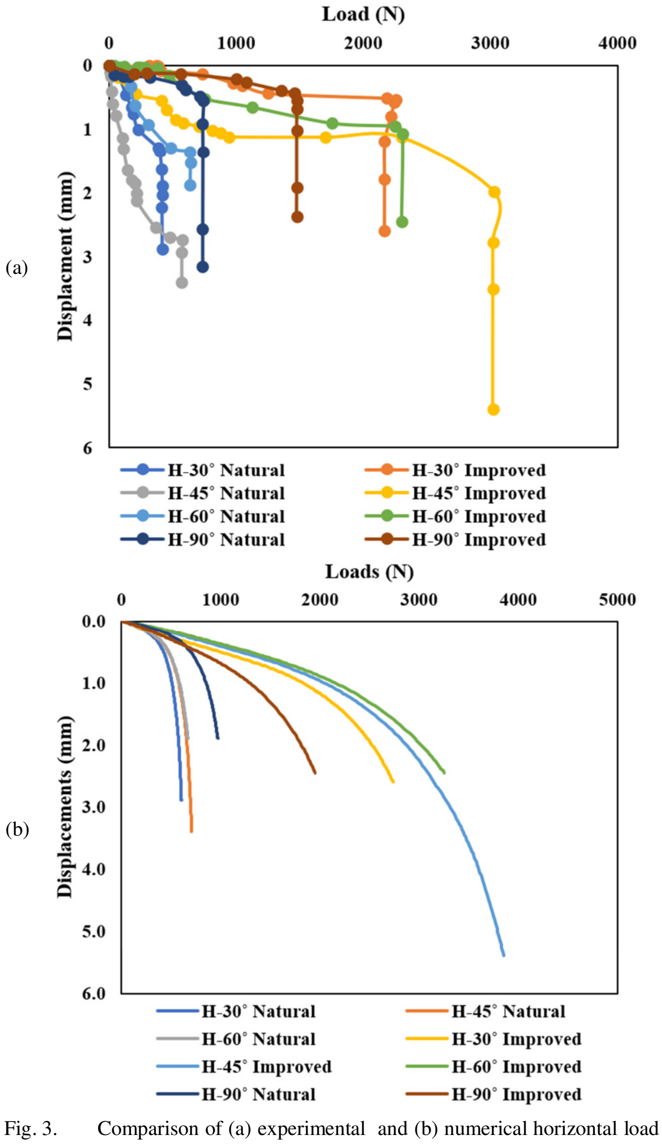

Fig. 3. Comparison of (a) experimental and (b) numerical horizontal load displacement curves for a double pile group under inclined pullout loads before and after asphalt soil stabilization.

Figure 4 compares the vertical load–displacement response for triple pile groups subjected to pullout loads inclined at 0°, 30°, 45°, and 60°, both experimentally and numerically, before and after improvement with asphalt. This comparison is made between soil conditions before and after improvement with asphalt. Experimentally, the 30° inclination angle exhibited the most significant enhancement in the load capacity (approximately 183.14%), substantiating its efficacy in optimizing the alignment between the applied force and the enhanced soil structure.

