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Pullout Response of the Pre-displacement Bladed Anchor in Cohesionless Soil

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Abstract

This study presents a new alternative technique, the pre-displacement pile, which aims to improve the uplift capacity of the regular pile. This modified pile intends to offer a bearing area underneath the sand during uplift using the blades. This method does not hinder the piles from being driven or penetrated the ground. An experimental study was conducted to investigate the uplift response of the modified anchor. The influence of the number of blades, the loading rate, and the relative density of the sand on the uplift capacity of the anchor pile with blades is studied. The ultimate pullout response of the pre-displacement anchor implanted in sand improves with an increase in blade number and loading rate. The percentage improvement in the pullout load for the anchor with four blades and a loading rate of 1 mm/s was (301%, 289%, and 249%) at sand relative densities of (30%, 50%, and 80%), respectively, compared to the unbladed pile. The existence of blades led to the creation of an ideal anchoring system. This piling modification is practical, suitable for marine projects, and easy to install for offshore applications.

Keywords Pre-displacement · Anchor · Blades · Pullout load · Break-out factor · Sand

Introduction

The pullout force applied to the foundation of various structures is resisted using anchors, a type of foundation system. The anchors allow the uplift force to be transferred to the ground at a deeper level [1, 2]. The mass of the nearby sand inside the failure zone and the resistance to shear acting on the surface of failure provide the anchors' uplift resistance [2]. Anchors are frequently employed to support structures that are subject to pulling tension, such as offshore buildings, underwater platforms, pier structures, subterranean pipelines, transmission towers, towering chimneys [1–4], and supporting solar facilities [5]. There are numerous types of anchors, including grouted anchors, mechanical anchors (for example, plate anchors, pile, drag, deadman, and helical), and combinations of these [2, 6, 7]. The embedment depth ratio, shape, and inclination of the anchor as well as the sand's properties, such as the angle of internal friction and unit weight, all have an impact on the eventual pullout force

of anchors [2, 8–11]. As a result, an extensive study was performed to investigate a methodology for altering anchors that enhances the anchor pullout load. These methods involved altering the pile geometry at a certain level or at the pile tip to increase uplift capacity. Other pile concepts, such as tapering or conical piles, have been investigated to improve the pullout load of the piles [2, 12–15]. Other modifications were also used to increase the pullout resistance of piles, such as enlarged base piles [16–18], screw piles [19–21], under-reamed piles [4, 22–24], irregularly shaped anchors [25], finned piles [3], piles with end gates [26], winged piles [1], and piles with blades [2].

Azzam and Al Mesmary [27] examined the results of increasing stress at the surface closest to the pile head as an alternate technique for enhancing the pullout resistance of monopiles. The behavior of an irregularly shaped anchor embedded in dry sand was studied by Niroumand and Kassim [25]. It was found that this anchor provided high uplift loads by increasing the embedment ratio. Azzam and Elwakil [3] investigated a finned pile anchor alteration technique that uses straight fins attached around the perimeter of the pile at the anchor end to increase the uplift capacity. Al-Suhaily et al. [26] presented an innovative approach that uses piles with two or four gates that are open-ended

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from both sides. The gates were linked at the shaft's end with hinges that allowed them to rotate 90 degrees. The pile with gates provided a good uplift response and increased the pullout capacity of piles. Sakr et al. [1] used a novel technique using wings to improve the tension load of piles. Such wings at the pile's tip improved pile behavior and increased the uplift capacity of the regular pile. An innovative plate anchor that expands its loaded area beneath the sand while lifting was proposed by Sabermahani and Nasirabadi [28]. The final pullout force was observed to increase as embedding depth increased [29], although the anchor vertical movement related to the ultimate uplift force only minimally increased. The ultimate pullout force increased, while the breakout factor decreased as the anchor width increased. The reinforcement impact of an anchored pile on uplift resistance was investigated by Jeong et al. [30]. It was found that four anchored piles had clearly greater reinforcement effects than two anchored piles, and anchored piles had fewer uplift displacements than unreinforced piles. Additionally, the reinforcement impacts in dense sand are higher than those in loose sand. Numerous studies have investigated how loading rate affects pullout capacity, and the results show that this capacity is significantly impacted. Thieken et al. [31] investigated the load-bearing behavior of suction buckets under variable pull-out rates. It has been demonstrated that a high pull-out rate causes a significant increase in tensile force. The impact of loading rate on the vertical pullout load of off-shore bucket foundations in sand was examined by Vincent et al. [32]. It was noticed that with increasing loading rates, suction pressure developed and significantly contributed to the uplift capacity. Ayyılmaz et al. [33] investigated the tensile capacity of suction buckets under various loading rates in dense sand. It was found that during lifting, the suction develops inside the bucket, and its rate increases as the loading rate also increases. Additionally, the tensile strength and suction increase according to the pullout rate.

Various researchers have employed a variety of methods to increase the uplift resistance of anchors. These systems are expensive, difficult to use, and considerably constrained by the site's conditions [2]. This new system contributed to overcoming some challenges with traditional systems as plate anchors that require a large amount of excavation prior to installation, as well as the difficulty of constructing under hard site conditions, such as in the case of marine structures.

Based on previous studies, the pre-displacement bladed pile is a new technique that aims to offer a bearing area underneath the sand during uplift using the blades without excavation. The proposed pre-displacement bladed piles can penetrate the ground by utilizing a vibratory hammer or driving the anchor into the sand. The main objective of this paper was to evaluate the effectiveness of blades for improving the uplift capacity of the regular pile in sand. The driving or penetration of the bladed piles into the ground is

not dissenting with this modified technique. It is simple and quick to install into the ground and can be suitable for off-shore and marine structures. In addition, geotechnical engineers may use the study's findings to improve their assessment of uplift capacity in future designs.
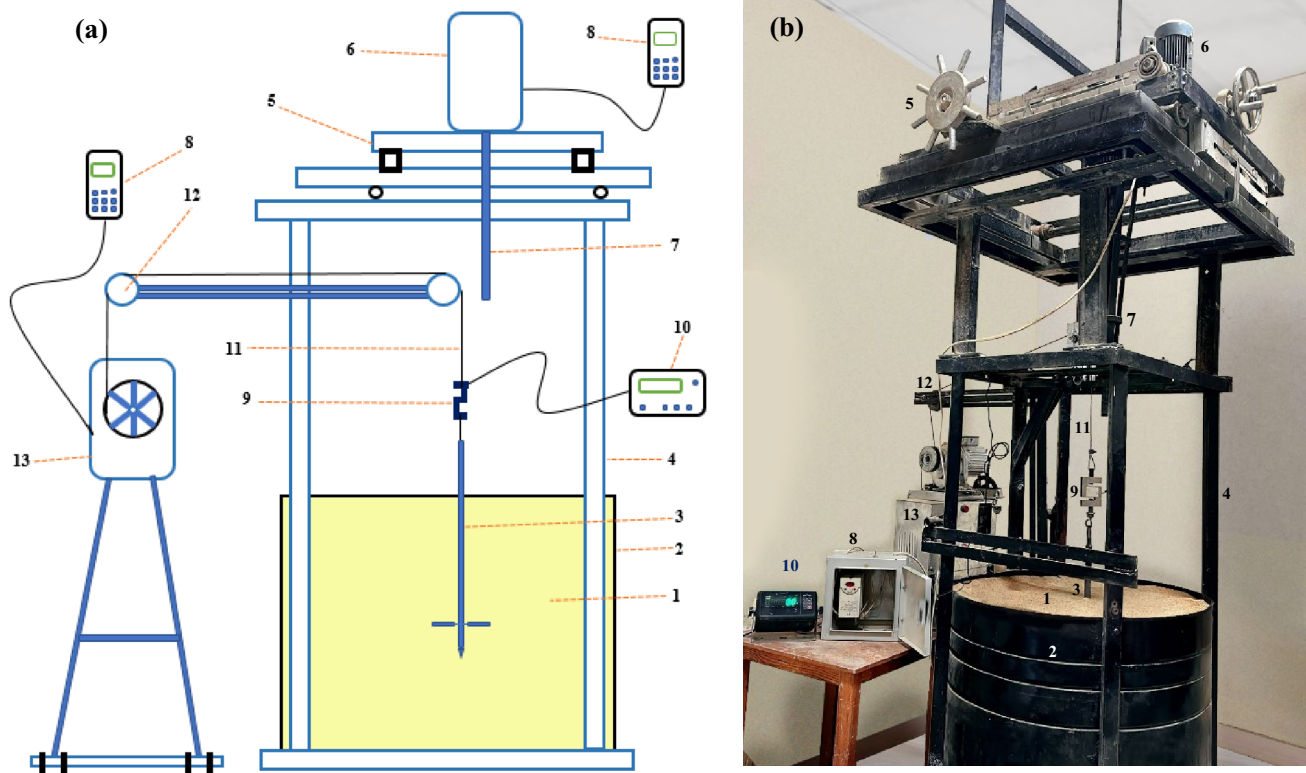
Work Experimental Setup

