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Investigation of the Deformation of Sandy Soil Near a Laterally Loaded Single Pile Using the Particle Image Velocimetry Technique

Balqees A. Ahmed[1] and Dhergham A. R. Al-Hamdani[1,2](✉)

[1] Civil Engineering Department, University of Baghdad, Baghdad, Iraq
balqees.a@coeng.uobaghdad.edu.iq
[2] Al-Furat Al-Awsat Technical University, Al-Najaf, Iraq
dherghamalhamdani@atu.edu.iq

Abstract. Particle image velocimetry (PIV) is an optical flow visualization method used in academic research. It is used to obtain instantaneous velocity measurements and related properties such as particle motions. According to that, the particles should be illuminated to be highly visible and easy to capture the motions. The soil deformation due to a laterally loaded pile is investigated by using the PIV technique. In this study, a special model setup is manufactured to examine the deformation of dry sandy soil near a laterally loaded pile. The experimental optical setup will be constructed to capture numerous images of the soil movements while pushing the pile inside the soil and laterally loading the pile with a half-circular cross-sectional area with three different lengths to diameter ratios (L/d) about (8, 12, and 16). The relative density of the sandy soil is selected depending on applying the raining technique and used about (60%). The vertical and horizontal soil deformations of many cases have been studied. The tests showed that the pile would crush the sand particle with an L/d ratio of 10. The deformation patterns in the sandy soil around the piles that loaded laterally will behave in different patterns than when the piles are subjected to inclined loading. The soil closed the pile shaft moved vertically more than moving laterally as the L/d increased.

Keywords: GeoPIV · Soil deformation · ROI · Target markers · Optical techniques

1 Introduction

The soil deformation near and around the piled foundation represents a critical aspect in the task of foundation design [1]. The function of the pile foundations is generally designed to resist the active (axially and/or laterally) loads subjected to the pile head. The development of the construction projects in civil engineering like Tunnels, Bridges, Ports, and Deep excavations using the piles subjected to combined axial and passive laterally loads [2]. In contrast to Karkush and Abdul Kareem's findings, applying vertical loads to the cap of a pile group resulted in a reduction in the pile's lateral displacement [3]. In

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other cases, human activities produce a variety of residues known as wastes, which can alter the soil's structure. The change in soil structure caused the soil structure to deform uncontrollably [4]. According to that, piles may use to retain the slopes and the unstable soil. In these cases, the thrust due to ground movements will produce additional lateral forces and bending moments on the piles which may cause damage to the pile structure [5].

In pile foundation, the axial and lateral soil displacement will occur after the pile is subjected to these loads, while this phenomenon is represented as a critical task when its value increases to the limited value in the design [6]. The free head pile behaves as an elastic member when the maximum soil displacement reaches the maximum value of about 0.4 pile diameter. The elastic solution tends to overestimate the soil displacement greater than 0.4 pile diameter [7]. Pile foundations are built to solve the problems of shallow footing but their behavior remains one of the largest sources of geotechnical engineering uncertainty. According to that, large safety factors are needed. Alternatively, expensive field trials must be carried out to deduce site-specific design parameters [8]. Many researchers study soil deformation that occurs surrounding the pile, the effects of the distribution and particle size on the soil-geogrid interactions due to pullout test by using the PIV technique was studied. The testing model with size (100 × 60 × 60 cm) was manufactured. Three granular soils with different grain sizes and distributions were reinforced with an HDPE geogrid. Digital images were captured and processed using PIV, and the case analyzed finite element analysis using ABAQUS. The results showed that the pullout forces and the shear zone thickness increased with the grain size and the strain distributions became more symmetrical. The finite element analysis results also showed close agreement with the experimental results [9].

The PIV technique was used to measure the deformation in sandy soil due to the laterally loaded piles. An experimental optical setup is manufactured to capture images of soil movement. Strain gauges measure the deflection of the pile. The ground surface movement and the displacement profile depending on the images are determined by using the PIV technique. The images illustrate that the sand rotated in a position approximately 160 mm deep. FEM is used to simulate and verify the model test. The results show that the PIV technique and the optical setup are suitable for solving interaction problems because this technique provides more accurate results compared with the double integration method [10]. The failure mechanisms in the silica and carbonate sands beneath the strip footing loaded vertically. Small-scale optical physical modeling tests were conducted in a geotechnical centrifuge was analyzed. PIV/DIC was used to analyze the images beneath the footing to visualize the failure mechanisms. The observed mechanisms are interpreted in conjunction with load-settlement curve and cone penetrometer resistance profiles. The failure mechanisms were illustrated through normalized vertical and horizontal displacement. The shear and volumetric strains were derived from the PIV technique. The results show that the responses of the carbonate sands and silica sand under shallow footing subjected to vertical loading were understudied clearly [11].

