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Piles Pullout Enhancement Subjected to Inclined Loads

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Abstract

This study focuses on the experimental and numerical analysis of pullout resistance for a single pile subjected to inclined loads in sandy soil, both before and after improvement with asphalt enhancement. The sandy soil, characterized by low cohesion, poses significant challenges for foundation stability under vertical and inclined loading conditions. Pullout tests were conducted experimentally at angles of 0°, 30°, 45°, 60°, and 90° for both vertical and horizontal components of inclined loads using a custom-designed testing setup. Cutback asphalt was introduced as an improvement agent. The experimental results revealed a significant reduction in displacement up to 62% and an improvement in pullout resistance for the asphalt-treated soil up to 55% and 72% for vertical and horizontal load directions, respectively. PLAXIS software was validated through numerical modeling, which confirmed the improved load-displacement behavior and stress distribution. The asphalt enhancement demonstrated an improvement in pullout resistance, underscoring its effectiveness in creating a cohesive soil matrix that enhances load transmission and reduces void ratios. This research provides valuable insights into the load's inclination and improvement with angle variations; the pullout capacity enhanced significantly with the inclination angle with vertical due to the formation of a bigger failure zone, thus offering practical solutions for improving the performance of pile-supported foundations in weak sandy soils under challenging inclined load conditions.

Keywords: Single Pile; Inclined Loads; Sandy Soil; Asphalt.

1. Introduction

Sandy soils, characterized by their loose structure and low cohesion, present unique challenges in foundation engineering due to their limited ability to provide sufficient load-bearing capacity and shear resistance, especially under inclined loads [1]. These properties make sandy soils susceptible to excessive deformation or failure under loading conditions typical for pile-supported structures like bridges and towers [2]. Consequently, soil improvement techniques are often applied to enhance the stability and load-bearing capacity of sandy soils, which is critical for ensuring the performance and longevity of piles subjected to inclined and pullout forces [3].

Several common methods are used to improve sandy soils, each with distinct mechanisms and benefit [4]. Water and emulsifying agents modify the particle so that it dissolves and links with water to form asphalt emulsion, a soil asphalt dispersion. Depending on its kind, this material can also form bonds with other materials and harden over a variety of periods [5]. The most popular and affordable kind of asphaltic material for stabilizing soil is cutback asphalt, particularly the medium-curing varieties made in refineries [6].

Pile foundations are a fundamental component in civil engineering, essential for transferring loads from structures to deeper soil layers where stability is more assured [7]. They are particularly crucial in projects such as

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high-rise buildings, offshore platforms, towers, and bridges, where lateral or inclined loads frequently impact the structural integrity [8]. These inclined loads, which arise from wind, waves, or even seismic activity, present unique challenges in design due to the complex interactions between the pile and surrounding soil [9]. Piles in these situations not only support vertical loads but also need to withstand significant lateral and inclined forces that can lead to complex stress distributions along the pile-soil interface [10]. Inclined loads add complexity to soil-pile interaction mechanics, especially in sandy soils, which are inherently loose and exhibit lower cohesion than clay soils [11].

Pullout resistance is especially important in ensuring structural stability under inclined loading conditions, as it directly impacts a pile's capacity to anchor the structure against lateral and uplift forces [12, 13]. Misestimating pullout resistance can lead to inadequate foundation design, resulting in potential failure or excessive settlement that compromises both safety and structural longevity. Therefore, enhancing the understanding of pullout resistance in piles, particularly under inclined loading in improved sandy soil, is integral to engineering practice [3, 14, 15] . This study aims to address these challenges by analyzing pullout resistance both experimentally and numerically, providing insights that could advance foundation engineering in sandy soils under inclined loading conditions [16-18].

There are several researches that studies the concept of single pile, Hanna et al. [19] investigated the pullout resistance of both helical and plate anchors under varying conditions, focusing on key factors including embedment depth, anchor geometry, helix configuration (for helical anchors), plate dimensions, soil density, and loading rates. Laboratory-scale model tests were conducted in controlled sandy soil environments to evaluate the influence of these parameters on anchor performance. The results indicate that pullout resistance increases with greater embedment depth and higher soil density for both anchor types, with helical anchors demonstrating superior performance due to the screw-like action of their helices, which mobilize additional resistance compared to traditional flat plate anchors. The study also highlights the distinct failure mechanisms of the two anchor types [20], where plate anchors rely on the uplift of surrounding soil, while helical anchors benefit from the additional resistance provided by their helices. Empirical and theoretical models were developed to predict pullout resistance, offering practical design tools for engineers [17].

Meyerhof & Yalcin [21] conducted studies on tiny pile groups and flexible model piles on layered soil, consisting of clay over sand, exposed to eccentric, inclined, lateral, and axial stresses [18, 22]. The final pile capacity depends on the ratio of top layer thickness to pile embedment, as well as the load's slope and eccentricity. Albusoda & Alsaddi [23] conducted a series of 25 model experiments to assess the performance of several kinds of laterally loaded piles (regular, battered, and finned) in stratified sandy soil. Results indicated a substantial enhancement in the ultimate lateral load-bearing capability of single piles when the pile type was changed from conventional to battered and fined.

A fined pile is characterized by Lee & Gilbert [24] as a pile with four plates welded at a right angle to the top of a conventional monopile. Peng et al. [25] conducted a three-dimensional analysis of laterally loaded fin piles and claimed that the lateral load capacity of model tests on a monopile significantly improved with the addition of fins. Assessing the lateral resistance in relation to the movement of the pile head reveals the increase in lateral resistance once fins are affixed to a pile, and numerical analysis indicates that an augmentation in fin length results in heightened lateral resistance. Additionally, Yang et al. [26] performed several experiments on individual fined and vertical piles of diverse dimensions and configurations, concluding that when the pile diameter is equivalent to the fin width ($w_f/D = 1.0$), the fin efficiency increased by approximately 75% for short piles and 90% for long piles.

The study introducing asphalt as a binding agent, the research investigates its effects on improving the cohesion, stiffness, and shear strength of sandy soils, which are naturally characterized by low cohesion and permeability. Using a custom-designed testing system, experimental tests were carried out to assess the load-displacing behavior of piles under many angles (0°, 30°, 45°, 60°, and 90°), both before and after improvement. Through experimental and numerical analysis incorporating PLAXIS software modeling to confirm soil-pile interaction and stress distribution under challenging loading situations, the study advances geotechnical engineering. The results show that asphalt stabilization offers a workable way to increase the load-bearing capacity of sandy soils by greatly lowering displacement and improving pullout resistance. This work offers insightful analysis and useful tools for improving foundation design, therefore enabling safer and more effective pile-supported construction in poor soil conditions. The research methodology that has been adopted in the current dissertation can be described as shown in Figure 1.

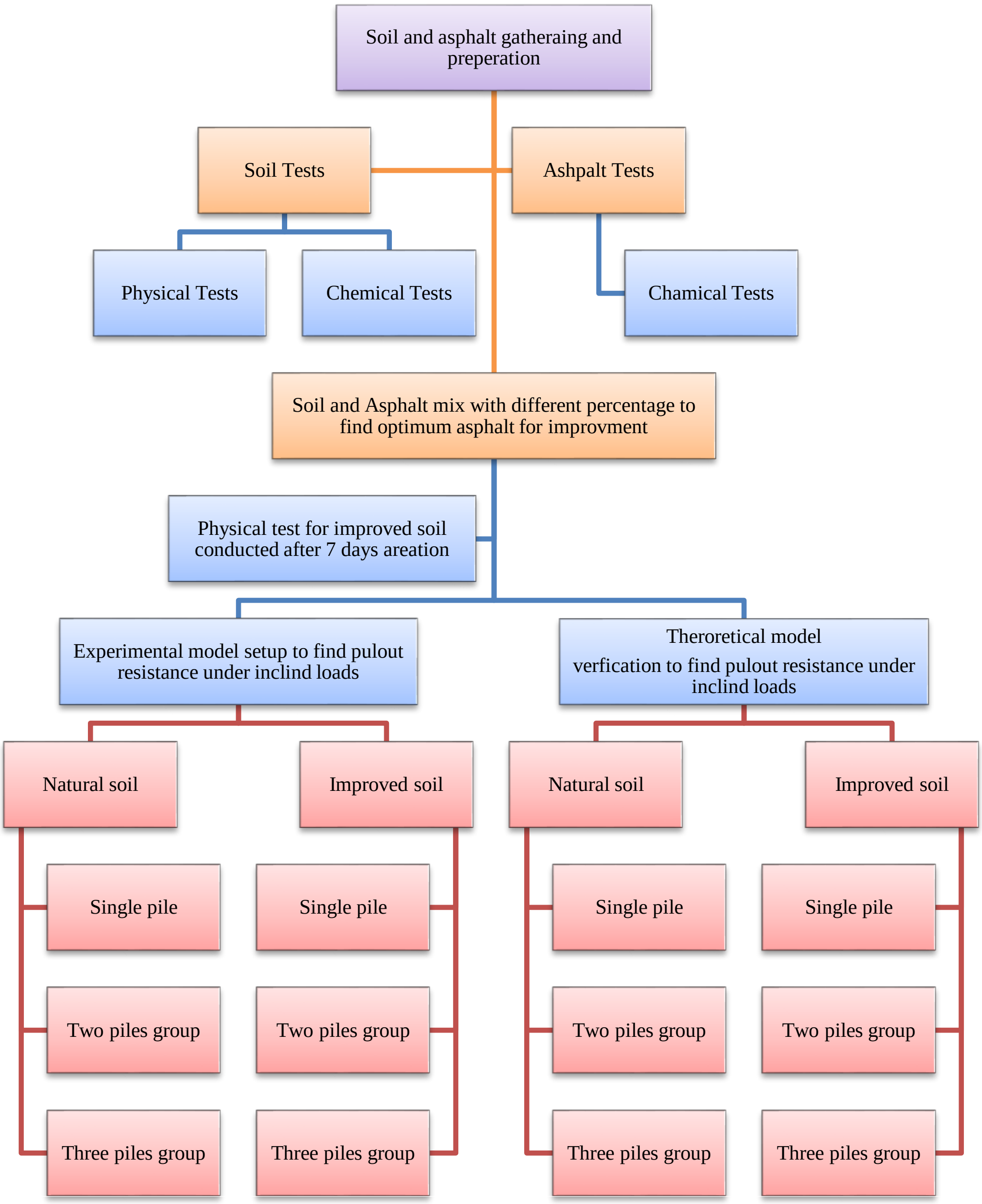


Figure 1. Research methodology flowchart

2. Experimental Part

2.1. Materials and Testing

The materials utilized in this work are as follows:

2.1.1. Sandy Soil

This research used Sandy soil from Karbala City, categorized as poorly graded sand (SP) based on the Unified Soil Classification System (USCS) and found using grain size distribution analysis (ASTM D2487–2011) as shown in Figure 2. Al-Ma`awal Laboratory assessed the specific gravity of the soil using the pycnometer technique (ASTM D854). ASTM D4253-2014 and ASTM D4254-2014 respectively helped one to ascertain the maximum and lowest dry unit weights and matching void ratios. Using exact deformation and load measurements, the direct shear test (ASTM D3080-2011) examined factors related to shear strength including cohesion and friction angle, as listed in Table 1. Following the British Standard (B.S. 1377:3, 1988), chemical tests also were conducted to examine the proportions of oxides, total soluble salts, organic content, sulfate (SO3), carbonate (CaCO3), pH, and chloride content in the soil mixes. These tests provide a complete awareness of the mechanical, chemical, and physical characteristics of the soil as listed in Table 2.