Test Tank

The test setup involved a sand container, motor winch, movable cart, loading system, and model pre-displacement pile, as presented in Fig. 1. A steel cylinder-shaped container was constructed, measuring 1000 mm in height and 950 mm in diameter. The thickness of the side walls was 3mm. The size of the soil container was determined in order to keep the zone of failure around the model anchor from reaching the side walls [1, 2]. The tank wall was strengthened using vertical frames [1, 2, 34], enhancing its durability and avoiding lateral wall distortion [35]. A spirit level was utilized to check the horizontality and verticality levels of the model test setup [2]. The movement in the x and y tracks is made possible by a mobile cart that is linked to the top of the vertical frame. The motor in the mobile cart produces rotating force, which is converted into linear motion and used to push the pile into the sand. An electric converter managed the pushing pace while the piles were being installed. A smooth pulley system connected the loadcell and the model anchor pile to a motor winch and a pulling rope. The lifting force for the model pile was applied using a motorized winch [2, 25]. During lifting, the loading rate on the wire ranged from 0.5 to 1.0 mm/s. During the tests, an electric inverter was used to regulate the elevating rate. The applied uplift force was measured in the lab using a loadcell with a 20 kN capacity.

Model Pre-displacement Bladed Pile

The pre-displacement anchor pile is composed of a cylindrical shaft, movable blades, and a hinge, as seen in Fig. 2. The cylindrical shaft was 1000 mm in height and had a 25 mm stem diameter (d_p). The movable blades confine the circumference of a cylindrical pile shaft as a part of a pipe with outer and inner diameters of 35 and 25 mm, respectively. The model pre-displacement anchor before and after opening the blades is displayed in Fig. 3. In the studies, the embedment depth was 32 times the pile diameter, the blade length-to-pile diameter ratio was 2, and the blade angle (θ) was 90°. The blades and pile shaft were attached by a hinge system, which made it simple for the blades to rotate and reach the permitted blade angle (θ). In the case of two blades, the blades were placed three times the pile diameter away from the pile end, while in the case of four blades, two blades

1. Sandy soil, 2. Soil tank, 3. Bladed pile anchor, 4. Vertical frame, 5. Movable cart,
6. Motor, 7. pushing down arm, 8. Inverter, 9. Loadcell, 10. Load read out unit,
11. Cable, 12. Pulley, 13. Motor winch.

Fig. 1 The experimental work setup: **a** schematic diagram; **b** physical diagram

were placed three times the pile diameter away from the pile end, and the other two blades were placed seven times the pile diameter away, as presented in Fig. 4. The edges of the blades were sloped inward, and as a result, the sand over the sloped edges aided in rotating the blade easily with the upward movement. The blades may be opened and closed by moving the anchor axially up and down; therefore, the model pile is able to be installed by pushing it axially into the ground or utilizing a vibratory hammer. The substantial benefit of this modification pile is that it creates a bearing area underneath the soil, adding weight and increasing the uplift force.

Sand Properties

The results of the sieving method used to determine the grain size distribution curve for the used sand are displayed in Fig. 5. The sand used in these lab tests was categorized as poorly graded sand (SP). The tested sand has rounder grains [36], which, in accordance with [1, 2], minimize friction between the container edges and the sand. The specific gravity (G_s) of the used sand was obtained utilizing the jar technique [1, 2]. The average specific gravity throughout the three tests was 2.63. Maximum and minimum densities were 18.82 and 15.62 kN/m^3, and the maximum and minimum void ratios were accordingly 0.695 and 0.39. Tests were performed at three relative densities: $D_r = 30\%$, 50%, and 80%. Three densities of the used sand were attained in the sand container: 16.4, 17.05, and 18.13 kN/m^3 at D_r of (30%, 50%, and 80%). The angle of internal friction for the used sand was obtained using the direct shear test. At D_r of (30%, 50%, and 80%), respectively, the internal friction angles (φ) were (31.8°, 35.2°, and 38.9°). Table 1 lists the characteristics of the tested sand.

Preparation of Tested Sand Bed

An experimental study program was carried out to investigate the performance of the pre-displacement anchor when it was subjected to lifting forces in sand with various densities. A layer with an average depth of 100 mm was filled with a predetermined weight to achieve the appropriate relative

Fig. 2 The components of the pre-displacement anchor

densities [2, 4, 37]. A 30 N, 150 mm-diameter hammer was utilized to compact each layer after leveling sand until it reached the top of the container [3, 4]. Utilizing small, known-sized cans that were positioned at various positions in the sand container to measure the requisite sand densities

that were achieved during tests [2]. The relative densities of the tested sand that were determined by small containers were in the range of $D_r = 30 \pm 1.8\%$ for loose sand, $D_r = 50 \pm 1.5\%$ for medium-dense sand, and $D_r = 80 \pm 1.3\%$ for dense sand [2, 38]. According to Sakr et al. [1] the sand bed height was chosen to guarantee that the sand strata extend below the anchor pile for at least 100 mm.

Test Installation Procedures and Parameters

The Installation Procedures

The cylindrical container was filled with the tested soil. Two rulers placed on a movable cart that pointed in the X and Y tracks were utilized to position the anchor at the container center. The pile rod was connected to an engine that could provide linear progress, and this system was utilized for pushing the pile into the ground at a constant rate [39] of one hundred millimeters per minute until achieving the predetermined embedment depth. Before entry into the sand layers, throughout penetration, and before lifting, the blades were closed. A motor winch was used to generate a lifting rate throughout the uplifting process [2, 28, 29]. The blade edges' slopes facilitate their rotating and opening during lifting. The anchor pile is lifted during the experiments to pre-displacement (S_o) which permits the blade to rotate and open. The pre-displacement (S_o) influenced by manifold factors such as blade dimension, embedment depth, relative density, and loading rate. After acquiring the required