The deformation in the clayey soil caused by the buckling in a pile was studied. Transparent soil and PIV approaches were used to measure the buckling deformation of fully embedded model piles and the consequent soil deformation under different conditions. A laser light sheet was used to observe the movement of soil and capture digital images of the buckling deformation of the model piles. The results showed that the constraint mode at the pile tip on the buckling depends on the change in pile strength and slenderness ratio. The movement of soil in both sides of the maximum buckling point fits the theory of Rankine's earth pressure [12]. The soil deformation and wheel traction on loose sand by using the PIV technique was analyzed. Soil deformation under grouser wheel and wheel traction performance were studied. The wheel traction is measured by a force-torque (FT) sensor, while the PIV technique measures the soil deformation. The results showed that the soil around the grouser moves in the directions from the front and to the rear of the wheel. The soil deformed as arced shaped. The effects of normal load on the wheel on the soil deformation, where they found the normal wheel load on the thickness of the soil deformation, were also investigated. In addition, the results showed that this work helped to understand the interaction between soil and wheel [13]. There is a lack of knowledge and little literature studying soil behavior near the laterally loaded pile. A novel method is developed and applied to a plane strain testing chamber to investigate the deformation caused by lateral loading applied during the installation of displacement piles.

2 Materials and Methods

The sand used in the study is tested to estimate the physical properties of the used sand. Tests include sieve analysis, soil fraction, specific gravity, maximum unit weight, and minimum dry unit weight. The experimental tests were conducted according to the standard testing methods. The results of these tests are presented in Table 1. The sand placed the constructed optical model by using the raining technique; after reviewing the related literature size and shapes of piles used in the small-scale model, the size and shape of model piles were selected to be considered representative. A circular brass shaft with a 25 mm diameter is used as a pile model. Initially, the shaft slit was made by the milling machine with (2 mm) width and the pile longitudinally. The slit extends along the shaft length and stops before the shaft's two ends with a 30 mm distance to allow the bolt to fix the pile with a cap. The slit shaft is divided into two halves. The two half-cylindrical shafts are tabard at one end and leave the other end as a circular shape. The purpose of using brass material is too easy to slight longitudinally. The embedding ratio that symbolized (L/D) that depends in the present work for single piles are (8,12, and 16). The final pile's lengths are (26, 36, and 46) with a half-circular cross-section. The purpose of using a half-circular section pile is to model the behavior of the pile in-plane pass through the center of the pile. Because of the present work is study a special case of the pushed pile in sandy soil, the pile is pushed inside the soil when it is in contact closely with optical wall explained later to be able to observe the soil deformation during pushing or loading by recording the video and process it by GeoPIV8.

The dimensions of the soil container were chosen after reviewing the setups that developed in the literature to be appropriate dimensions. A special experimental setup was manufactured. A steel soil container made of a thick steel plate having a thickness of 3 mm with internal dimensions of 800 mm long, 450 mm width, and 750 mm height is manufactured as a soil container. One of the large sides of the box is made of tempered glass with a thickness of 10 mm to allow soil behavior observation. A 60 cm long, 10 cm

Table 1. Physical and mechanical properties of used soil.

Property	Unit	Value	Standard of the test
Gravel (>4.75 mm)	%	0	ASTM D422–2005 and ASTM D2487–2005
Sand (0.075 – 4.75 mm)	%	96	
Fine (<0.075 mm)	%	4	
D_{10}, D_{30}, D_{50}, D_{60}	Mm	0.16, 0.34, 0.58, 0.75	
Cu	-	4.68	
Cc	-	0.96	
Classification	-	SP	USCS
Gs	-	2.64	ASTM D854–2006
γ_{max}	kN/m^3	18.4	ASTM D4253–2000
γ_{min}	kN/m^3	14.5	ASTM D4254–2000
e_{max}	-	0.96	ASTM D4254–2000
e_{min}	-	0.72	ASTM D4253–2000

wide, and 4 mm thick gate is located in the center of the container's backside. The steel container is emptied of soil through this gate. The container's inner surface is divided into six layers, each of which was ten centimeters thick. The container's upper right and left edges are provided with two M20 bolts welded with the horizontal plate. The function of these two bolts is to support the guide tool and prevent movement by pushing the piles. Figure 1 explains the details of the soil container used.