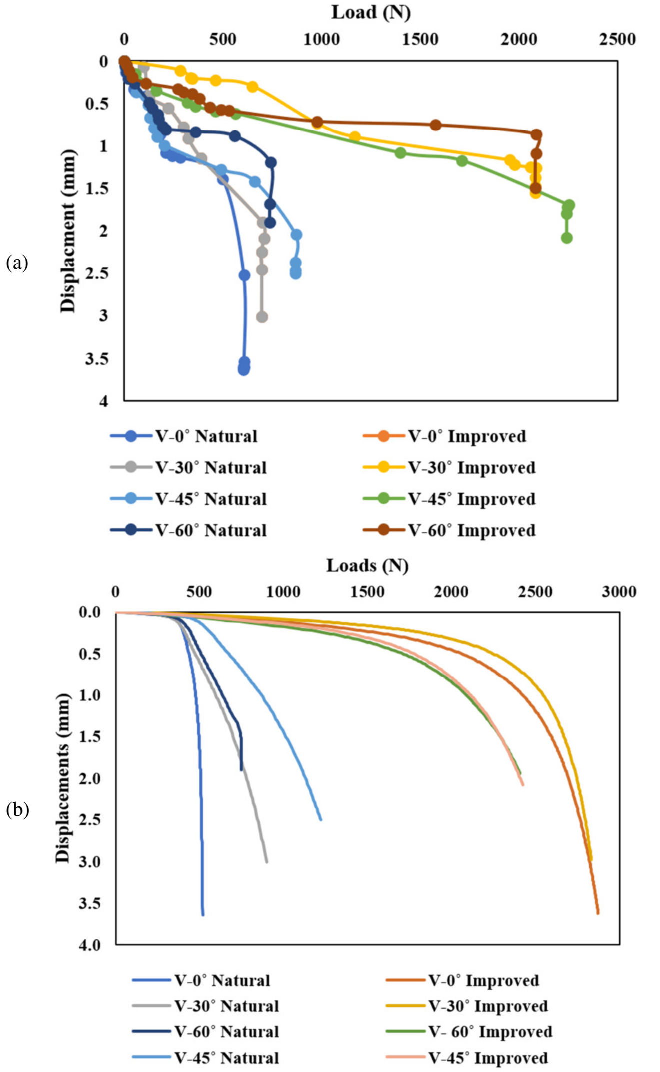

Fig. 4. (a) Experimental and (b) numerical vertical load–displacement behavior of triple pile groups under inclined pullout loads before and after asphalt improvement.

However, this enhancement was achieved at the expense of increased displacement (approximately 165.34%), indicating potential deformation concerns. In contrast, the 60° inclination exhibited a balanced performance, characterized by an 182.00% increase in load and a 27.86% reduction in displacement. This configuration emerged as the most effective strategy for enhancing both strength and stiffness. The 45° case demonstrated significant enhancements, with a 159.15% increase in the load gain and a 17.00% reduction in displacement. Conversely, the 0° vertical loading exhibited a marginal enhancement, with a 40.61% rise in the load and a 36.56% rise in displacement. This suggests a diminished compatibility with the stabilization method in that orientation.

However, the 60° inclination angle exhibited the optimal balance between the augmented pullout resistance and diminished displacement, rendering it the most suitable angle for practical applications. The present findings may be consistent with those of previous studies, which support the applicability of asphalt stabilization in enhancing the pullout behavior under complex loading conditions [22, 23].

Figure 5 compares the horizontal load–displacement response for triple pile groups subjected to pullout loads inclined at 30°, 45°, 60°, and 90°, examining the effects of the asphalt improvement on the soil conditions before and after the application.

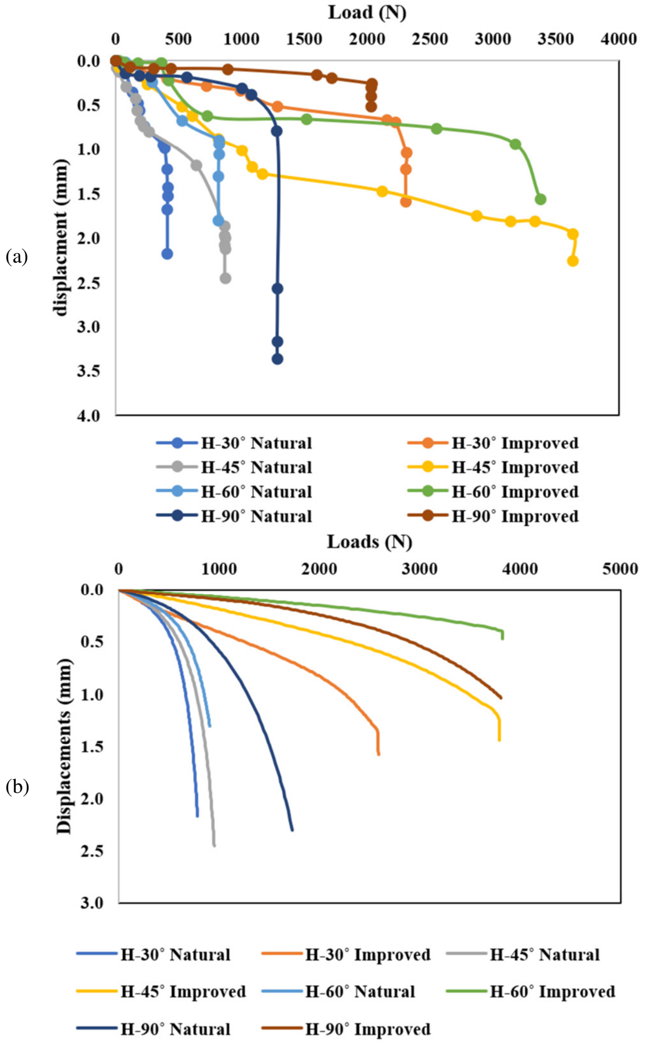

Fig. 5. Comparison of (a) experimental and (b) numerical horizontal load-displacement curves for a triple pile group subjected to pullout loading, before and after asphalt soil improvement.