Fig. 3 The pre-displacement anchor: **a** before lifting; **b** after lifting
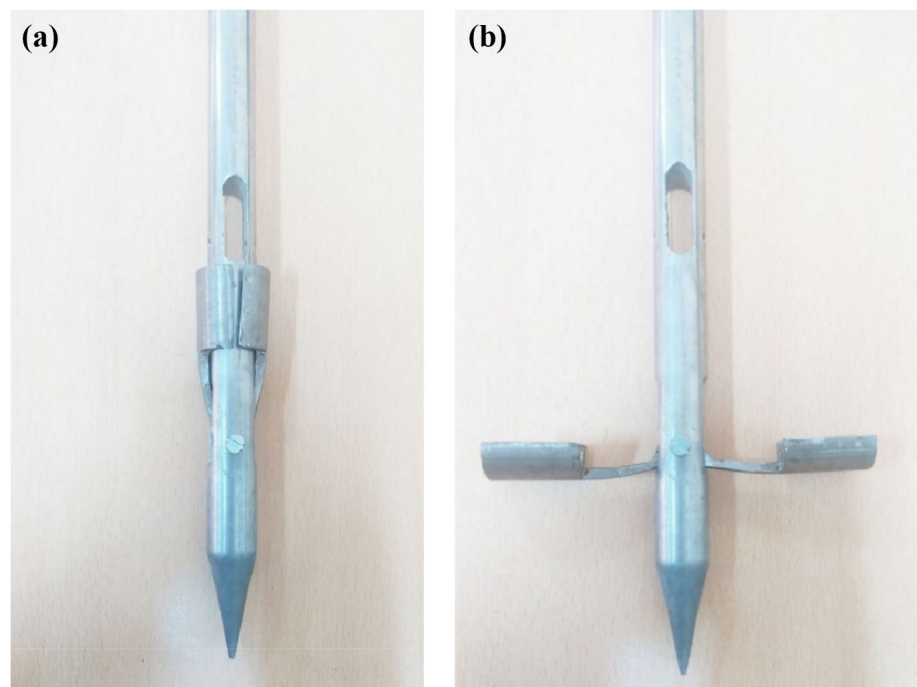
Fig. 4 The pre-displacement anchor: **a** two blades; **b** four blades
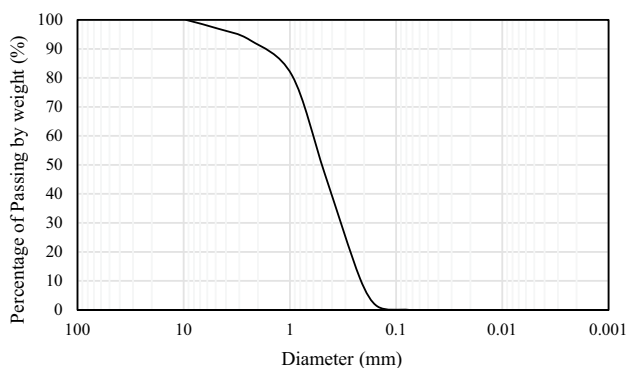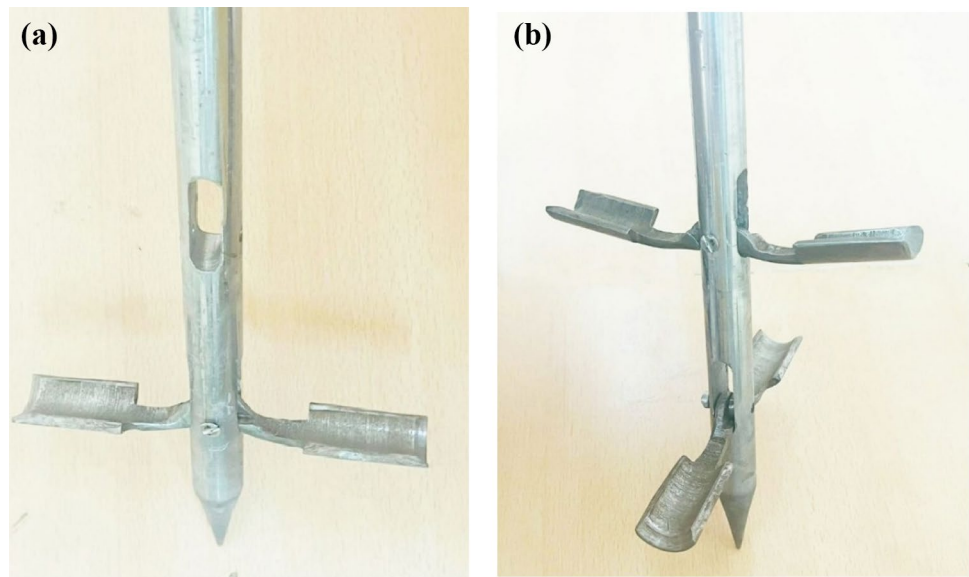
Fig. 5 Grain size distribution of the used sand

Table 1 Sand properties

Property	Value
Specific gravity, G_s	2.63
Effective size, D_{10}	0.21 mm
Coefficient of curvature, C_c	0.786
Uniformity coefficient, C_u	3.33
Maximum unit weight, $\gamma_{d\,max}$	18.92 kN/m³
Minimum unit weight, $\gamma_{d\,min}$	15.52 kN/m³
Maximum void ratio, e_{max}	0.695
Minimum void ratio, e_{min}	0.39
Maximum angle of internal friction, φ_{max}	41.8°
Minimum angle of internal friction, φ_{min}	31°

pre-displacement (S_o), the blades become active and work to resist the pullout force. The lifting persisted until the anchors were pulled from the sand strata. Figure 6 shows the installation process of a pre-displacement anchor pile.

Testing Strategy

The experiments were carried out to investigate the response of the pre-displacement anchor to resist lifting loads in sand. The laboratory experiments were performed on pre-displacement anchors embedded in sand at different numbers of blades (N_b), various loading rates (L_R), and diversified relative densities (D_r). The model pre-displacement bladed pile with the studied parameters is shown in Fig. 7. The tests were conducted in a sand bed with three conditions: $D_r = 30\%$ for loose sand, $D_r = 60\%$ for medium-dense sand, and $D_r = 80\%$ dense sand. The pre-displacement anchor with two and four blades was studied. The examined values of the loading rate (L_R) were 0.5, 1.0, and 2, as presented in Table 2. During experiments, the blade length to pile diameter was 2, the embedment depth to pile diameter was 32, and the blade angle was 90°. To determine how blades can impact the ultimate uplift load, experiments were conducted on unbladed piles.

Results and Discussion

Load Settlement Curves

The modified pile behavior can be evaluated with the aid of the experiment findings obtained from the load-vertical movement relationships for various numbers of blades (N_b) and diversified loading rates (L_R) for sand with varied D_r values. The test findings generally follow the same pattern for uplift force vs. vertical movement. Figure 8 presents the general uplift force-vertical movement response for the pre-displacement bladed anchor pile. The uplift load-vertical movement curves for modified anchors can
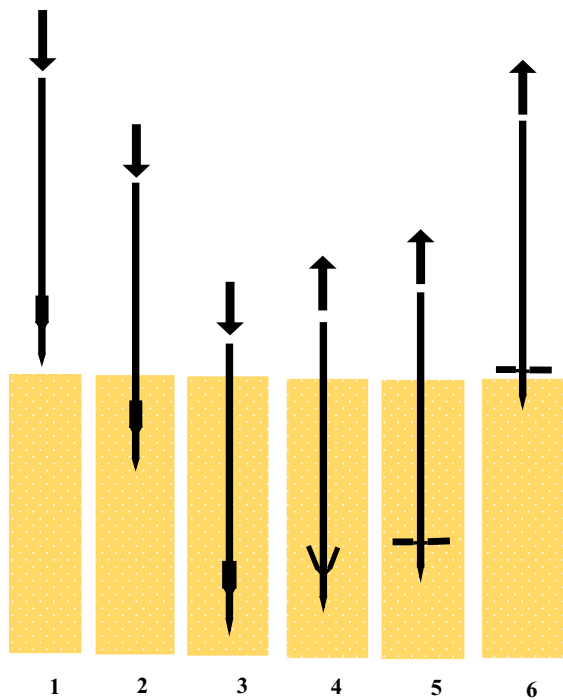
1. Positioning the anchor in the center.

2. Pushing the anchor into the soil strata.

3. Reaching the required embedment depth.

4. Lifting the anchor and opening the blades.

5. Achieving the pre-displacement (S_o) and activating the blades.

6. Lifting continued until the anchor was pulled from the soil strata.

Fig. 6 The installation procedures for pre-displacement bladed pile

Fig. 7 The model pre-displacement bladed pile

be partitioned into four stages during lifting, corresponding to the blade angle (θ) during lifting. In the first stage (from node I until node II), the friction resistance is axially rallied sideways, and the blades are still closed. The blade started to rotate at point II of the second stage (from node II to node III), and by the time it reached node III, it had rotated and reached a blade angle of 90°. In the third stage (from node III to node IV), the lifting resistance increased rapidly as the displacement increased, reaching an ultimate lifting load value (P_u) at node IV. The fourth stage, the failure stage, from node IV to node V, saw a sharp decline in the uplift load as the displacement increased. The findings of Sabermahani and Nasirabadi [28] and Aamer et al. [2] confirm this observation. These stages depend on blade size, embedment depth, blade angle, sand relative density, and loading rate. The ultimate pullout force of the pre-displacement anchor pile is at the point where the curve shows a maximum load value [2].
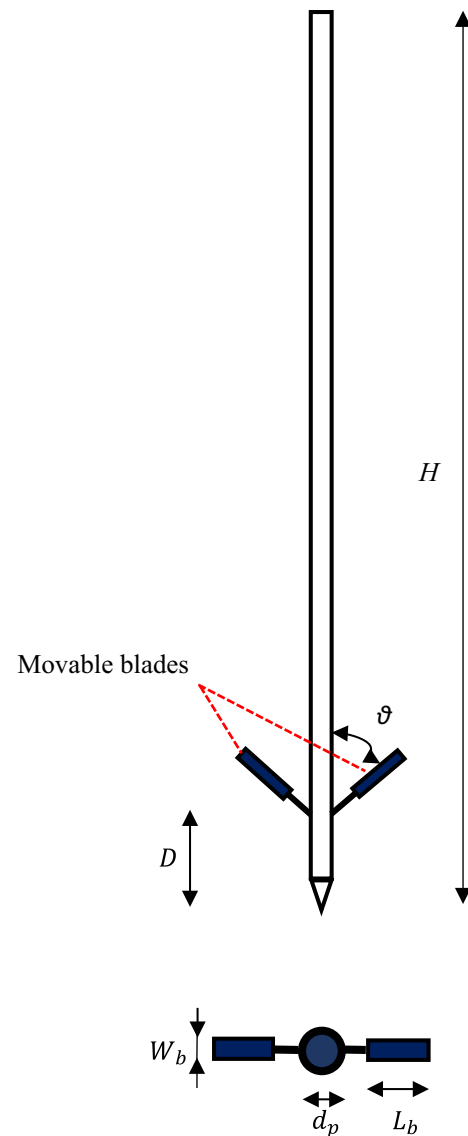
The existence of blades significantly modifies and enhances the load-vertical movement response of the pre-displacement anchor and increases the lifting capacity in accordance with relative density, number of blades (N_b), and loading rate (L_R).