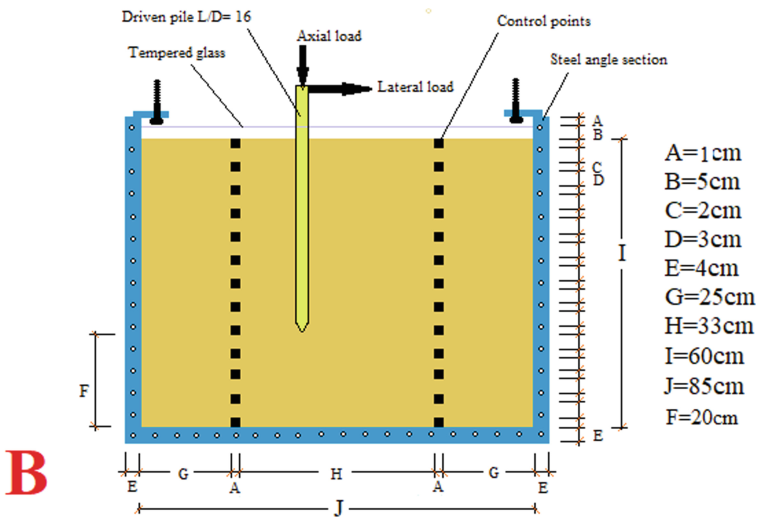


Fig. 1. The final shape of the pile and soil container used in the present work.

Target markers were used to calibrate the camera and convert the image from pixel to mm. These points represent control points to eliminate the unwanted noise during processing the images. The distance and the way of distribution of the control points are discussed in previous works, the present work is close from the work conducted in reference [14]. In this study, the vertical distance between the control points is (50 mm). Finding the centroid of these control points was done by comparing the inputted coordinates and the finding coordinates during targets marker processing. The main structure of the installation and loading used in the present work consists of four opposite columns of U-section with size 100 mm web, 40 mm flange, and 1500 mm length. These columns are welded with two horizontally I-ground beams with size 140 mm web, 90 mm flange, and 1200 mm length.

As shown in Fig. 2.A, the main structure is installed on the ground to ensure that there is no vibration as a result of the movement and operation of the device and the generation of noise that affects the results by welding the ground beams at each end. While the upper ends of the four columns were welded with four beams of the same U-section used in the four columns, these beams faced each other to make a rectangular shape. The steel frame of the sand raining was fixed on the four corners of the four upper beams by welding and welding an additional frame in a vertical direction that represents a guide for the loading shaft. When the gear of the loading shaft rotates, the loading shaft begins to move down vertically. Another base has been installed for the zero-max derive that generates the rotational movement and additional bases for the gears to transfer the rotational movement of the loading shaft. Double-toothed ginger was used to increase its durability. Finally, two steel beams were welded in the middle of the U-sections columns. Each beam is welded with two front and rear columns in the same direction. These two beams were provided with screws to prevent the movement of the soil container horizontally. In addition, two-direction roller supports were added to the base of the soil container, which was used to move the soil container laterally while pushing the piles and also allow to move back during raining and front during the pushing stage.

In a variety of applications, adjustable or variable speed drives provide simple and precise speed control. A simple way to precisely control output speed as a ratio to input speed is to move a lever control through an arc or turn the hand-wheel of a screw-type control. The special object in this frame is the loading stroke. During the loading case, the electrical motor is operated by a two-way switch provided. The switch turns on with two sides, left and right. The difference between these sides is in the left side. The electrical motor will be powered off automatically, while on the right side, the electrical motor will be powered on continually. These two ways of power are required when loading to be the head of the piles that are pushed in the same level and preventing the level of the pile head contact with the side glass wall of the soil container. The rate of loading is sited to 0.35mm/second as recommended [15]. When beginning to push the pile in the soil, the pushing guide is required to the product. This part of the experimental model represents the most influential on the results, despite its simplicity. It consists of five parallel cylinders with an inside diameter of 26 mm and 100 mm in length, as shown in Fig. 2.B. There is an equal distance between these cylinders, about 1.6 times pile diameter. The main function of this part is to hold the pile during its inserting as a result