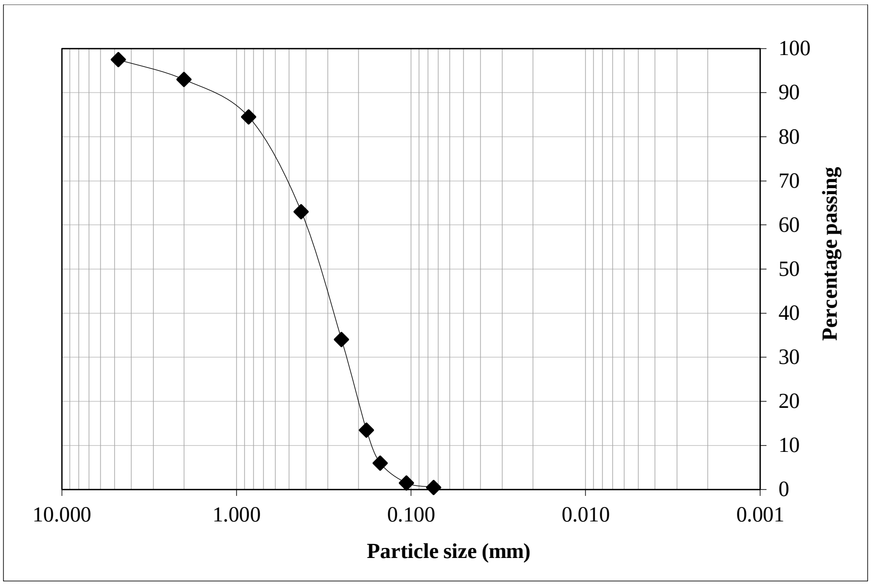


Figure 2. grain size distribution

Table 1. Soil properties

Property	Value
Classification of Soil (USCS)	PS
D_{10}(mm)	0.17
D_{30}(mm)	0.23
D_{60}(mm)	0.4
C_U	2.35
C_C	0.78
Dry Unit Weight (γ_{dry})	15.9 kN/m^3
$\gamma_{\max}$	17.51 kN/m^3
$\gamma_{\min}$	15.9 kN/m^3
Specific gravity	2.61
Void Ratio (e)	0.637
$e_{\max}$	0.71
$e_{\min}$	0.49
C	3.79 kN/m2
Ø	30.8

Table 2. Chemical Composition of the Natural Soil

Chemical composition	Test result
Total soluble salt (T.S.S)	1.9%
Organic content	1.12%
Total (SO4)	0.68%
Total (CaCO3)	1.47%
PH value	7.6
Total (CL)	0.004%

2.1.2. Cutback Asphalt

Comprising about 42% kerosene and 58% penetration-grade 80/100 bitumen, MC 30 cutback bitumen is classed as a medium curing type. This formulation is appropriate for uses needing intermediate curing durations, usually about 48 hours as it lets viscosity at ambient temperatures be reduced. Usually carried out at specialist refineries, MC 30 is manufactured by mixing intermediate volatility solvents, including kerosene, with pure bitumen, a procedure requiring extensive knowledge as listed in Table 3. MC 30 emphasizes the technical accuracy necessary in its manufacture unlike simpler formulations as it cannot be produced by just combining solvents with bitumen.

Table 3. Cut-back asphalt (MC30) chemical properties

Chemical properties	Limits of standard requirements	Results
Viscosity centistokes at 50 °C	30-60	45
Lower limit of flash point °C	38	38
Water %	0.2	0.2
Distilled volume from total distilled to 225 °C Upper limit	25	25
Distilled volume from total distilled to 260 °C Upper limit	40-70	60
Distilled volume from total distilled to 315 °C Upper limit	75-93	80
Remaining distillation at 360 °C%	50	50
Permeability at 25 °C	120-250	180
Drawability at 25 °C/cm	100	100
Solubility%	99	99

2.2. Design of Soil-cutback Asphalt Mixture

2.2.1. Preparations of Specimens

To prepare the specimens for the direct shear test, the pulverized and homogenous soil was oven dried at temperature of (100 ˚C). Soil was mixed with the required percentages of Asphalt by hand for two minutes until the Asphalt dispersed through the mixture with a different percentages of cutback asphalt (0.75, 1.5, 2.25, 3, 3.75 and 4.5) % has been mixed with sand in order to investigate the optimum cut-back asphalt ratio as shown in Figure 3, and mixed by rubbing the mixture and proper coating of soil particles with asphalt occurred. The mixture was allowed to aeration for two hours at room temperature (20±5 ˚C) as was recommended by Al-Nadaf [27] and Subair & Aljorany [28] then compacted and allowed to cure for (8) days as was recommended by Mostafa et al. [29] . The average of three samples that had the same fluid content was calculated and considered for analysis as recommended by Sarsam & Ibrahim [30] (. Direct shear test was conducted for the specimens to calculate the optimum strength parameters, the best result of mixture was for 2.25% asphalt and the strength parameters shown in Table 4.

Figure 3. Mixed sand with cut-back asphalt in various ratios

Table 4. Shear Strength Results of Optimum Mixed with Asphalt Soil

Property	Value
C	31 kN/m^2
Ø	23.4

2.3. Piles Testing Device

A thorough experimental setup used to assess the pullout capability of single pile under vertical and inclined loads makes up the pile testing tool. The configuration calls for a loading frame, a steel soil tank, and a hydraulic jack to apply stationary loads at different angles—0°, 30°, 45°, 60°, 90°. Comprising vertical legs, a horizontal beam, and a base, the steel loading frame supports the hydraulic jack for deliberate load application. Combining LVDTs for exact displacement measurement, a calibrated load cell, and a 5-ton capacity electrical jack, the loading system as shown in Figure 4. The tested soil is contained in a 0.7 m × 0.7 m steel soil tank; two 75 mm LVDTs coupled to a data logger monitor displacement. Using hollow steel pipes with a 22 mm diameter and 400mm length, the piles are designed with steel caps set in triangular patterns that guarantee inter-pile lengths surpass three times the pile width. A customized apparatus including plastic tanks and copper tubing with nozzles helps liquid asphalt injection into the ground for asphalt grouting. The grouting technique improves the bonding qualities of the ground by including tapered nozzles with many holes for consistent asphalt distribution. This combined tool guarantees a correct pile performance analysis under different circumstances.

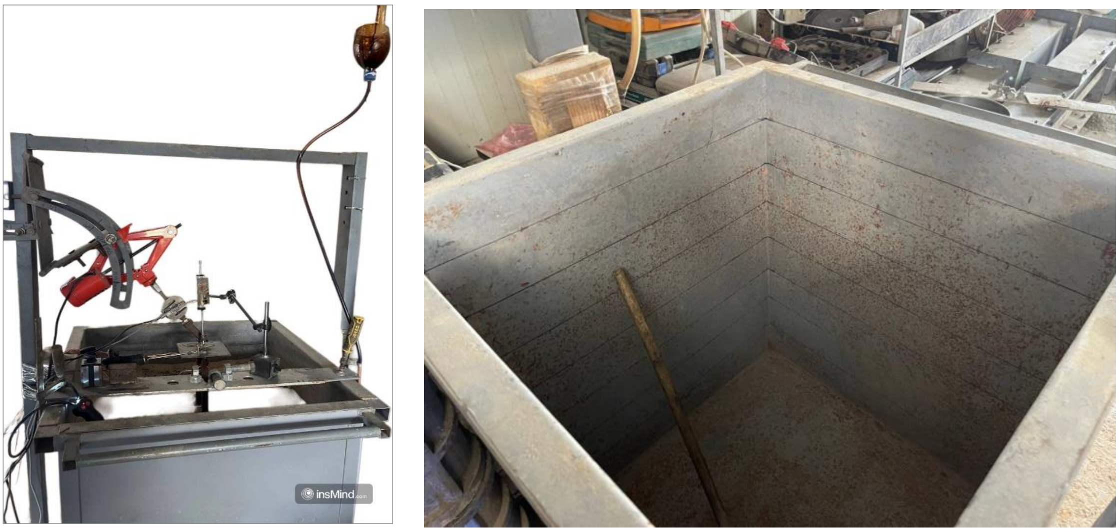


Figure 4. Model Setup for Test

2.3.1. Model Preparation and Sand Bed Preparation

The model preparation involved experimental testing on sand with a relative density (R.D) of 33%, requiring precise soil volume determination to fill the steel tank. The sand was deposited in six layers, each 10 cm thick, using a traveling pluviation (raining) method to achieve uniform density. A specially designed raining frame facilitated controlled sand placement. This frame consisted of adjustable-height columns with equidistant holes (100 mm steps) for elevation control. Longitudinal U-section beams supported a movable roller beam, equipped with a cone for sand pouring. This setup ensured uniform density by regulating the height of fall, as illustrated in Figure 5 [31].

Figure 5. Sand Raining System

2.4. Test Machine

The test machine was prepared following the manufacturing of the device, using both natural and improved soils. Sensors were installed to measure the strain on piles, while two LVDTs monitored the vertical and lateral displacements of single piles. All sensors were connected to a data logger. The testing procedure involved applying vertical or inclined pullout loads to the foundation setup, with sensors actively recording data. A locally developed data logger with 18 channels was linked to a laptop equipped with a DAQ program to collect data. The recorded data was saved as TDMS files for analysis in software like Excel, as shown in Figure 6.

Figure 6. Instruments for testing (Data logger)

3. Numerical Work

A soil model was created using PLAXIS, a geotechnical engineering finite element program, to investigate a single pile's pullout resistance under inclined loading. The research examined pile behavior under several loading orientations, including vertical angles (0˚, 30˚, 45˚, and 60˚) and horizontal angles (90˚, 30˚, 45˚, and 60˚). To assess soil treatment's pullout improvement, sandy soil was modeled before and after asphalt improvement. Detail numerical analysis, soil-structure interaction, and load-displacement simulation were possible using PLAXIS software, Mohr–Coulomb model was conducted. High-resolution analysis and soil-pile simulation were achieved using 20,153 elements and 30,832 nodes in the model as illustrated in Figure 7. The PLAXIS model used experimental sandy soil density, modulus of elasticity, and shear strength data. To imitate asphalt's improving benefits, soil cohesion and stiffness were adjusted to represent enhanced mechanical behavior. Asphalt improvement increased pullout resistance and decreased displacement under vertical and angled load applications, according to numerical data. PLAXIS' 3D soils model visualized stress distribution and deformation patterns, helping explain the pile-soil interaction process in stable and unimproved settings.