The pullout load-upward movement curves for the pre-displacement anchors with various numbers of blades (N_b) and a constant loading rate (L_R) of 1.0 mm/s at diversified relative densities are shown in Fig. 9. In all cases of D_r, the pullout loads for the bladed anchors with 2 and 4 blades are greater than those for non-blades. The pullout displacements of the bladed anchors are greater than those of the unbladed piles. The corresponding ultimate uplift loads for anchor bladed piles were (90.5, 259, and 362.7 N) for D_r of 30%, (221.4, 662.4, and 861 N) for D_r of 50%, and (326, 881,

**Table 2** Experimental investigation program

Series	Relative density, D_r (%)	No. of blades, N_b	Loading rate, L_R (mm/s)	Blade width ratio, W_b/d_p	Opening of the blades
S1	30%	0, 2, 4	1	$\pi/3$	Self-opening
S2	50%	0, 2, 4	1	$\pi/3$	Self-opening
S3	80%	0, 2, 4	1	$\pi/3$	Self-opening
S4	30%	2	0.5, 1, 2	$\pi/2$	Self-opening
S5	50%	2	0.5, 1, 2	$\pi/2$	Self-opening
S6	80%	2	0.5, 1, 2	$\pi/2$	Self-opening
S7	30%	2	1	$\pi/2$	Self-opening, pre-opening
S8	30%	2	1	$\pi/2$	Self-opening, pre-opening
S9	30%	2	1	$\pi/2$	Self-opening, pre-opening
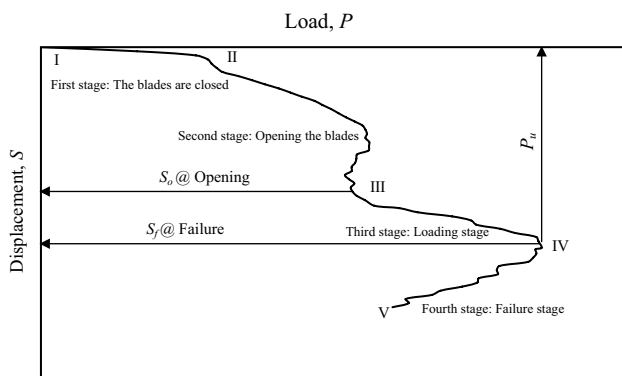
Fig. 8 The load-vertical movement response of the pre-displacement anchor pile

and 1140.2 N) for D_r of 80% at number of blades (N_b) of (0, 2, and 4), respectively. Whereas the upward movement values that corresponded to the maximum uplift loads of anchor piles were (9, 292, and 301 mm) for D_r of 30%, (16, 232, and 241 mm) for D_r of 50%, and (18, 212, and 249 mm) for D_r of 80% at the number of blades (N_b) of (0, 2, and 4), respectively. It is observed that the pullout capacity of the pre-displacement anchor improves as the number of blades (N_b) increases [26, 30]. It is noted that as the number of blades (N_b) increases, the vertical displacement at the pullout capacity also increases. This behavior can be observed for diversified relative densities (D_r). According to Fig. 9, the pullout force increases as D_r increases. Whereas the vertical displacement at the pullout capacity decreases as the relative density increases. It should be noticed that the opening of the blades significantly increases the lifting capacity. This is because there is more sand added to resist the pullout load by creating a bearing area beneath the surrounding sand. The uplift capacity consequently increased, which is consistent with the findings of the studies carried out by Al-Suhaily et al. [26]. The response of the anchor pile to uplift loads can be enhanced by using two or four blades at a certain depth.

The pullout load against vertical movement relationships for anchor piles with two blades at diverse loading rates (L_R) and various relative densities are illustrated in Fig. 10. The ultimate pullout capacities for pre-displacement bladed piles were (266.7, 299.8, and 330.7 N) for $D_r = 30\%$, (625.7, 683.2, and 765.5 N) for $D_r = 50\%$, and (807.3, 950, and 1030.7 N) for $D_r = 80\%$ at loading rates (L_R) of (0.5, 1.0, and 2.0 mm/s), respectively. It is seen that the pullout force of the pre-displacement anchor increases as the loading rate increases. It was observed that the upward displacement values corresponding to the ultimate pullout loads of the modified anchors were around (299, 303, and 316 mm) for $D_r = 30\%$, (232, 243, and 251 mm) for $D_r = 50\%$, and (224, 228, and 237 mm) for $D_r = 80\%$ at loading rates (L_R) of (0.5, 1.0, and 2.0 mm/s), respectively. It can be noticed that the upward movement corresponding to P_u increases as the loading rate (L_R) increases. All results for various loading rates show the same behavior. It should be stated that the loading rate has a significant impact on the ultimate pullout load of a bladed anchor pile. It can be observed that increasing the uplifting rate significantly increases the uplift capacity [31–33] of the pre-displacement anchor pile.

The lifting load against vertical movement relationships for pre-displacement anchor piles with two blades in the cases of self-opening and pre-opening with a constant loading rate of 1.0 mm/s at various relative densities are illustrated in Fig. 11. While the expression "pre-opening" refers to the anchor that was already set open, the term "self-opening" refers to the blades that were installed closed and opened themselves during lifting. The ultimate pullout capacities for the pre-displacement anchor piles were about (299.8 and 577 N) for $D_r = 30\%$, (683.2 and 1364 N) for $D_r = 50\%$, and (950 and 1746 N) for $D_r = 80\%$ in the cases of self-opening and pre-opening, respectively. It is noted that the pullout force of the bladed pile in the case of self-opening was greater than that in the case of pre-opening. It was observed that the upward movement values corresponding to the ultimate pullout loads of the bladed piles were (303 and 86 mm) for $D_r = 30\%$, (243 and 95 mm) for

a) $D_r = 30\%$.

b) $D_r = 50\%$.