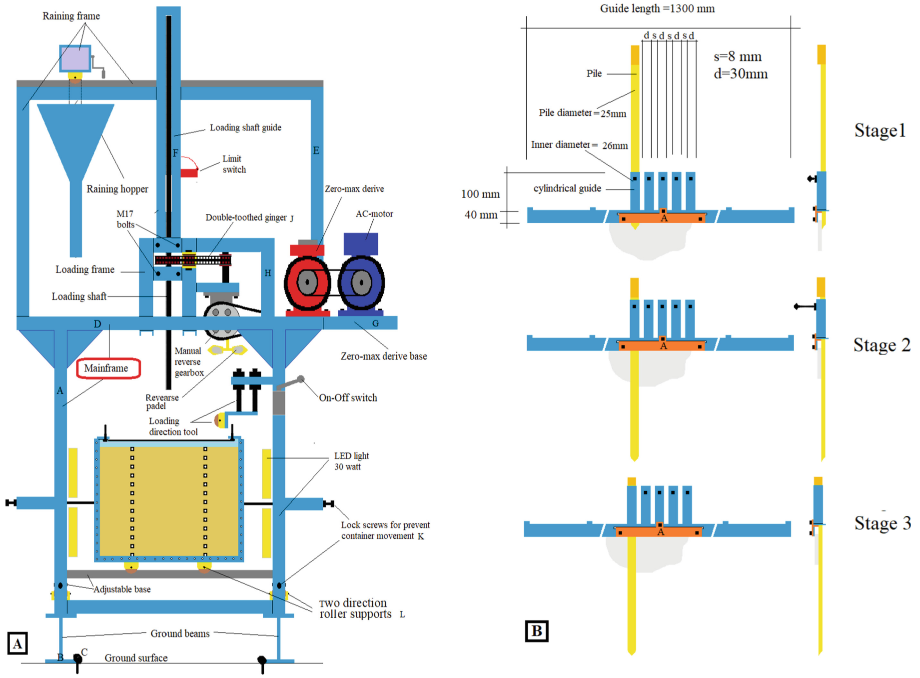


Fig. 2. Testing setup and pushing guide.

of pushing it in the soil so that it is closely adjacent to the glass and prevent any space between the glass and the flat surface of the pile. Before beginning the experimental work, the pile's flatness was ascertained by scraping a layer about 1 mm from its thickness.

The function of the holder is to confine the pile to the back of the cylinder and prevent longitudinal movement and rotate around the inner circumference of the cylinder. Front additional holders are installed to perform the same purpose as described previously. These bolts were used instead of the steel angle. During the process of pushing the pile down inside the soil, the bolts push the pile back, and when the pile reaches stage 3, the bolt must be removed because its presence will obstruct the pile and create a problem with the experiment. The location of this part is adjusted by observing the site and looking with the eye inside the cylinder. The distance between the glass and the holder angle is about 1–1.5 mm, measured between the edge of the holder angle and the edge of the glass. This distance is a means of pressure on the glass by the pile to ensure that the soil particles do not enter between the glass and the pile. When entry a small amount of soil particles in front of the piles leads to the formation of a small gap, and this small gap gradually enlarges and becomes filled with sand, which changes the reliability of the soil deformation around the pile.