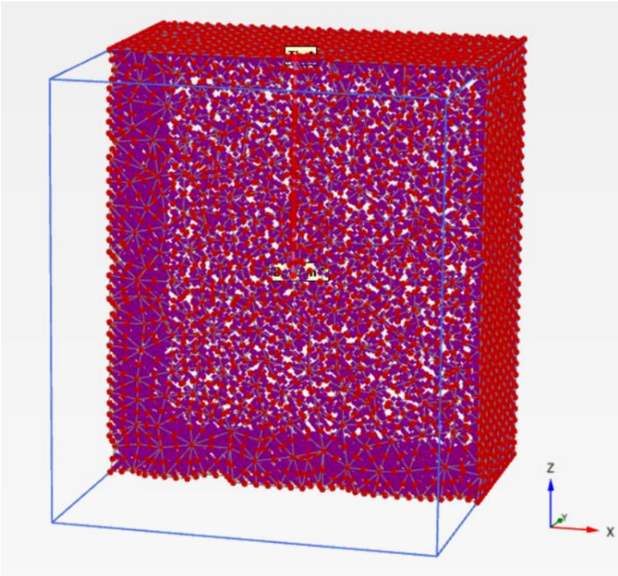


Figure 7. the utilized model in PLAXIS

4. Results and Discussion

4.1. Experimental Work Results

Figure 8 compares single pile vertical load-displacement performance with and without asphalt soil enhancement under pullout loads angled at 0°, 30°, 45°, and 60°. The x-axis shows the pullout load (N) and the y-axis the displacement (mm). The graphs show that asphalt soil enhancement improves pile resistance by reducing displacements under identical loads at all inclined angles. Vertical loading (0°) causes less displacement than inclined loads, indicating angled pullout forces' higher stress. Asphalt-treated soil reliably reduces displacements, increasing soil-pile interaction and pullout performance. The change in curved steepness with inclination angles indicates the pile-soil system's mechanical reactions to vertical and inclined pullout pressures. Asphalt treatment mitigated displacement and increased pullout capacity in all evaluated situations. Asphalt greatly improved sandy soil's load-bearing capability and deformation resistance. Asphalt strengthened soil particles, creating a more cohesive and less permeable matrix that sustained loads. This improved soil-pile interaction decreased displacement under identical loading conditions and boosted pile foundation pullout capability. Asphalt soil enhancement made weak sandy soils more solid and durable for foundation stability.

Asphalt's binding properties increase soil particle cohesiveness, improving sandy soil performance. The results show an enhancement in pullout strength about (47-55) % and significant displacement reduction between (36-62) % under vertical load component. This bonding lowers soil permeability and limits particle movement under stress, increasing shear strength and stiffness [32-34]. Asphalt also protects soil particles, minimizing empty areas and compacting the soil matrix [35]. Microstructure changes increase load transmission between the pile and soil, increasing pullout capabilities and reducing displacement [36]. Asphalt-treated sandy soil is more resistant to deformation and may carry larger loads, especially in loose sandy soils that would collapse under identical circumstances [37].

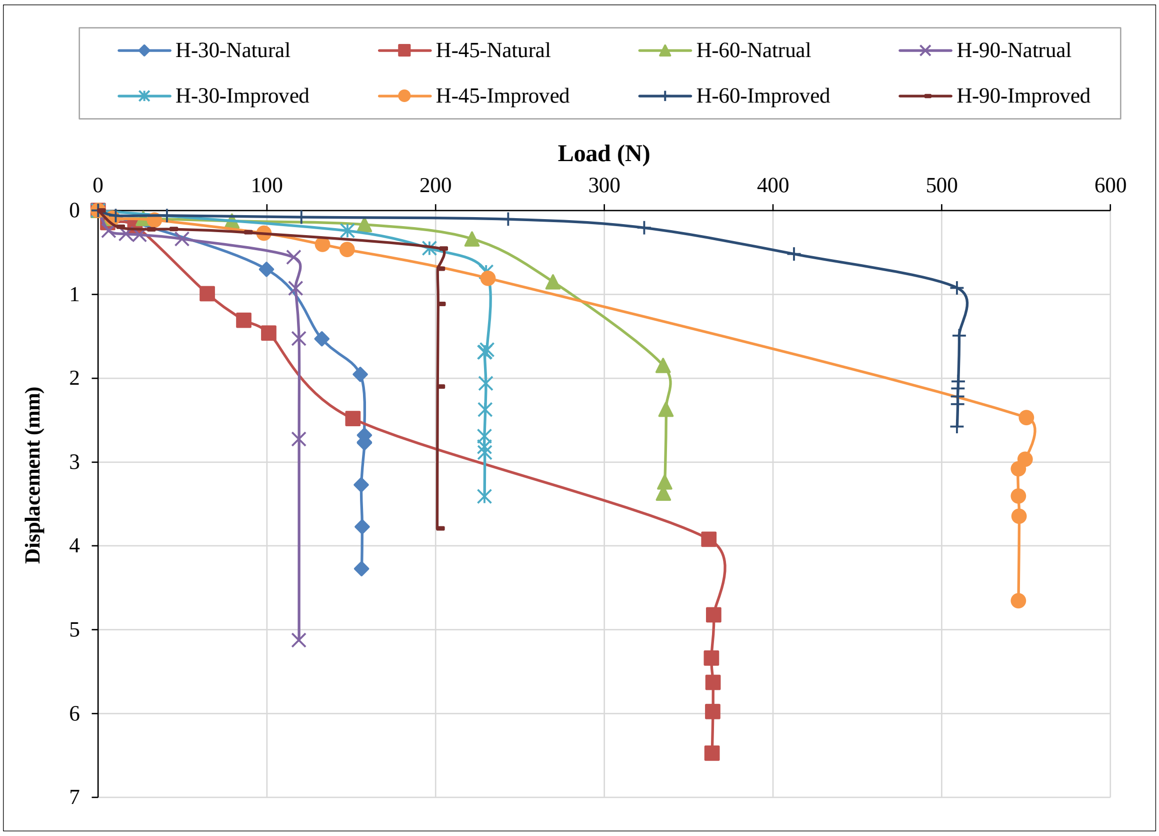


Figure 8. Horizontal Load - Displacement curve of single pile under pullout loads inclined 0˚, 30˚, 45˚, 60˚ with vertical before and after improvement with asphalt experimentally

Figure 9 illustrates the Horizontal Load-Displacement behavior of a single pile subjected to pullout loads inclined at 90°, 30°, 45°, and 60° relative to the vertical axis, comparing the performance of the pile before and after soil improvement with asphalt. The horizontal axis represents the applied load (N), while the vertical axis depicts the corresponding displacement (mm). It is evident that the asphalt-treated sandy soil demonstrates a significant enhancement in load-bearing capacity and reduced displacement for all inclination angles. The curves for the improved soil exhibit higher resistance to pullout loads, particularly under vertical loads (90°), where the enhanced cohesion and reduced soil particle movement due to asphalt stabilization yield the highest pullout capacity.

In contrast, the untreated soil displays larger displacements and lower resistance, particularly under inclined pullout loads, indicating weaker soil structure and limited interaction between the pile and surrounding soil. These results confirm the effectiveness of asphalt improvement in increasing the shear strength, stiffness, and overall stability of the soil-pile system under various loading conditions. Asphalt fills the voids between sand particles, reducing the soil's permeability and increasing its density, which improves its resistance to deformation underload. Additionally, asphalt stabilizes the soil structure by creating a semi-rigid matrix, thereby increasing the frictional resistance and adhesion between the pile and the surrounding soil. A (49-52) % pullout enchantment was demonstrated for (30°, 45°, and 60°) loads inclination condition while a considerable improvement was shown for (90°) up to 71%, the deformations were improved for about (20-58) %. This results in higher pullout resistance and reduced displacement, as the stabilized soil effectively distributes the applied load across a larger area. Furthermore, the viscoelastic properties of asphalt contribute to energy dissipation during loading, enhancing the soil's ability to resist inclined and vertical pullout forces. This explains why the treated soil exhibits significantly better performance compared to untreated soil which showed an improvement trend mostly fit with Oluyemi-Ayibiowu [38] and Shakir [39] regarding the strength and displacement behavior.