c) $D_r = 80\%$.
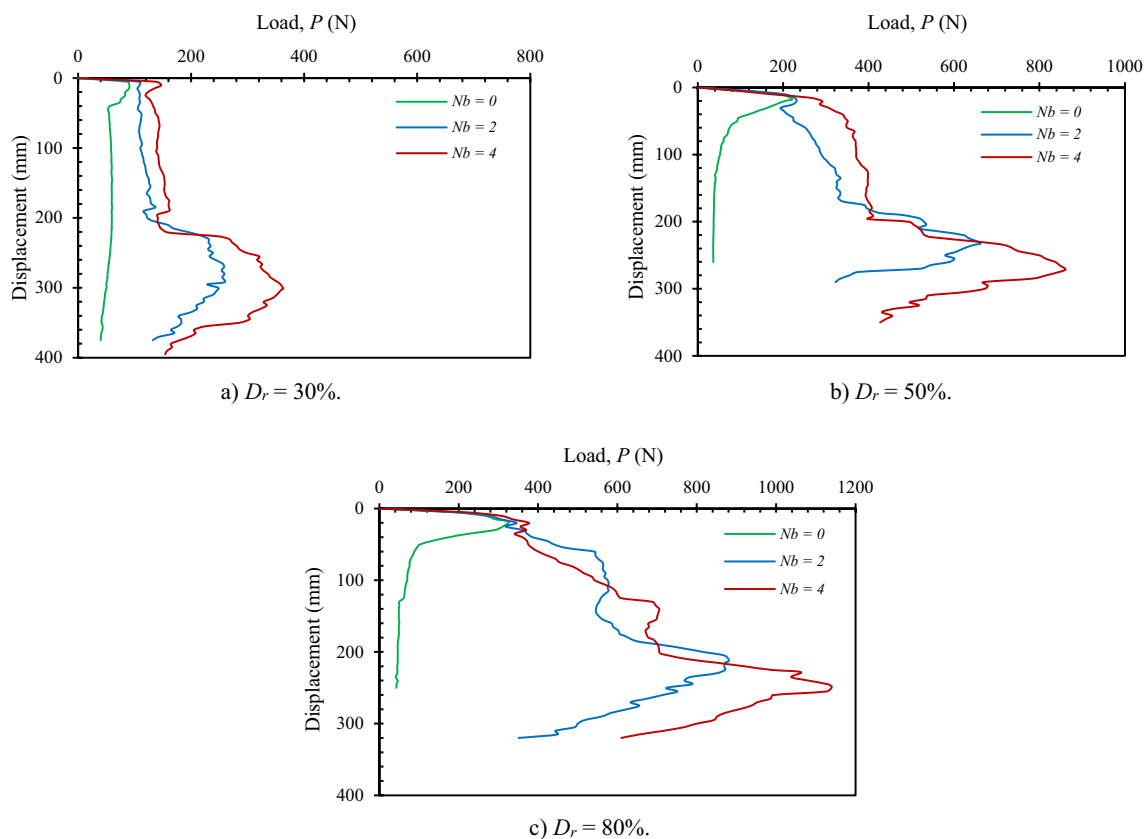
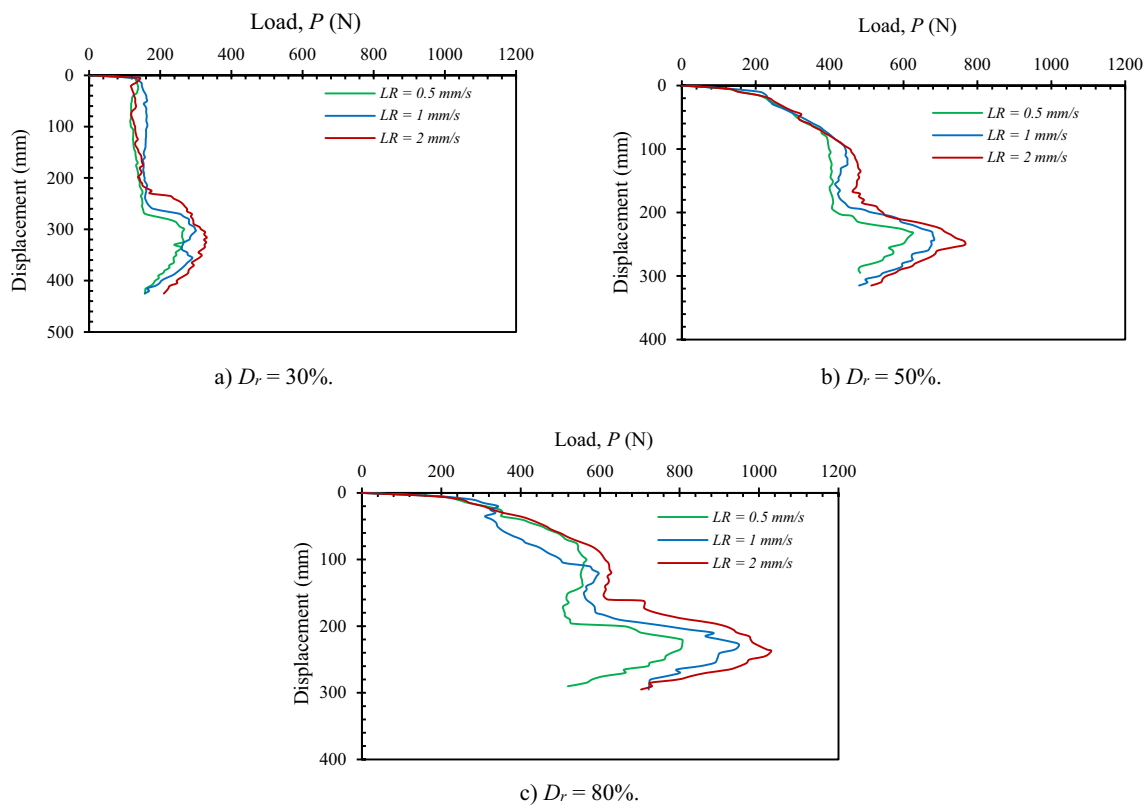**Fig. 9** Variation of load with upward movement for various N_b; $L_R = 1.0$ mm/s

$D_r = 50\%$, and (228 and 99 mm) for $D_r = 80\%$ in the cases of self-opening and pre-opening, respectively. It can be noticed that the upward movement corresponding to P_u in the case of pre-opening is smaller than that of self-opening. It is noted that there is a loss in the uplift load due to the self-opening of the blades.

Influence of Number of Blades (N_b)

The impact of the number of blades (N_b) on the anchor lifting capacity of an anchored pile at diverse relative densities was studied. Figure 12 shows the variation of the ultimate uplift load of anchor piles with the number of blades and a constant loading rate (L_R) at diverse D_r values. The existence of blades enhances the pullout response of the pre-displacement anchor when compared to an unbladed pile for the same D_r value. In all cases, the pullout force increases as the value of D_r increases. The improvement in the pullout force was about (168% and 301%) for $D_r = 30\%$, (199% and 289%) for $D_r = 50\%$, and (170%, and 249%) for $D_r = 80\%$ for anchors with 2 and 4 blades, respectively, compared with a regular pile without blades. It has been found that increasing the number of blades increases the percentage improvement in the ultimate pullout force. Figure 12 shows

that, as compared to an ordinary unbladed pile, in the case of an anchor with four blades, the impact for $D_r = 30\%$ is more effective than those for $D_r = 50\%$ and 80%. In the case of an anchor with two blades, the influence in the cases of $D_r = 30\%$ and 80% is less than that of $D_r = 50\%$ in comparison to an unbladed pile. The primary objective of utilizing the blades is to provide a bearing surface under the sand. It is concluded that a superior enhancement may be achieved by using the blades. It may be clarified by the fact that, by using the blades, more sand can be added over the blades to resist the lifting force. It is a fact that as the number of blades increases, more sand mass is added to resist the lifting force. It is noted that as the relative density increases, the mass of the nearby sand inside the failure zone and the resistance to shear acting on the surface of the failure increase, which increases the uplift capacity. Figure 13 offers the value of normalized movement corresponding to the ultimate pullout force (S_f/d_p) with the number of blades (N_b) at diverse D_r values. It is seen that as the number of blades (N_b) increases, the ratio of S_f/d_p increases. It can be found that at the number of blades (N_b) of (0, 2, and 4), respectively, the values of S_f/d_p were around (0.36, 11.68, and 12.04) for $D_r = 30\%$, (0.64, 9.28, and 9.64) for $D_r = 50\%$, and (0.72, 8.48, and 9.96) for $D_r = 80\%$. It is noticed that for cases of an anchor of two

a) $D_r = 30\%$.

b) $D_r = 50\%$.

c) $D_r = 80\%$.

Fig. 10 Variation of load with upward movement for different loading rate (L_R); $N_b = 2$

blades, there is a severe increase in S_f/d_p with increasing the D_r value, while for cases of an anchor of four blades, the value of S_f/d_p for $D_r = 50\%$ is less than those for $D_r = 30\%$ and 80%.