The numerical model exhibited a high degree of accuracy in predicting the experimental trends at lower displacements, thereby validating its reliability. However, minor variations in these measurements at higher loads and displacements may be indicative of simplifications in the model or experimental variability, such as boundary conditions or the roughness of the pile-soil interface. The horizontal pullout performance of triple-pile groups exhibited a substantial enhancement following asphalt stabilization, particularly at intermediate load inclinations. The most significant enhancement in the load capacity occurred at 30°, with a 453.52% increase, and a 32.8% reduction in displacement. This configuration was the most efficient in terms of strength and stiffness. While 90° exhibited the most important displacement reduction (74.7%), the overall load improvement remained modest (58.49%). Conversely, 60° and 45° exhibited remarkable load increments (310–321%), though their displacement responses were less favorable, with 60° demonstrating a significant increase in deformation.

IV. CONCLUSIONS

Asphalt stabilization significantly enhanced the pullout performance of both double and triple pile groups under vertical and horizontal loading. In the context of double piles subjected to vertical loading, the most significant enhancement in pullout capacity was observed at 30° (406.8%, with a 51.85% reduction in displacement), followed by 0° (299.3%, 48.7%), 45° (247.8%, 51.61%), and 60° (216.6%, 50.0%). In the context of horizontal loading, 30° exhibited optimal outcomes, with a 469% load enhancement and a 59.96% displacement diminution, followed by 45° (426.3%, 27.6%), 60° (262.3%, 21.75%), and 90° (99.4%, 0.18%). In the case of triple piles under vertical loading, 30° exhibited the greatest load gain (183.14%), though it resulted in a substantial increase in displacement (−165.34%). Conversely, 60° demonstrated the most balanced performance, with an 182.0% load improvement and a 27.86% displacement reduction. The 45° position demonstrated a substantial enhancement of 159.15% in displacement, with a 17.00% reduction in displacement. In contrast, the 0° position exhibited marginal improvement (40.61%) and an increased displacement of −36.56%. In the horizontal loading of triple piles, 30° exhibited superior performance, with a 453.52% increase in load and a 32.8% reduction in displacement. This was followed by 45°, which demonstrated a 321.11% increase in load with a 4.67% reduction in displacement, 60°, which exhibited a 310.42% increase in load with a 72.26% reduction in displacement, and 90°, which exhibited a 58.49% increase in load with a 74.7% reduction in displacement. A comprehensive evaluation of intermediate inclinations, specifically those at 30° and 60°, revealed a favorable correlation between strength and stiffness enhancement. This observation validates their efficacy in enhancing soil–pile interaction in asphalt-treated sandy soils.

REFERENCES

[1] M. Marjanović, M. Vukicevic, and D. Konig, "Flexible Pile Group Interaction Factors under Arbitrary Lateral Loading in Sand," *Journal of Marine Science and Engineering*, vol. 8, no. 10, Oct. 2020, Art. no. 800, https://doi.org/10.3390/jmse8100800.

[2] A. Vakili, S. M. A. Zomorodian, and A. Totonchi, "Laboratory and Three-Dimensional Numerical Modeling of Laterally Loaded Pile Groups in Sandy Soils," *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, vol. 45, no. 4, pp. 2623–2636, Dec. 2021, https://doi.org/10.1007/s40996-020-00502-w.

[3] B. Das and N. Sivakugan, Principles of Foundation Engineering, 9th ed. Boston, MA, USA: Cengage Learning, 2019.

[4] A. Paula and C. Sylvestre, "Construction Management and Foundation Designs for WPI Athletic Rooftop Parking Garage," B. Thesis, Worcester Polytechnic Institute, Worcester, MA, USA, 2013.

[5] H.-G. Kempfert and B. Gebreselassie, Eds., "Soil stabilisation with column-like elements," in *Excavations and Foundations in Soft Soils*, Berlin, Heidelberg: Springer, 2006, pp. 461–523.

[6] W. Han *et al.*, "Experimental Study of Wave Load Distributions on Pile Groups Affected by Cap Structures and Pile Spacings Under Varied Wave Conditions," *Journal of Marine Science and Engineering*, vol. 12, no. 11, Nov. 2024, Art. no. 2005, https://doi.org/10.3390/jmse12112005.