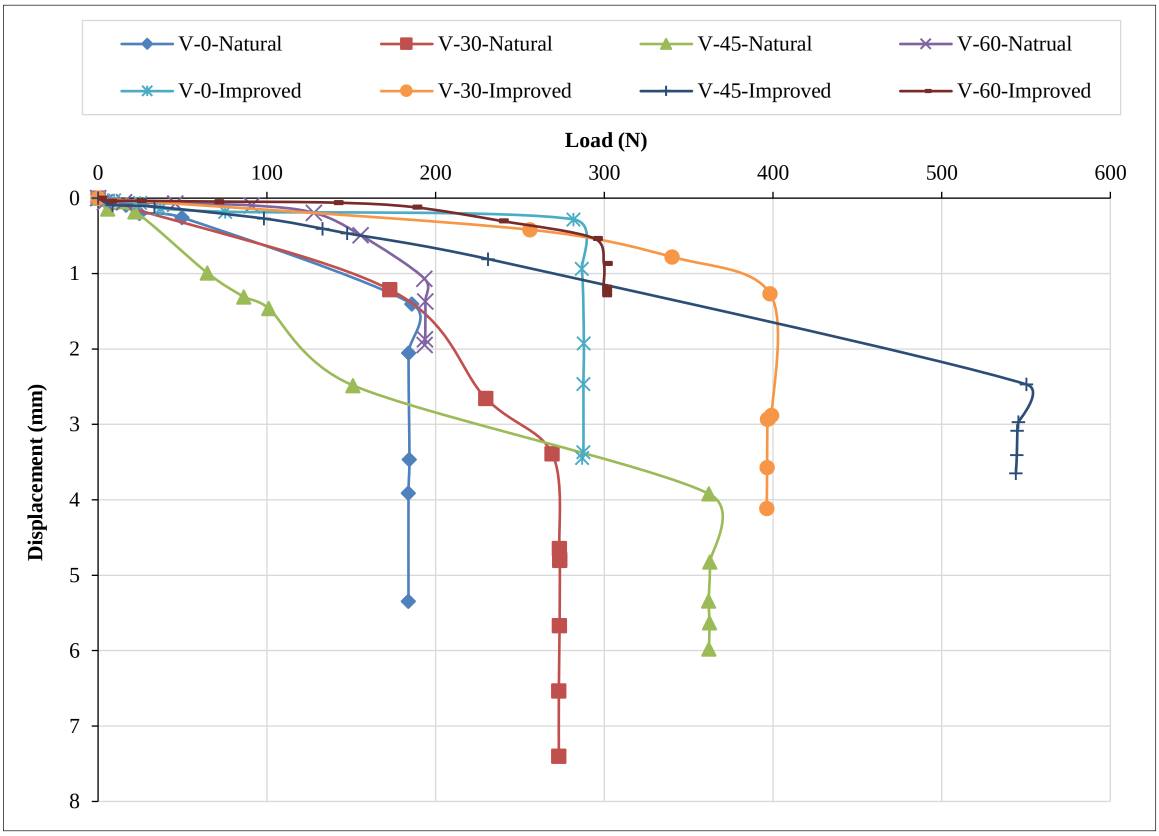
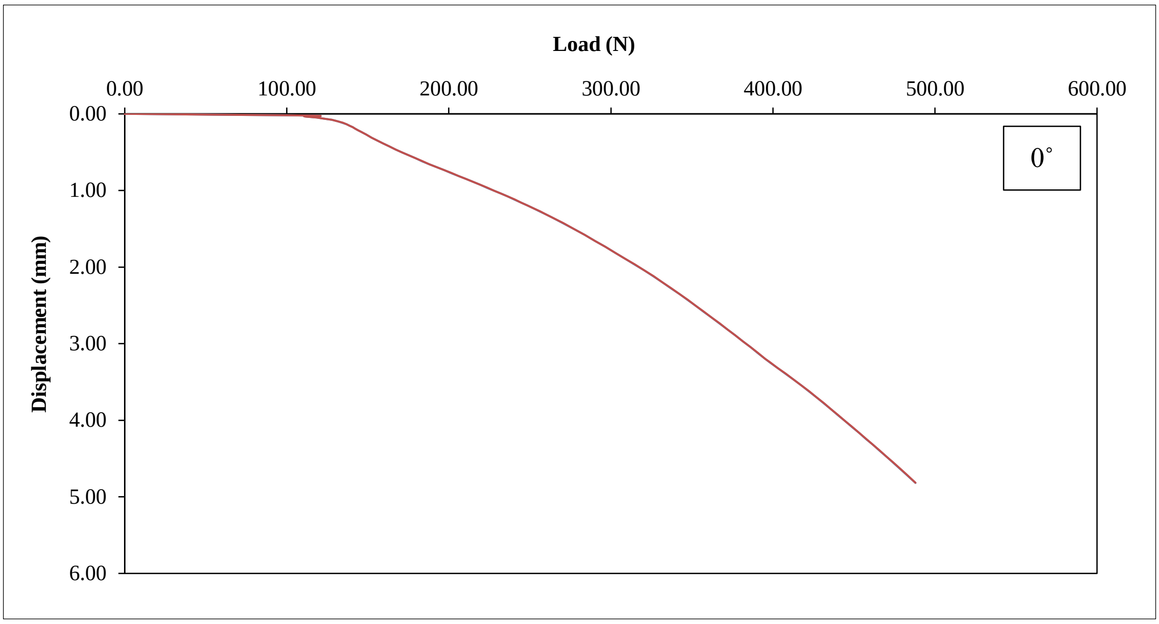


Figure 9. Vertical Load - Displacement curve of single pile under pullout loads inclined 90˚, 30˚, 45˚, 60˚ with vertical before and after improvement with asphalt experimentally

4.2. Numerical Work Results

Figure 10 illustrates load-displacement curves illustrate the behavior of a single pile subjected to pullout loads inclined at angles of 0°, 30°, 45°, and 60° under vertical conditions for an original soil scenario without any improvement through asphalt application. Each graph represents the relationship between applied load (N) and displacement (mm) at the tip of the pile. The results indicate that as the inclination angle of the applied pullout load increases, the load-bearing capacity and corresponding displacement behavior change significantly. For a 0° inclination, the load-displacement curve shows a relatively linear increase, indicating limited deformation at the pile tip. However, with increasing inclination angles (30°, 45°, and 60°), the curves reveal the same displacement trend at reduced load values, demonstrating a decline in load resistance as the inclination angle increases. The numerical results are more or less consistent with model results regarding strength for natural soil, this trend highlights the diminished performance of the pile under inclined pullout loads when the soil is left unimproved. The results shown an agreement in behavior with Hussain et al. [40] as the uplift capacity of inclined piles under vertical and inclined pulls load increase with increasing the load inclination angle until reaching the maximum value. The numerical and experimental improvement figure were identical with Mukherjee et al. [41] and experience matching improvement conductance related to pullout resistance. The absence of asphalt treatment results in less stiffness and cohesion, contributing to higher displacements and reduced pullout resistance across all inclination angles. These observations emphasize the need for soil improvement techniques to enhance load-bearing capacity and mitigate displacement under varying pullout load inclinations.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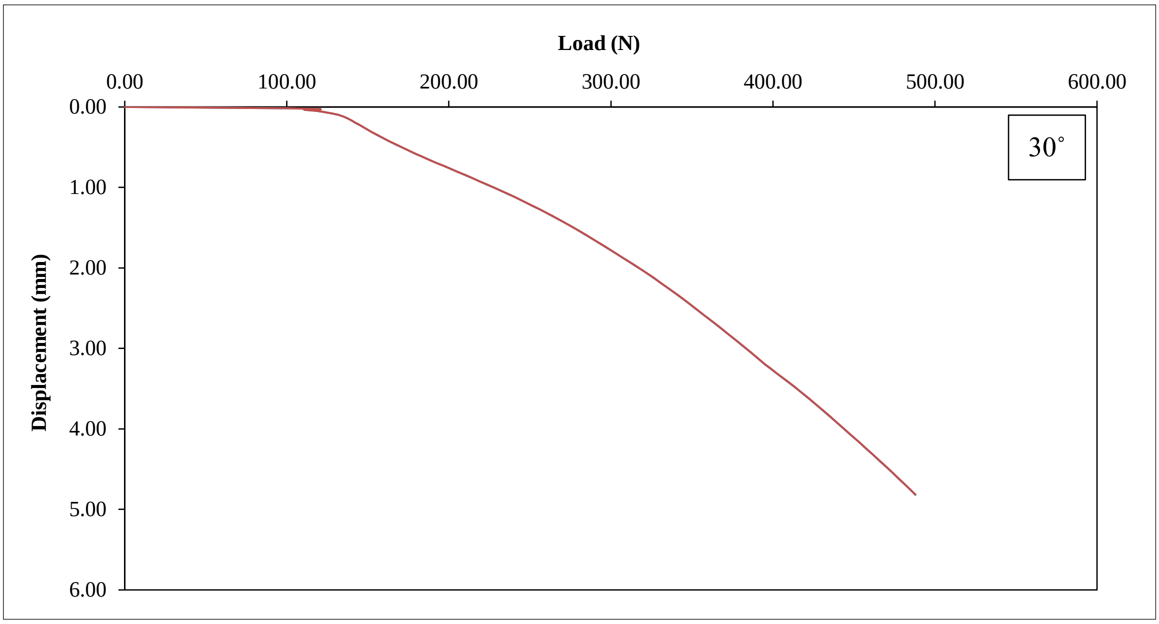
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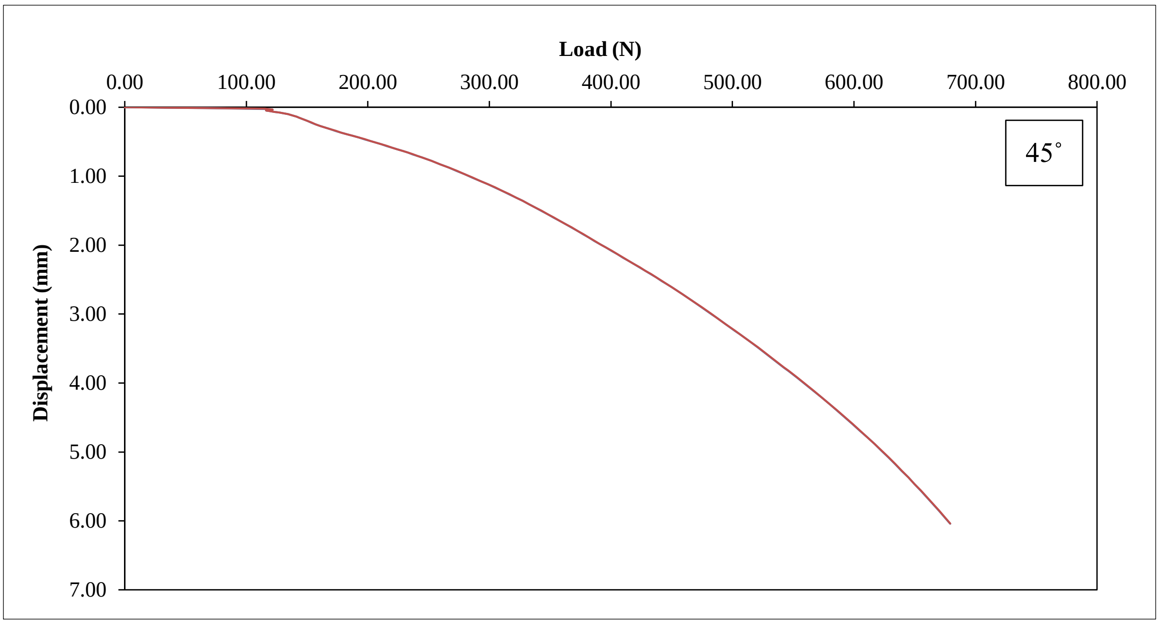
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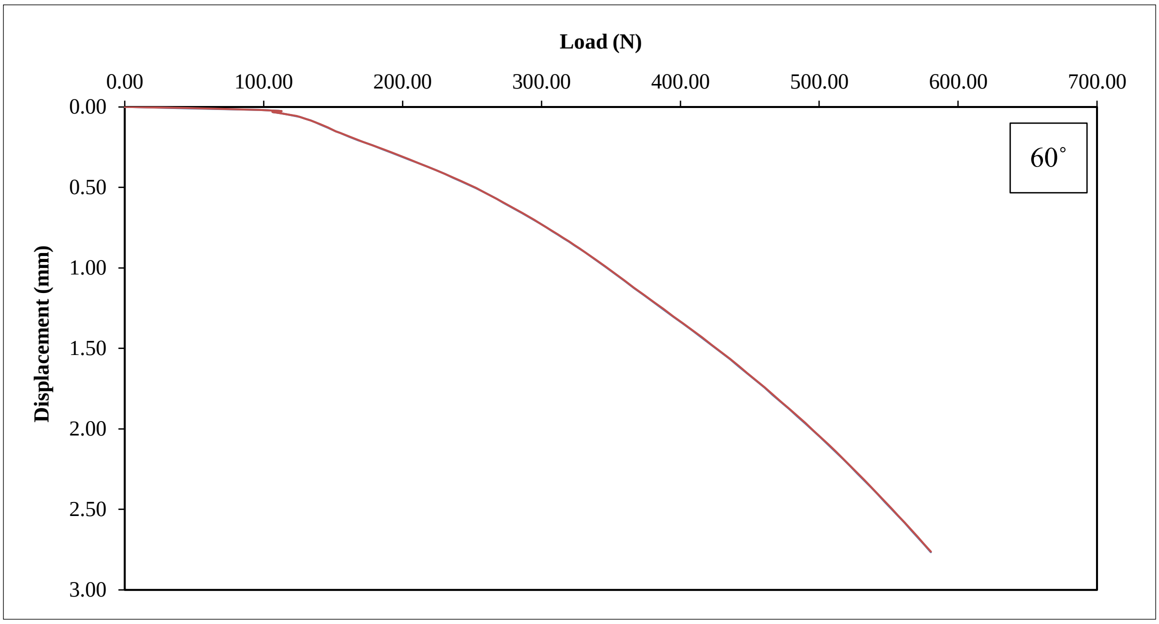
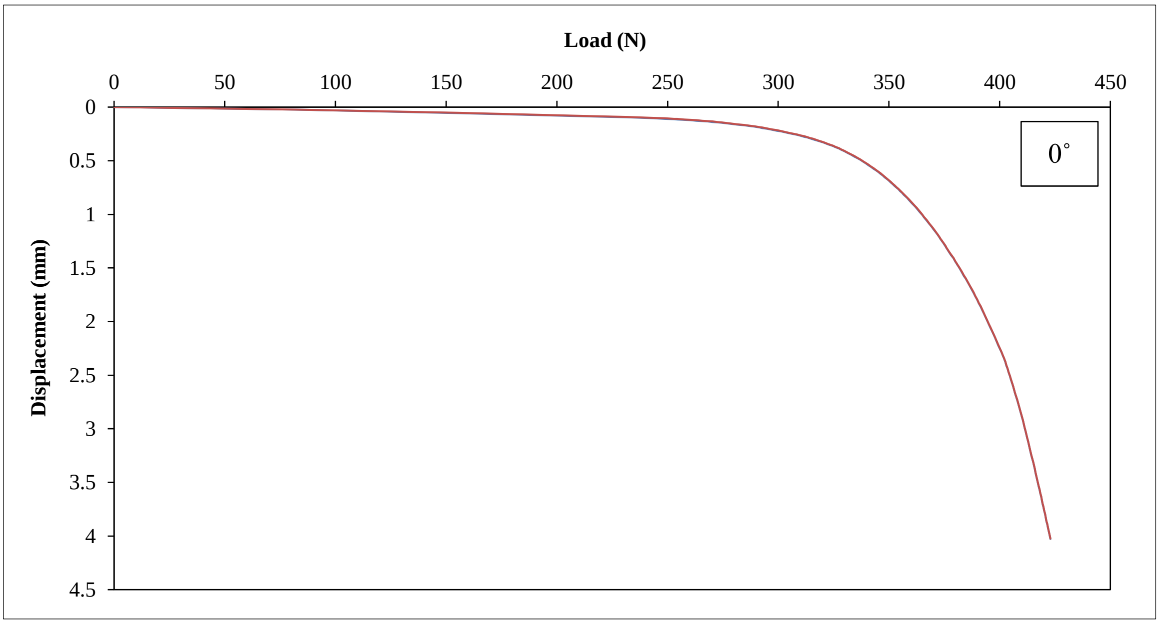