Impact of Loading Rate (L_R)

To study the effect of the loading rate (L_R) on the ultimate uplift load of pre-displacement anchor piles at diverse D_r values, the loading rate ranged from 0.5 to 2.0 mm/s. Figure 14 shows the relationship between the ultimate uplift load and the loading rate (L_R) at various D_r values and an anchor with two blades. It is apparent that as the loading rate (L_R) increases, so does the ultimate pullout force [31–33] of the pre-displacement anchor pile for the same D_r value. It is noticed that for all loading rate values, the ultimate pullout force increases as the values of D_r increase. It is observed that increasing the loading rate from 0.5 mm/s to 1.0 mm/s led to an increase in the pullout load of (12.4%, 4.2%, and 7.07%) at D_r values of (30%, 50%, and 80%), respectively. Whereas increasing the loading rate from 1.0 mm/s to 2.0 mm/s led to an increase in the uplift capacity of (10.3%, 12.05%, and 7.44%) at D_r values of (30%, 50%, and 80%), respectively. It can be noted that the loading rate effect in the case of $D_r = 30\%$

is greater than those of $D_r = 80\%$ and 50% for the loading rate of 1.0 mm/s, while for $L_R = 2.0$ mm/s compared to the case of $L_R = 0.5$ mm/s, the impact of L_R in the case of $D_r = 50\%$ is higher than those of $D_r = 80\%$ and 30% compared to the case of $L_R = 1.0$ mm/s. A greater loading rate can achieve better enhancement [31–33] because, as the loading increases, the skin friction increases [32]. The needed value of S_o to activate the blades lowers as the loading rate increases. The increase in uplift capacity with higher loading rates is explained by the blades opening at a deeper depth and an increase in their effective depth of embedment, which allowed for the addition of more soil to the blades to resist the lifting force. The effect of loading rate (L_R) on the normalized displacement value corresponding to the ultimate uplift load (S_f/d_p) at diverse relative densities was checked. Figure 15 shows the variation of S_f/d_p values with the loading rate (L_R) at various relative densities. It is observed that S_f/d_p increases slightly as the value of L_R increases. The values of S_f/d_p were about (11.96, 12.12, and 12.64) for $D_r = 30\%$, (9.28, 9.72, and 10.04) for $D_r = 50\%$, and (8.96, 9.12, and 9.48) for $D_r = 80\%$ at loading rates (L_R) of (0.50, 1.0, and 2.0 mm/s), respectively. At the same loading rate, the values of S_f/d_p in the case of $D_r = 30\%$ are higher than those for $D_r = 50\%$ and 80%.
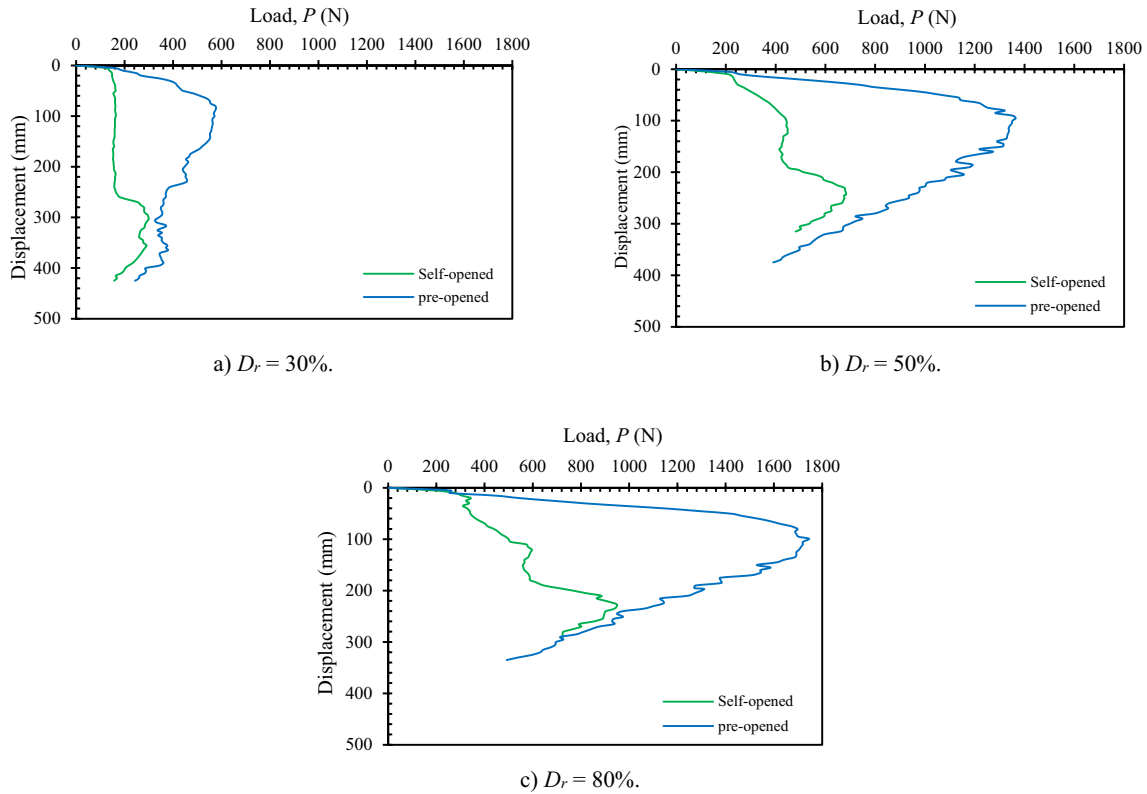
a) $D_r = 30\%$.

b) $D_r = 50\%$.

c) $D_r = 80\%$.

Fig. 11 Variation of load with upward movement for self-opening and pre-opened anchor; $L_R = 1.0$ mm/s; $N_b = 2$
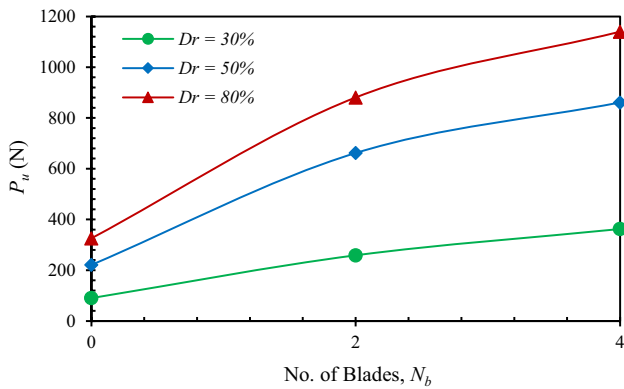

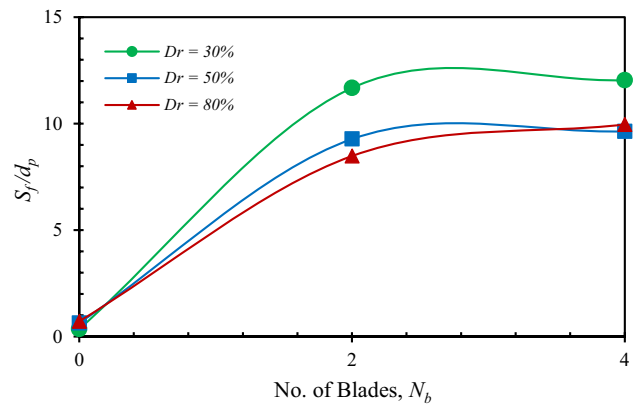**Fig. 12** Variation of P_u with number of blades (N_b) at different D_r values; $L_R = 1.0$ mm/s