The present work used the raining technique to prepare the sandy soil model to achieve a uniform layer with the desired density. To begin remolding the soil, sandy soil is air-dried by distribution on the ground surface and leaves to dry by air. After the soil dried, the raining technique was carried out using a steel hopper. Many trials with different falling heights of sand were conducted to achieve the desired value of relative density by finding the relationship between the falling height and the density. In each trial, metal tins are placed at several levels in the testing box and collect the small samples to calculate the dry density of soil. The results of calculating the densities (ɤ), void ratios (e), and relative densities (Dr) versus the falling height. The free fall height will be 700 mm used to prepare the sand with a relative density that depends on the present work. The digital video camera types CANON-XA15 are manually and automatically focused to capture sharper images. Two dowel light types were used after installing in the probable position on the mainframe columns depending on the image quality. The light required is positioned on the left and right side of the region of interest (ROI), two on each side to be capture clear and sharp images by digital camera. High illumination is affected the image quality. The high illuminations are reflected in the camera lens and cause noise in the processing of the images. According to that, camera lens polarizing filters were used in digital photography for a variety of purposes. A polarizing filter, often known as a "polarizer," is a photographic filter that is typically placed in front of a camera lens to reduce reflections, reduce haze, and boost color saturation. It's a popular filter for landscape, cityscape, and architecture photographers, but it is also popular for other sorts of photography. It is important to get a scaled model to study the soil behavior by developing a prototype. Scaling laws are strictly observed in the design of the models to ensure the reality of the behaviors between the scaled model and the corresponding prototype. The scaling factor between the model and the prototype for linear dimensions is 1 to N, where N is the scale factor [16]. In this study, the scaling factor is 0.035. The displacement and strains scale factors are 1 to N and 1 to 1, respectively.

3 Results and Discussion

PIV analysis was used in the present work to continuously track soil deformations during pile pushing vertically in the soil and deformations during lateral and inclined loading of the pile. PIV was used to analyze a series of video recordings that were divided into several frames (images). The length to diameter ratio and lateral and inclined loading cases are discussed as correlations between the variations. The outcomes from the proposed model were compared to the results proposed by other studies to verify the observed results. This section compares the soil deformations that occur during laterally and inclined loading.

3.1 Region of Interest (ROI) and Patches Size

The results of the PIV analysis are determined the soil displacement, its position, and strains. The displacement position is measured depending on the control points. Control points are reference points located at the right and left edges of the region of interest. The region of interest is the zone of probable motion that occurs during pushing and loading the piles. This zone is determined by the control points for simplification of the processing. The present work is selected inside the control points area. Figure 3 shows a sample of image and ROI and the position of the control points used. The distance between each point in the vertical direction is 50 mm, and the distance between the two columns of control points is 330 mm. The region of interest (ROI) is divided into many patches. The number of patches depends on the size of the ROI. The ROI, as shown in Fig. 3.A is approximately doulas times the ROI in length as shown in Fig. 3.B. Where its size depends on the area of probable soil movement surrounding the pile shaft and below the pile tip. The expected soil movement was covered when the processing time increased significantly. ROI is manually selected on the first image in the analyzed case. In PIV analysis, ROI was divided into patches. The size of patches depends on the number of pixels selected to analyze. Sub-windows may cover only a few grain diameters when the patch size is small. Neither continuity nor a smooth spatial displacement can be expected in the fine distribution of measuring points. The probable number of pixels that are suitable for the grains size used in the present work to be the patches motion smooth distribution during processing is 20 × 20. Figure 4 shows the PC's screenshot while analyzing the series of used images.

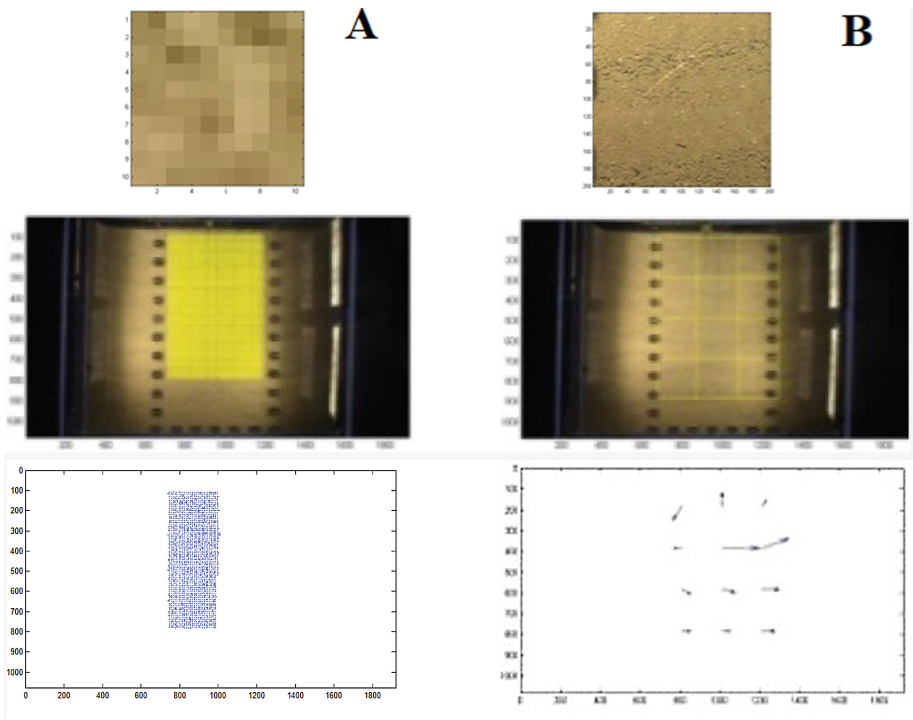


Fig. 3. Patches and ROI size.