Figure 10. Vertical Load-Displacement curve of single pile under pullout loads inclined 0˚, 30˚, 45˚, 60˚ with vertical for original soil without improvement by asphalt numerically

Figure 11 illustrates load-displacement curves demonstrate the behavior of a single pile under pullout loads at inclination angles of 0°, 30°, 45°, and 60°, following numerical improvement using asphalt. At a vertical inclination of 0°, the pile exhibits a steep load-displacement curve, indicating high resistance to pullout with minimal deformation. At 60°, the load capacity shows a gradual increase with displacement, suggesting stress redistribution due to the inclined load while maintaining reasonable resistance. However, at inclination angles of 45° and 30°, there is a pronounced reduction in load capacity and an increase in displacement, with the 60° angle exhibiting the most rapid decline in load resistance. This behavior can be attributed to the amplified shear and bending stresses induced by steeper pullout angles. The asphalt improvement enhances the pile's overall performance, as reflected in the displacement characteristics, but its effectiveness diminishes with increasing inclination angles. In general, the results have the same behavior in terms of strength and a slight deviation in terms of displacement, but within the same behavior in comparison with experimental study. The numerical models predict a strength improvement between (60-90) % and a displacement reduction from 50% to 60%. These findings highlight the critical role of asphalt as a reinforcement technique and underline the necessity for optimization in pile design and treatment to ensure adequate resistance under varied pullout load conditions, particularly in scenarios involving significant lateral or inclined forces.



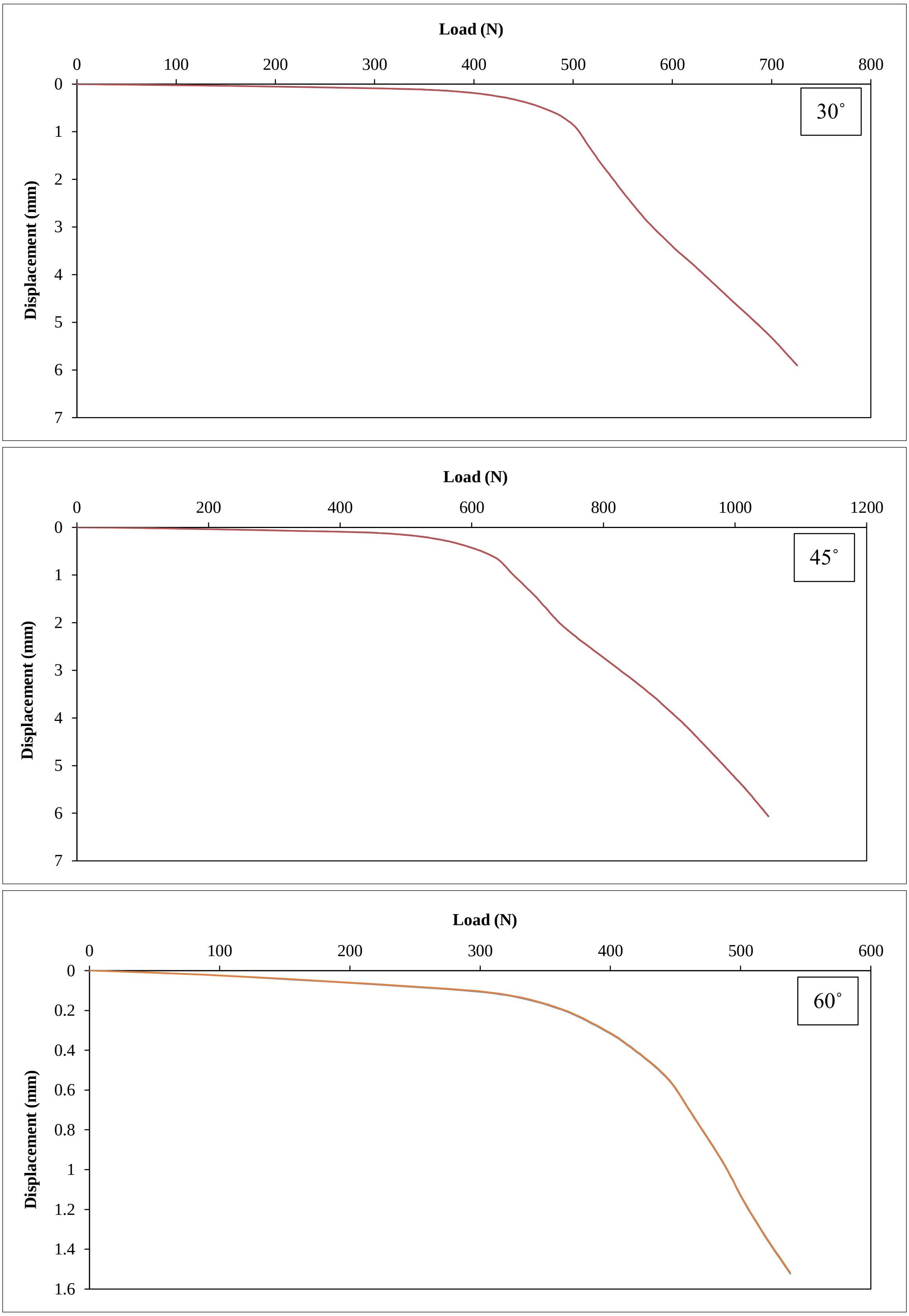
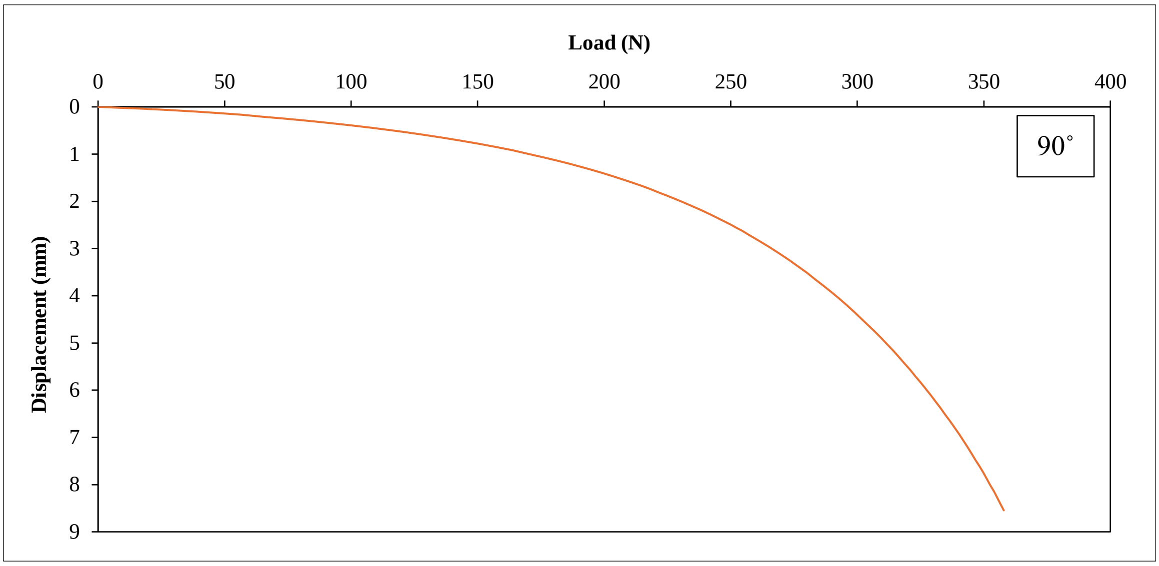
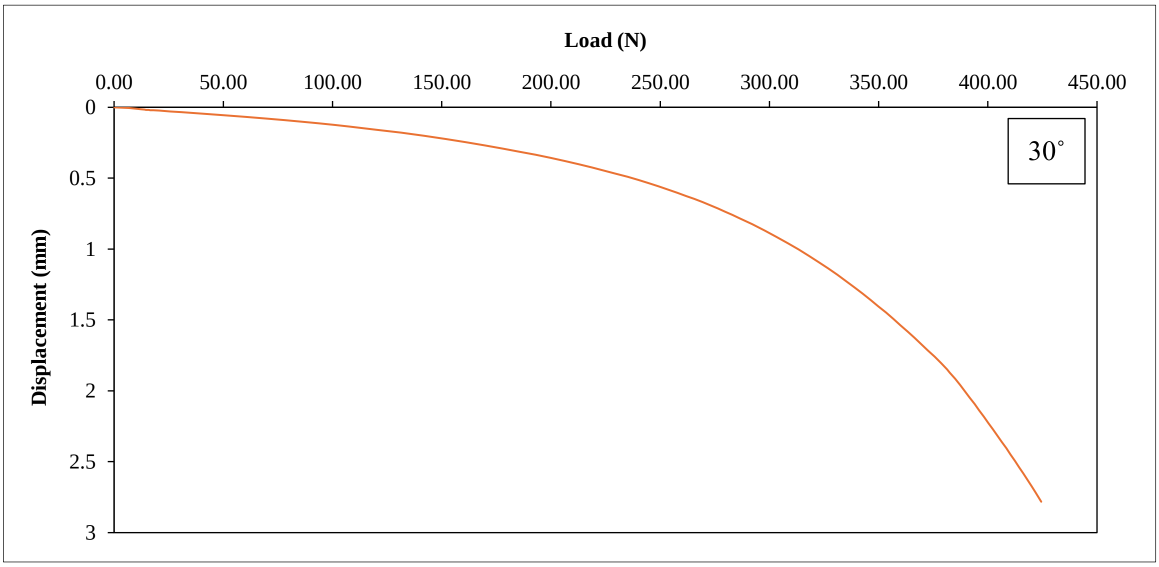
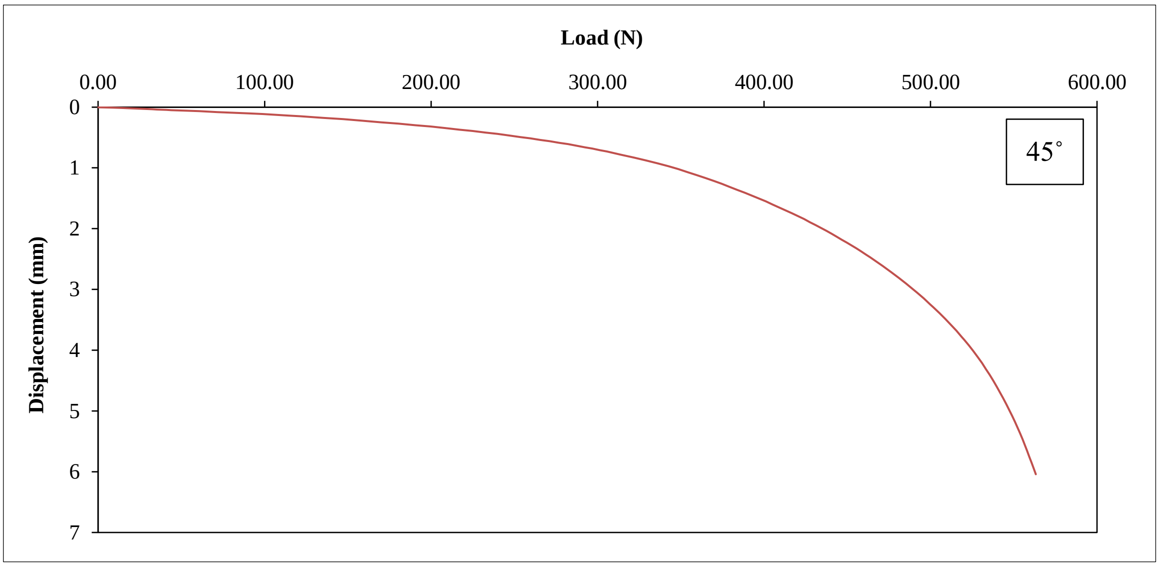