Fig. 13 Variation of S_f/d_p with number of blades (N_b) at different D_r values; $L_R = 1.0$ mm/s

limitation for the Blade's Activation

To attain this functioning of the pre-displacement anchor pile during lifting tests, the anchor is raised an upward distance to activate the blades, which are defined as the pre-displacement (S_o), which makes the blades work to resist lifting loads. Numerous variables, including blade size, embedment ratio, blade angle, loading rate, and relative density, have an impact on the movement needed to open the blades. When the blades attain this upward motion (S_o), they become opened and begin to withstand the pullout force. The impact of the number of blades (N_b) on the value of S_o/d_p for the pre-displacement anchor pile in sand at various D_r values was investigated. Figure 16 demonstrates the variation of S_o/d_p with the number of blades (N_b) at diverse relative densities. It was found that the values of S_o/d_p were about (8.16 and 8.84) for $D_r = 30\%$, (7.48 and 7.84) for $D_r = 50\%$, and
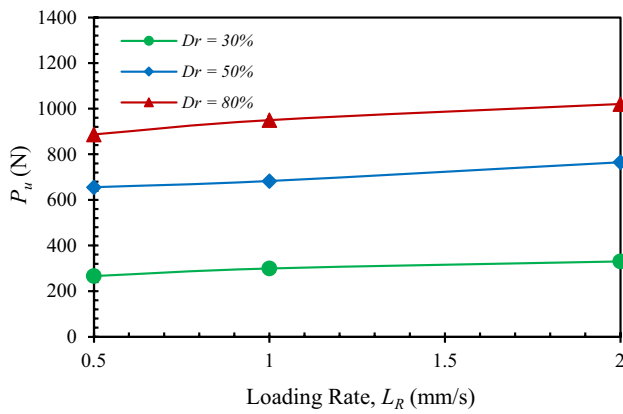
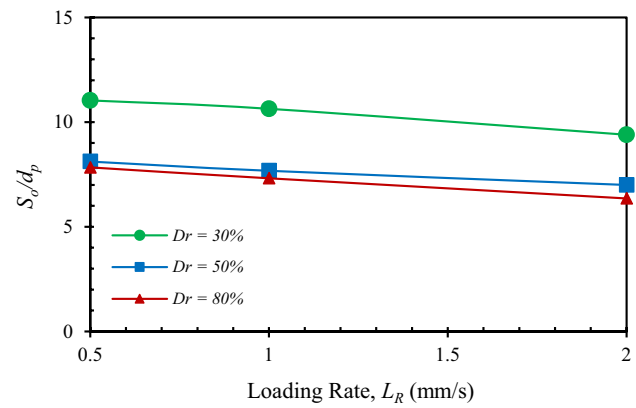**Fig. 14** Variation of ultimate uplift load versus loading rate (L_R) at different D_r values; $N_b = 2$
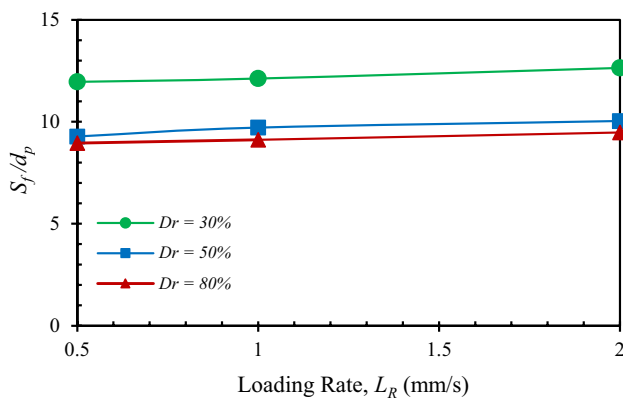

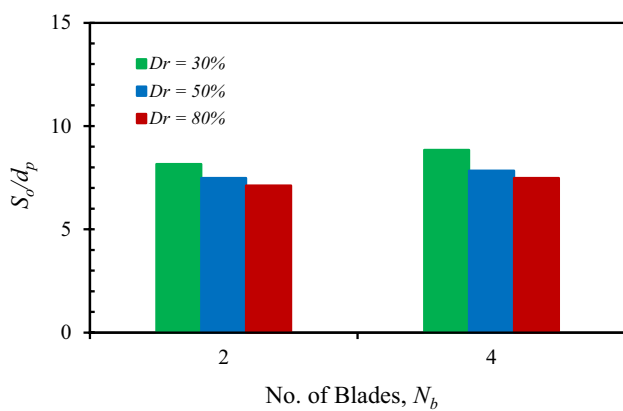**Fig. 15** Variation of S_f/d_p with loading rate (L_R) at different D_r values; $N_b = 2$

Fig. 16 Variation of S_o/d_p with number of blades (N_b) at different D_r values; $L_R = 1.0$ mm/s

Fig. 17 Variation of S_o/d_p with L_R at different D_r values; $N_b = 2$

(7.12 and 7.48) for $D_r = 80\%$ for anchors with 2 and 4 blades, respectively. For the same value of D_r, as the number of blades increases, S_o/d_p increases. It is also observed that S_o/d_p decreases as the D_r values increase for the same number of blades. S_o/d_p values for $D_r = 30\%$ are found to be higher than those for $D_r = 50\%$ and 80%, while a decrease in S_o/d_p is found to be lesser in the case of $D_r = 80\%$ when compared to that of $D_r = 50\%$. It is shown that the number of blades has an impact on the vertical movement required to open the blades. The impact of the loading rate (L_R) on the value of S_o/d_p for the pre-displacement anchor at diverse D_r values was investigated. Figure 17 shows the relationship between the values of S_o/d_p and the loading rate (L_R) at different D_r values. It was seen that the loading rate had a significant impact on the required S_o value to open the blades. It was noted that the values of S_o/d_p were around (11.04, 10.64, and 9.4) for $D_r = 30\%$, (8.12, 7.68, and 7.0) for $D_r = 50\%$, and (7.84, 7.32, and 6.36) for $D_r = 80\%$ at loading rates (L_R) of (0.5, 1.0, and 2.0 mm/s), respectively. It is noted that as the loading rate increases, the value of.

S_o/d_p decreases for the same D_r values. It is seen that when the L_R value increased from 0.5 mm/s to 2.0 mm/s, the decrease in S_o/d_p value in the case of $D_r = 30\%$ was higher than that of $D_r = 50\%$ and 80%. As the loading rate rose, the blades opened at a deeper depth, and the effective depth of embedment of the blades increased. As can be seen, the relationships between the value of S_o/d_p and the loading rate are nearly linear. Based on the studied parameters, the value of S_o required to activate the blades ranged from 6.36 to 11.04 times the pile diameter.

Effect of Blades on the Break-Out Factor

The break-out factor (N_q) is one of the key factors used for measuring the pullout load of anchors. The dimensionless factor N_q, which is used to determine the uplift resistance of the pre-displacement anchor pile, may be calculated using
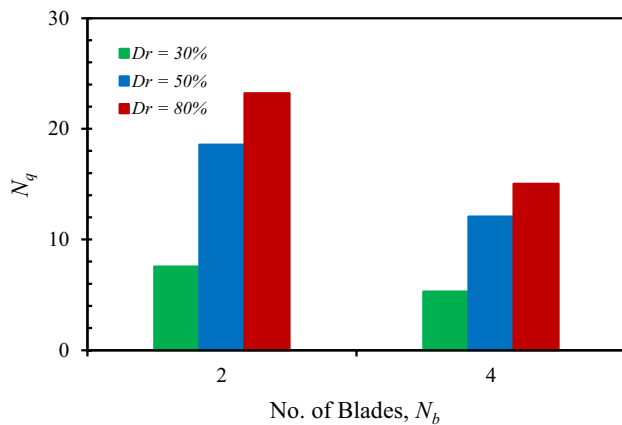
Fig. 18 Variation of N_q with N_b at various D_r values; $L_R = 1.0$ mm/s
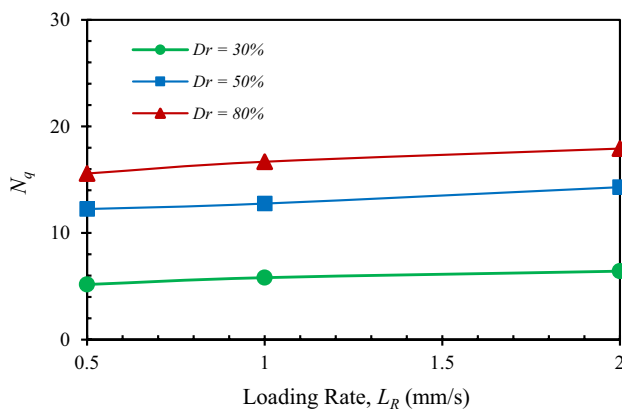
Fig. 19 Variation of N_q with L_R at various D_r values; $N_b = 2$

the equation $N_q = P_u / (H\, N_b\, L_b\, W_b\, \gamma)$. Where: P_u is the uplift capacity; H is the embedment depth; N_b is the number of blades; L_b is the length of the blade; W_b is the width of the blade; and γ is the sand unit weight. The impact of the number of blades (N_b) on the value of N_q at diverse D_r values was studied. Figure 18 shows the relationship between N_q and the number of blades at various D_r values. The N_q value was about (7.544 and 5.282) for $D_r = 30\%$, (18.559 and 12.062) for $D_r = 50\%$, and (23.213 and 15.021) for $D_r = 80\%$ at anchors with 2 and 4 blades, respectively. It was found that the value of N_q decreased as the number of blades increased from 2 to 4. Meanwhile, D_r has a considerable influence on the break-out factor. It can be noticed that the breakout factor increases when the value of D_r increases for the same blade number. When D_r is increased from 30 to 50%, N_q increases significantly, but when D_r is increased from 50 to 80%, N_q increases less dramatically. The impact of the loading rate on the value of N_q at various D_r values was studied. Figure 19 shows the relationships between the N_q value and the loading rate (L_R) at diverse relative densities. The breakout

factor was found to be around (5.179, 5.822, and 6.422) for $D_r = 30\%$, (12.247, 12.761, and 14.298) for $D_r = 50\%$, and (15.586, 16.687, and 17.929) for $D_r = 80\%$ at loading rates (L_R) of (0.5, 1.0, and 2.0), respectively. It is evident that the loading rate and breakout factor have relationships that are nearly linear. It can be noted that the value of N_q increases as the loading rate increases. Increasing the loading rate led to a decrease in the value of S_o/d_p. As a result, the effective embedment ratio increases with the increase in loading rate. Therefore, the blades activate at deeper depths with an increase in loading rate. It is concluded that the greatest enhancement may be attained at a higher loading rate.