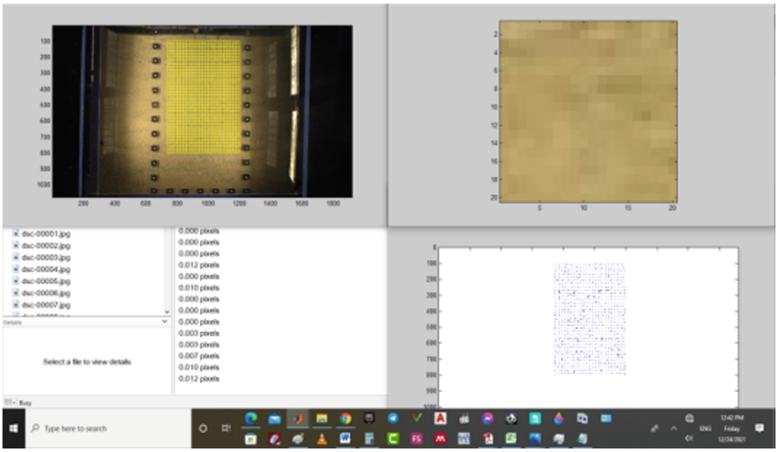


Fig. 4. PIV analysis window for the present work

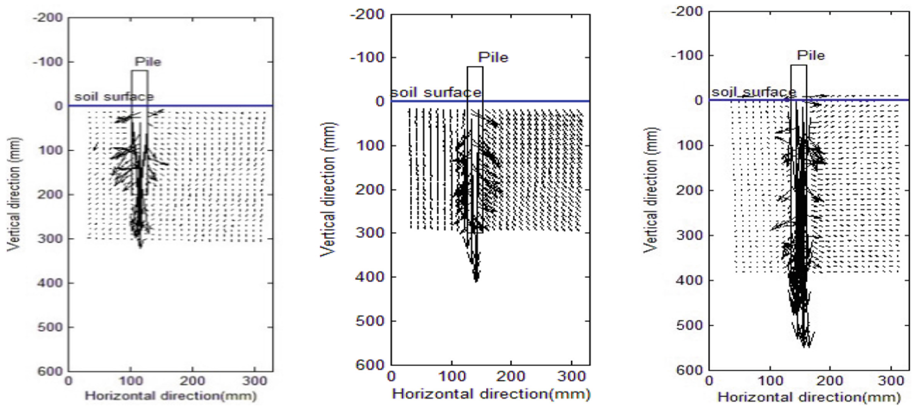
3.2 Patterns of Displacement Around the Pile

In pile-soil interaction problems, PIV is the most suitable means used to evaluate the apparent displacement surrounding the piles. This led to defining the labeling principle. The labeling principle for the graphical output differs from the held belief that the displacement is usually positive. The positive contours indicate displacement, and negative contours indicate heave in the vertical displacement contour plots. The contours surrounding the pile shaft, positive contours indicate the movement in rightward and negative contours, indicate the leftward movement in the horizontal displacement contour plots.