Figure 11. Vertical Load - Displacement curve of single pile under pullout loads inclined 0˚, 30˚, 45˚, 60˚ with vertical after improvement with asphalt numerically

Figure 12 illustrates load-displacement curves illustrate the performance of a single pile subjected to pullout loads inclined at 90°, 30°, 45°, and 60° relative to the horizontal plane under original soil conditions without asphalt enhancement, as evaluated numerically. For the 90° inclination, the displacement shows a significant linear increase with load application, indicating considerable deformation capacity prior to failure. At a 30° inclination, the load-displacement behavior is less pronounced, with minimal displacement, suggesting reduced deformation under lower inclination angles. At 45°, the pile exhibits a moderate increase in displacement as the load rises. For the 60° inclination, the curves indicate a sharper increase in displacement, reflecting the influence of the steeper inclination on load distribution and soil resistance. The verification showing an acceptable convergence for tests within inclined loads (45°,60°) while it`s poorly verified for (90°, 30°) loads. Theses discrepancies might be due to inhomogeneity of soil surrounding pile. These findings underscore the influence of pullout load inclination on pile performance, highlighting variations in load-bearing capacity and deformation characteristics across different angles, providing critical insights into pile behavior under horizontal pullout loads in untreated soil conditions.







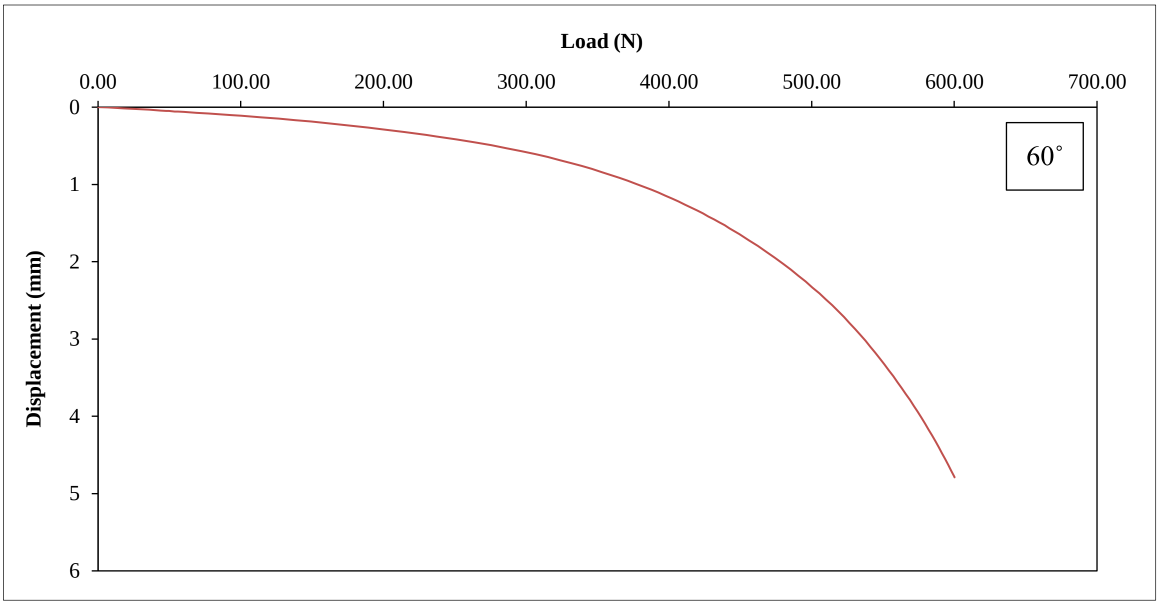
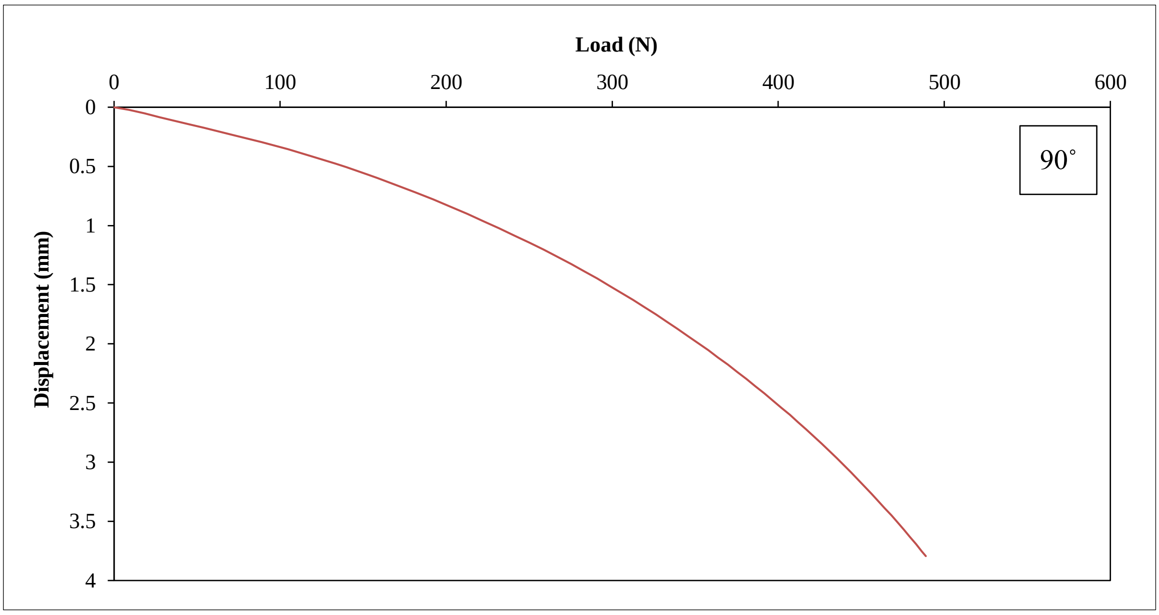


Figure 12. Horizontal Load - Displacement curve of single pile under pullout loads inclined 90˚, 30˚, 45˚, 60˚ with vertical for original soil without improvement by asphalt numerically

Figure 13 illustrates load-displacement curves the performance of a single pile subjected to pullout loads at inclinations of 90°, 30°, 45°, and 60° relative to the horizontal axis after implementing asphalt as an improvement measure, analyzed numerically. At a 90° inclination, the pile demonstrates an efficient load transfer mechanism with a gradual and consistent increase in displacement, confirming the effectiveness of asphalt in reducing displacement under vertical loads. For the 30° inclination, the load capacity increases steadily, and displacements align well with expected behavior under inclined loads, indicating enhanced load resistance. At 45°, the curve shows an increase in load with noticeable changes in displacement trends, revealing the progressive impact of the inclination on both ends of the pile. The 60° inclination curve highlights a reduced capacity for resisting pullout loads compared to lower inclinations, with the displacement becoming more pronounced. The verification diagnoses the same for natural soil subjected to the specified load inclinations. Pullout capacities showing an enhancement about (27-44) % with the displacements decreases up to 33%. Across all inclinations, the presence of asphalt contributes significantly to the stabilization of the pile, minimizing deformation and enhancing the overall pullout-bearing capacity. These findings underscore the suitability of asphalt as an improvement method for mitigating pullout displacement in inclined pile applications.