Load Losses Due to the Self-Opening

The load losses due to the self-opening of the pre-displacement anchor pile are discussed in this section. The load losses due to self-opening of the pre-displacement anchor pile were found to be around (48.04%, 49.91%, and 45.59%) from the case of pre-opening for D_r of (30%, 60%, and 90%), respectively. Whereas the pre-displacement needed to activate the blades was about (11.64, 7.68, and 7.32%) times the pile diameter for D_r (30%, 60%, and 90%), respectively. The self-opening anchor is elevated by a distance equal to pre-displacement to activate the blades (S_o), which permits the blades to open and activate to mitigate the lifting force. Which means the effective embedment depth at the blade opening is less than that of the pre-opening by the value of S_o. This explains why the load losses occurred and why the ultimate uplift force for self-opening is lower than for pre-opening. The pre-displacement bladed pile is a new technique that aims to offer a bearing area underneath the sand during uplift using the blades without excavation. Although the pre-opened anchor gained a higher bearing capacity than the self-opened anchor, implementing the pre-opening anchor requires excavation of the soil to the required depth and refilling it after positioning the open anchor, and this represents a major challenge in the case of deeper depths. While the self-opening anchor is considered an advantage, it can be installed without excavation. However, the penetration depth can be increased during the implementation of the anchor by the amount of pre-displacement to achieve the same uplift capacity as the pre-opening anchor.

Scale Effect and Limitations

Many experimental tests are carried out using small-scale models because of the costs associated with full-scale testing, which is labor- and resource-intensive and requires a substantial amount of equipment and building [2]. To expect performance at full size utilizing the effect seen at a smaller scale, scaling implications need to be kept to a minimum

[40]. Also, because of the impact of size and the nature of the sand grains, sand performs differently in laboratory model testing than it does in field testing. These variations are due to the various levels of stress found during model testing in contrast to field tests [41]. The laboratory testing utilized a similar installation process as the field tests. The size of the soil particles, the boundary conditions, and the construction techniques are the primary factors that influence small-scale experiments [1, 2]. According to Franke and Muth [42], to limit the scaling effect, the diameter of the pile (d_p) must be greater than 30 times the mean diameter of the sand grains (D_{50}). The ratio of d_p/D_{50} in this investigation was 50; hence, the impact of particle size was only marginally significant. To reduce the impact of the soil tank's boundaries, the testing tank's height and diameter were designed. According to Nasr [38], the soil tank's internal measurements, which were three to eight times bigger than the exterior edges of the blades, were considered to lessen the border impact. In this investigation, the diameter of the sand box was 4.22 times the width of the blades outside edges, and its internal diameter was 38 times greater than that of the pile diameter. According to Sakr et al. [1], the sand bed height was chosen to guarantee that the sand strata extend for a minimum of 100 mm beneath the anchor pile. A vertical clearance eight times the pile diameter was provided below the pile tip, even though no end-bearing force is anticipated at the pile tip [43]. Therefore, the designed testing tank has no effect on the results obtained from the experiments. The side friction and the boundary conditions have little to no impact on small-scale models' findings when the container is substantial in size and has a flat inner face [44]. In order to reduce any potential friction with the soil during the experiments, the internal surface of the sand container was smooth. As a result, it becomes easy to ignore the friction that exists between the test tank's inner face and the sand strata. Bolton [45] found a significant correlation between dilatancy and relative density. Rowe and Davis [46] investigated how anchor behavior in sand was affected by dilatancy. It was found that when exposed to dilatancy, anchors experience a significant level of pressure. Because dry sand expands in volume more readily when sheared, this increase in strain was shown to be more apparent in dry sand than in wet sand. The research also emphasized the significance of the D_r value in the dilatancy process. It was found that sand required a greater relative density for anchors to be more impervious to dilatancy.

The recommended findings of the experimental results are limited to pile and soil limits. The model pre-displacement anchor used in the testing has a 1000 mm length and a 25 mm diameter. During tests, the embedment depth to pile diameter ratio was 32, the blade length was 2 times the pile diameter, the distance (D) to the pile diameter was 3 for the lower blades and 7 for the upper blades, and the blade angle (θ) was 90°. The studied anchors were anchors with two blades, anchors with four blades, and unbladed anchors. While the checked loading rate (L_R) ranged from 0.5 to 2.0 mm/s. The sand container is 950 mm in diameter and 1000 mm in height. The experimental tests were conducted in dry sand. The mean diameter D_{50} of the sand grains was 0.49 mm, D_{10} was 0.21 mm, the coefficient of curvature was 0.786, and the uniformity coefficient was 3.33, corresponding to the grain size distribution of the sand. The value of G_s for the sand was 2.63. The values of e_{max} and e_{min} of the tested soil were 0.695 and 0.39, respectively, and the corresponding $\gamma_{d\,max}$ and $\gamma_{d\,min}$ were 18.92 kN/m^3 and 15.52 kN/m^3, respectively. The tests were carried out at D_r values of 30% (loose), 50% (medium-dense), and 80% (dense), and the corresponding friction angle (φ) values in the same order were (31.8°, 35.2°, and 38.9°).

Conclusions

Utilizing a small-scale test model, the performance of the pre-displacement anchor pile under lifting forces was investigated. This modified pile intends to offer a bearing area underneath the sand during uplift using the blades. The pre-displacement anchor pile is a pile modification methodology for enhancing the anchor lifting force. The existence of blades led to the creation of an ideal anchoring system. The impact of diverse parameters such as number of blades, loading rate, and relative density on the pullout loads of the new modified anchor pile was investigated and compared with the unbladed pile. The main findings of the present study may be summed up as follows:

1. The pre-displacement anchor is elevated upward by a distance S_o, which allows the blade to be active. The blades open and begin to operate against the lifting force once the desired distance S_o has been reached. The pre-displacement (S_o) is affected by various factors such as embedment ratio, blade dimensions, blade angle, number of blades, loading rate, and relative density. Based on the studied parameters, the value of S_o required to activate the blades ranged from 6.36 to 11.04 times the pile diameter.
2. The pile modification methodology for enhancing the anchor lifting force is effective, and the ultimate pullout load of the conventional anchor pile is enhanced by using the blades.
3. The effects of four blades are unquestionably greater than those of two blades, but the uplift displacements of anchored piles are fewer than those of unbladed piles. Additionally, the blade effects in dense sand are higher than those in medium-density sand and loose sand. As

the number of blades increases, the break-out factor decreases.

4. When the loading rate (L_R) increases, the pullout load of a pre-displacement anchor pile also improves, and the pre-displacement (S_o) to open the blades is also increased.

5. The value of the break-out factor decreased as the number of blades increased from 2 to 4. Meanwhile, the breakout factor increases when the value of D_r increases.

6. The percentage improvement in the pullout load for the anchor with four blades and a loading rate of 1 mm/s was (301%, 289%, and 249%) at sand relative densities of (30%, 50%, and 80%), respectively, compared to the unbladed pile.

7. The load losses due to self-opening of the pre-displacement anchor pile were found to be around (48.04%, 49.91%, and 45.59%) from the case of pre-opening for the relative densities (D_r) of (30%, 60%, and 90%), respectively.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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