[7] C. Wang, F. Liang, and X. Yu, "Experimental and numerical investigations on the performance of sacrificial piles in reducing local scour around pile groups," *Natural Hazards*, vol. 85, no. 3, pp. 1417–1435, Feb. 2017, https://doi.org/10.1007/s11069-016-2634-0.

[8] H. W. P. Gunasekara and L. I. N. De Silva, "Behaviour of rock socketed pile groups," in *Proceedings of Civil Engineering Research Symposium 2024*, Moratuwa, Sri Lanka, Sep. 2024, pp. 75–76, https://doi.org/10.31705/cers.2024.38.

[9] B. M. Das, *Principles of Foundation Engineering*, 7th ed. Stamford, CT, USA: Cengage Learning, 2011.

[10] M. Gunaratne, Ed., *The Foundation Engineering Handbook*, 2nd ed. Boca Raton, Fl, USA: CRC Press, 2014.

[11] A. A. G. Al-Saidi, "Correction Factor for Methods of Installation of Piles Group in Sandy Iraqi Soils," *Journal of Engineering*, vol. 22, no. 9, pp. 172–181, Sep. 2016, https://doi.org/10.31026/j.eng.2016.09.11.

[12] J.-S. Park and D. Park, "Vertical bearing capacity of bucket foundation in sand overlying clay," *Ocean Engineering*, vol. 134, pp. 62–76, Apr. 2017, https://doi.org/10.1016/j.oceaneng.2017.02.015.

[13] S. S. Al-Amery and M. H. Al-Dahlaki, "Behavior of Piles subjected to Combined Axial and Lateral Loading," *Engineering, Technology & Applied Science Research*, vol. 15, no. 2, pp. 21187–21196, Apr. 2025, https://doi.org/10.48084/etasr.9798.

[14] B. Mishra, "A Study on Ground Improvement Techniques and Its Applications," *International Journal of Innovative Research in Science, Engineering and Technology*, vol. 5, no. 1, pp. 72–86, 2016.

[15] M. A. Alafeena and A. N. Aljorany, "Experimental Study on the Modulus of Subgrade Reaction for Sandy Soil Improved by Grouting Materials," *Key Engineering Materials*, vol. 857, pp. 358–366, 2020, https://doi.org/10.4028/www.scientific.net/KEM.857.358.

[16] P. Latham, W. Fiore, M. Bauman, and J. Weaver, "Effects matrix for evaluating potential impacts of offshore wind energy development on the U.S. Atlantic coastal habitats," U.S. Department of the Interior Bureau of Ocean Energy Management, Fairfax, VA, USA, BOEM OCS study BOEM 2017-014, 2017.

[17] M. M. Abdel-Rahman, "Review of Soil Improvement Techniques," in *Advancements in Geotechnical Engineering*, Cham, Switzerland, 2021, pp. 175–199, https://doi.org/10.1007/978-3-030-62908-3_14.

[18] S. Bang, K. D. Jones, K. O. Kim, Y. S. Kim, and Y. Cho, "Inclined loading capacity of suction piles in sand," *Ocean Engineering*, vol. 38, no. 7, pp. 915–924, May 2011, https://doi.org/10.1016/j.oceaneng.2010.10.019.

[19] H. Mroueh and I. Shahrour, "Numerical analysis of the response of battered piles to inclined pullout loads," *International Journal for Numerical and Analytical Methods in Geomechanics*, vol. 33, no. 10, pp. 1277–1288, 2009, https://doi.org/10.1002/nag.765.

[20] S. A. Dantas Neto, C. G. F. Pereira, and A. A. Abreu, "Stabilization of sandy soil with high content of asphalt emulsion," *REM - International Engineering Journal*, vol. 73, pp. 163–169, Apr. 2020, https://doi.org/10.1590/0370-44672019730118.

[21] G. White, "State of the art: interface shear resistance of asphalt surface layers," *International Journal of Pavement Engineering*, vol. 18, no. 10, pp. 887–901, Oct. 2017, https://doi.org/10.1080/10298436.2015.1126270.

[22] R. Al-Jarazi, A. Rahman, and C. Ai, "Estimation and evaluation of interface shear strength in asphalt pavement using the CART model," in *Advances in Functional Pavements*, 1st ed., London, UK: CRC Press, 2023.

[23] C. Sun, P. Li, B. Niu, Y. Xu, and W. Zhang, "Structure stability and shear failure behaviors of asphalt mixtures from the perspective of aggregate particle migration," *Construction and Building Materials*, vol. 408, Dec. 2023, Art. no. 133653, https://doi.org/10.1016/j.conbuildmat.2023.133653.