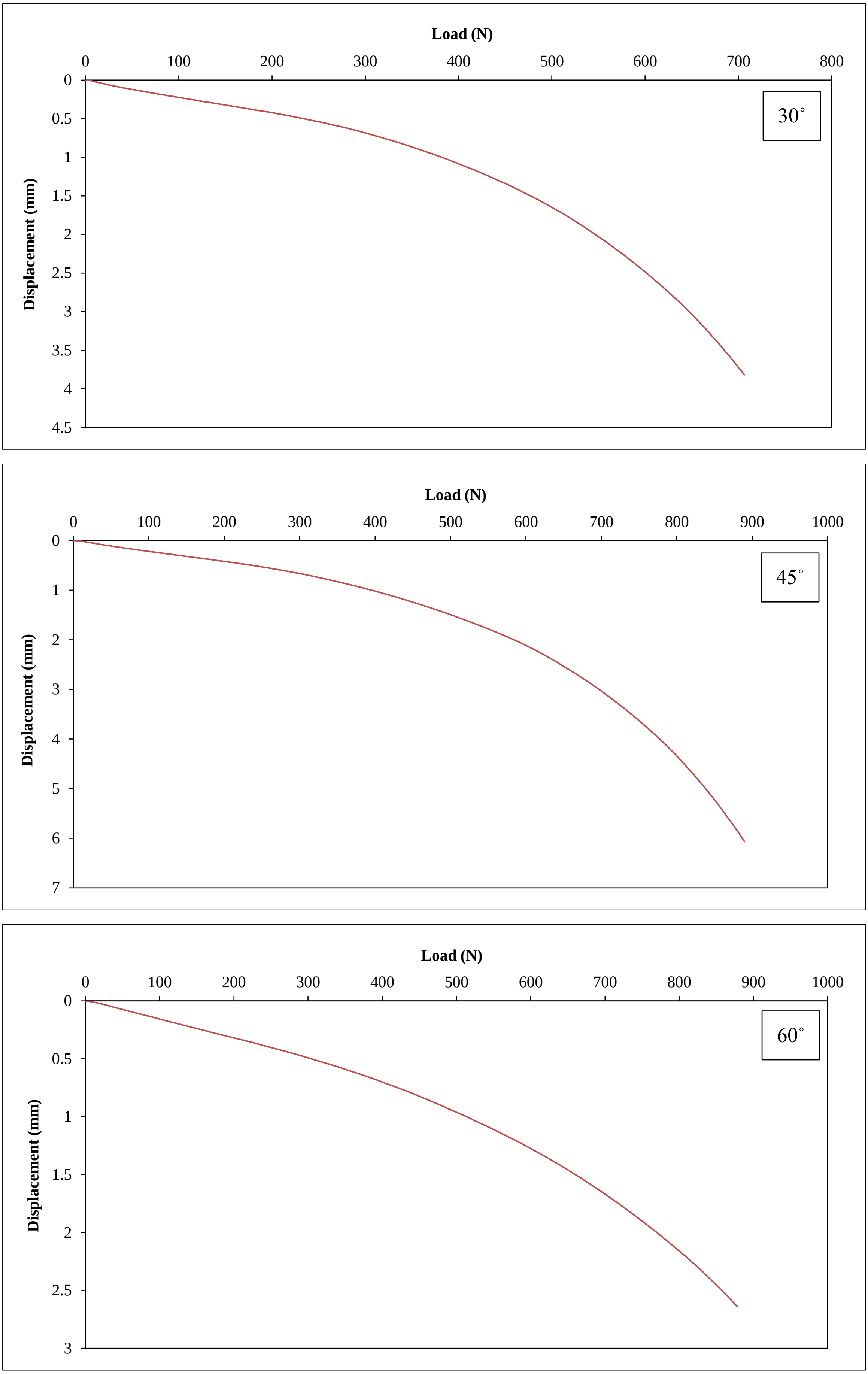
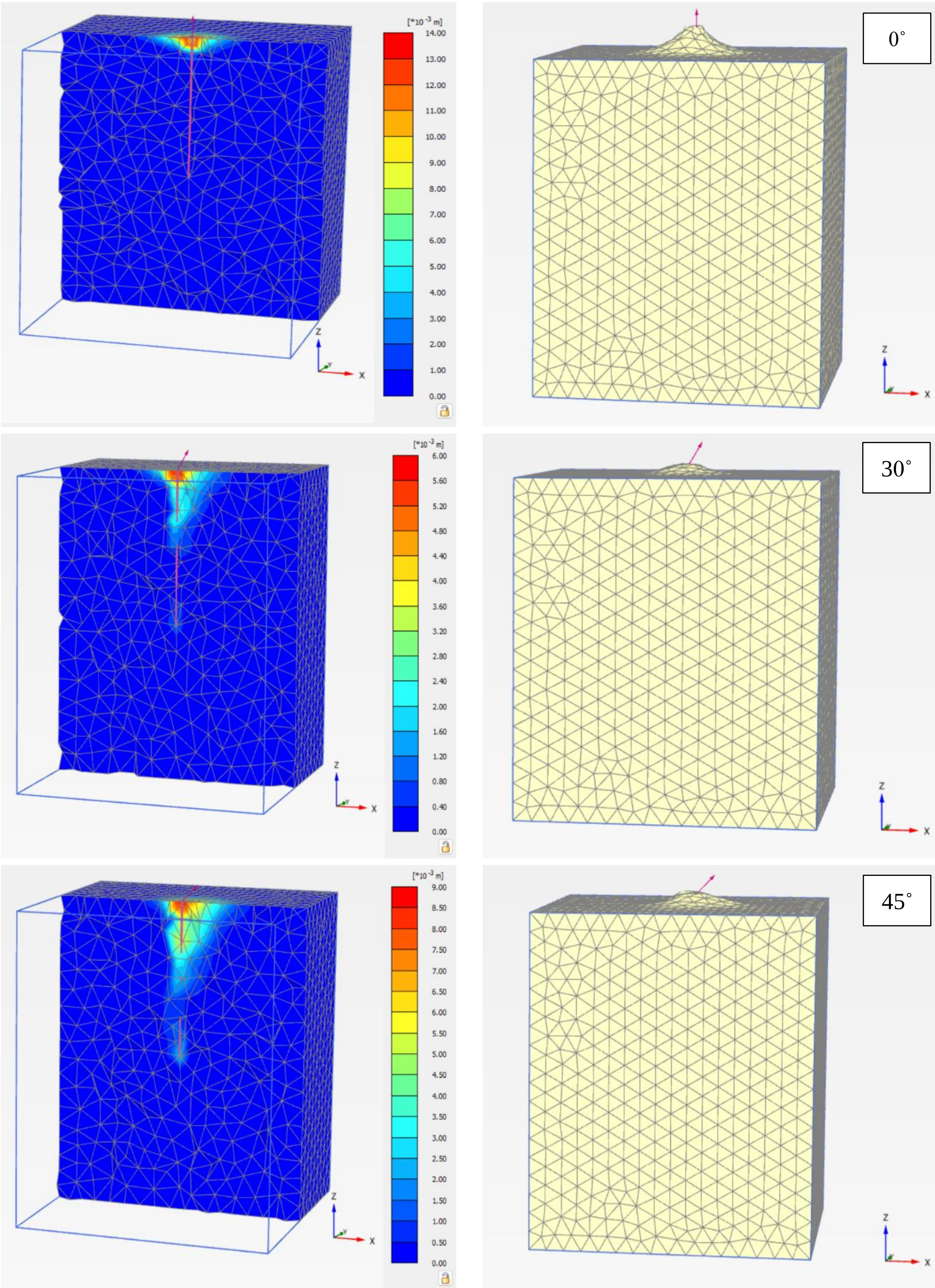


Figure 13. Horizontal Load - Displacement curve of single pile under pullout loads inclined 90˚, 30˚, 45˚, 60˚ with Vertical after improvement with asphalt numerically

Figure 14 illustrates the deformation patterns of a single pile subjected to pullout loads inclined at angles of 0°, 30°, 45°, 60°, and 90° in untreated sandy soil. Each row represents the deformation behavior corresponding to a specific load inclination angle. The left-side images display the color-coded stress distribution in the soil model using PLAXIS numerical simulation, where red zones indicate areas of maximum stress concentration and blue zones signify minimal stress. The right-side images depict the overall deformation shape of the soil and pile system. At 0° (vertical load), the stress is concentrated directly beneath the pile, indicating axial load transfer along the pile's length. As the load inclination increases (30°, 45°, and 60°), the stress distribution shifts laterally, with stress concentration zones migrating diagonally away from the pile axis, reflecting increased lateral interaction. At 90° (horizontal load), the stress zones are concentrated near the pile head, with substantial lateral displacement observed. The figures highlight the impact of load inclination on soil-pile interaction. The untreated sandy soil demonstrates significant deformation and reduced pullout resistance, especially under inclined loads, due to the soil's inherent low cohesion and permeability. This behavior underscores the challenges in designing pile foundations in loose sandy soils under varying load conditions, emphasizing the need for soil improvement techniques to enhance stability and load-bearing capacity. These visualizations provide critical insights into stress behavior and deformation mechanisms under inclined pullout loads.



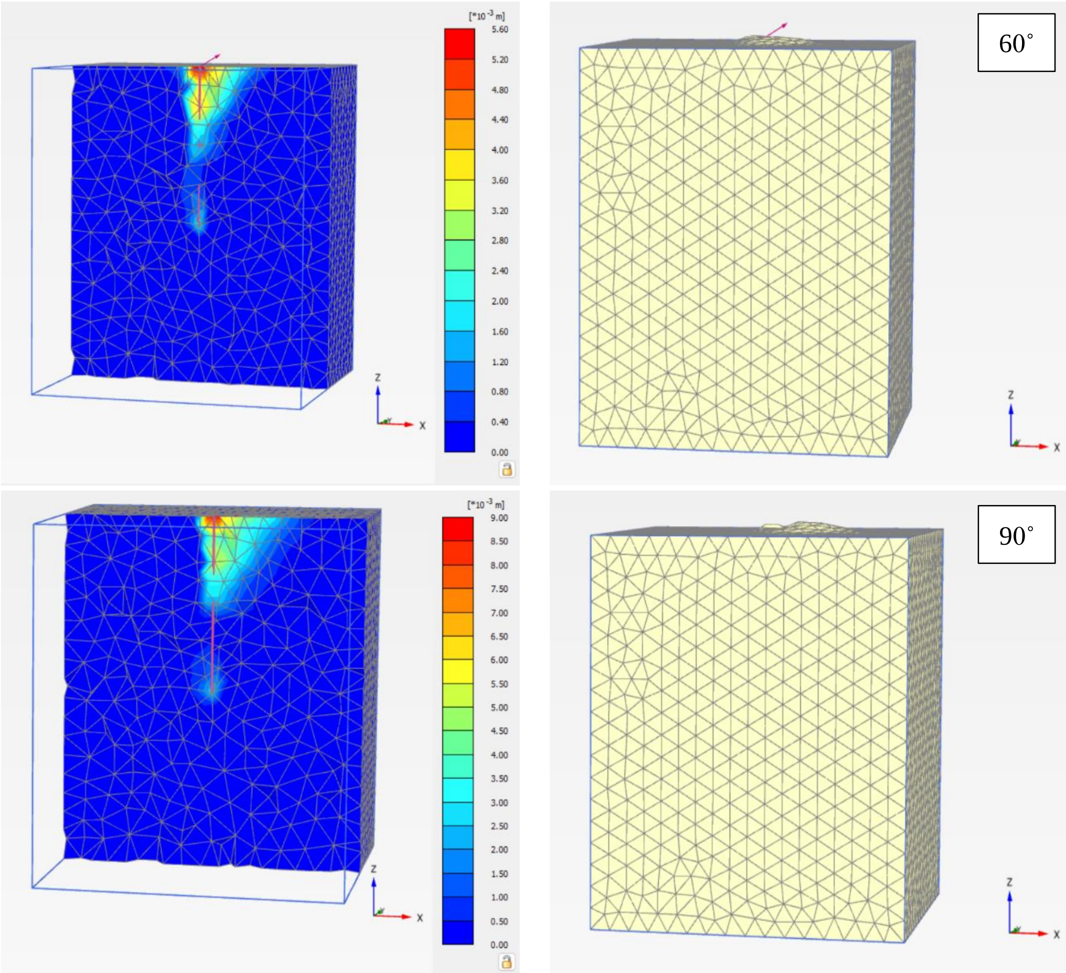
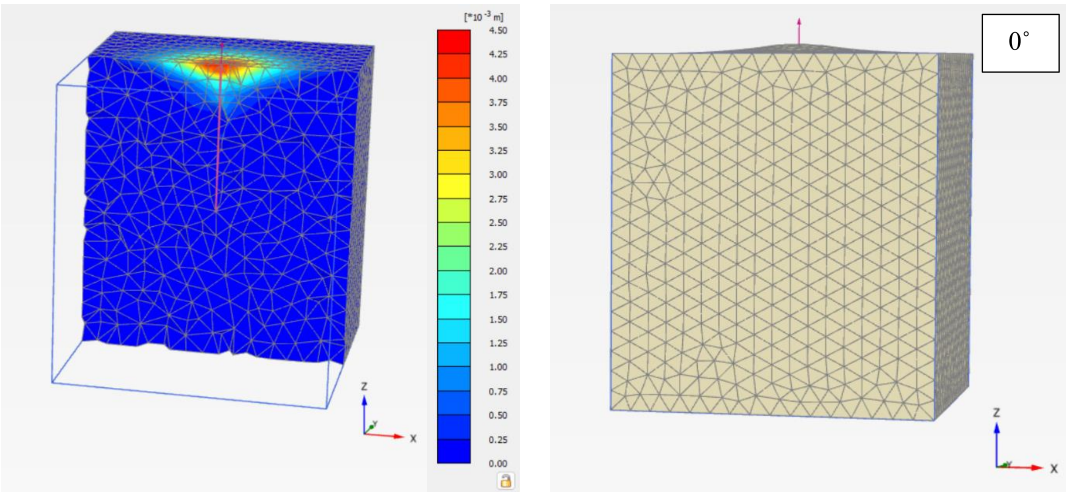


Figure 14. Deformation of single pile under pullout loads inclined 0˚, 30˚, 45˚, 60˚, 90˚ for untreated soil

Figure 15 shows a single pile deforming under pullout loads inclined at 0°, 30°, 45°, 60°, and 90° on asphalt-treated sandy soil. Contour graphs show deformation intensity from blue (minimum) to red (highest). Asphalt treatment reduces soil deformation under identical pullout loads, indicating that it enhances load-bearing ability. Asphalt improves stiffness and resistance at 0° inclination (vertical load), with a concentrated stress zone along the pile-soil contact producing little deformation. The distortion spreads farther from the pile as the inclination angle rises (30°, 45°, and 60°), showing the problems of slanted loads. The treated soil still has lesser displacement and greater resistance than untreated soil, demonstrating asphalt stabilization's improved cohesion and shear strength. Asphalt reinforces the soil against lateral stresses, since the deformation is more widespread throughout the soil matrix at 90° (horizontal pullout load) but still controllable. These findings demonstrate the necessity of soil improvement methods like asphalt stabilization in maximizing pile foundation performance under diverse loading circumstances to ensure structural stability and longevity.



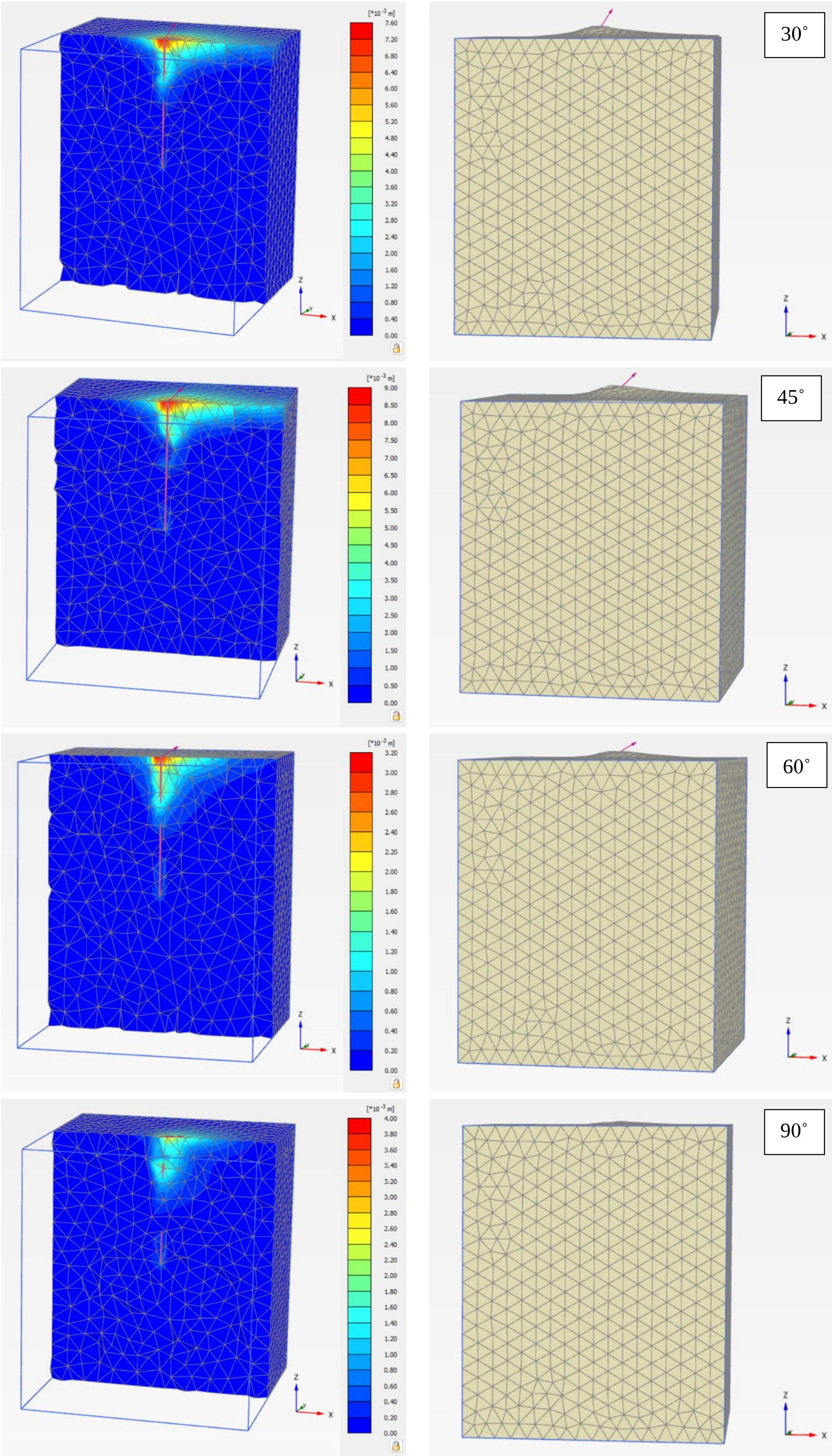


Figure 15. deformation of single pile under pullout loads inclined 0˚, 30˚, 45˚, 60˚, 90˚ for treated soil by asphalt

5. Conclusion

This study investigates the pullout resistance of single piles subjected to vertical and inclined loads in sandy soil, both untreated and stabilized with asphalt. Asphalt stabilization enhanced the pullout resistance of sandy soils by up to 90%, demonstrating its effectiveness in improving soil strength and cohesion. Experimental results showed a significant reduction in displacements across all load inclination angles, particularly under vertical loads (0°), due to improved soil-pile interaction. The asphalt-treated soil exhibited increased cohesion and shear strength, creating a cohesive matrix that improved load-bearing capacity and deformation resistance.

PLAXIS simulations confirmed the experimental findings, providing detailed insights into stress distribution and deformation patterns under different loading conditions. While some discrepancies were noted due to modeling limitations, both experimental and numerical analyses consistently demonstrated the benefits of asphalt stabilization. but the soil homogeneity factor and asphalt distribution within soil depth were significant. Asphalt stabilization reduced void ratios and increased soil stiffness, leading to enhanced load transfer and minimized deformation under inclined loads. The findings highlight the potential of asphalt-treated soils for improving foundation stability in weak sandy soils, offering practical solutions for pile-supported construction under challenging loading conditions.

The pullout capacity enhanced significantly with the inclination angle with vertical due to the formation of a bigger failure zone. Since the variation of the inclination angle from 0° to 45°, the vertical pullout capacity increased from (185, 269, and 362) N to (286, 398, and 550) N for vertical directions, respectively, and from (155, 362, and 335) N to (231, 550, and 510) for horizontal direction for inclination angles from 30° to 60°, respectively.

6. Declarations

6.1. Author Contributions

W.A. and A.A. contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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