3.3 Direction of Soil Deformation Trajectories Due to Pile Installation

A series of experimental setups were prepared and tested as described in chapter three to validate the findings of the displacement surrounding the pile with some variables: three lengths to diameter ratios and deformations during installation and loading. Experiments were repeated in general more than one time to ensure that the precise deformation behavior achieved was repeatable and consistent. For piles with the length to diameter ratios equal to (8, 12, and 16), the process of installation was repeated 20 times during the experimental work. The cumulative horizontal and vertical displacement contours as they increased for a penetration range of (0 mm to 13 mm) derived from the average of these 20 tests. The results show that many conclusions may be summarized as the pile will crush the sand particle with an L/D ratio of about (10). The vector of particle movements during the penetration process of the individual piles has (L/D) equal to (8, 12, and 16) are shown in Fig. 5. The dotted points at two sides of the pile shaft refer to that no movements are occurring. Some areas of soils closer to the pile shaft do not move due to pile installation. This is maybe due to the remolding occurring in these areas not changing the structures of these parts and the GeoPIV8 program not sensing this motion. As that appears in Fig. 5, the direction of the movement of the grains varies between the movement in the horizontal direction and the vertical direction, as when the length to diameter ratio is equal to 8. The movement is somewhat directed towards the bottom, and the movement to the sides is fewer than that directed towards. When the length to diameter ratio is increased to the value equal to 12, the movement will be almost equal in the horizontal and vertical directions.

When the length to diameter ratio increased more to the value equal to 16, the direction of movement generally represents vertically downward under the pile tip. Finally, the observation of the soil particles is not appeared by the instantaneous velocity field because it cannot provide a better understanding of the penetration mechanism than the observation of the full trajectory of soil elements during model pile installation. However, trajectories of the soil deformation do not produce a systematic variation path with the depth. This observation is closest to that suggested by the work of other researchers [8].



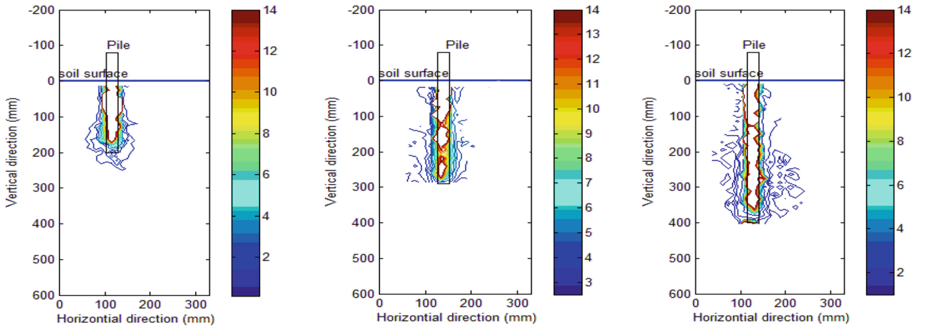
(L/D=8) (L/D=12) (L/D=16).

Fig. 5. Particle movement trajectories due to the installation of a single pile.

3.4 Soil Deformation in the Horizontal Direction Due to Pile Installation

The horizontal soil displacement surrounding the single pile during the installation process is discussed in this section. Three lengths to diameter ratios (8, 12, and 16) were used in this study. Experiments were repeated more than once to ensure that the precise deformation behavior was achieved. For the piles with length to diameter ratios (8, 12, and 16), the installation process is repeated 20 times during the experimental work. Generally, four results of the horizontal deformation patterns selected randomly are presented in Fig. 6. Also, Fig. 6 shows the same results for the other two lengths to diameter ratios (12 and 16), respectively, and the same way of repetition (20 times) for everyone. The deformation that occurs in the soil around the pile extends from the beginning of the pile to the end along the contour of the pile.

In general, the last contour line in blue color represents the deformation values of the region far from the substrate and the region near the substrate where no contour line appears. The contrast of the shape of the contour line between one pile and another represents the realism in the representation of the deformation, which depends on the remolding soil in which the soil structure is formed and the distribution of grains around the pile. Also, the areas in which a high amount of movement appeared (the dark red color) are either the presence of a coarse grain of soil or its rush to the sides due to preparing the appropriate place for moving soil particles on the sides. The achieved results is supported by the results suggested by other researchers [17, 18]. The contour lines that lie in front of the piles refer to the soil before the pushing process.



(L/D=8) (L/D=12) (L/D=16)

Fig. 6. Horizontal displacement due to the installation of a single pile.

3.5 Soil Deformation in the Vertical Direction Due to Pile Installation

The vertical soil displacement surrounding the single pile during the installation process is conducted, and the experiments are repeated in the same way that the horizontal displacement does. The deformation in the soil occurs in the vertical direction as a result of the densification of the soil surrounding the pile due to the installation process of the pile. The amount of soil deformation increases with an increase in the penetration depth of the pile as shown in Fig. 7. Bulbs of horizontal and vertical strain extend below and to the side of the pile. The bulb of horizontal strain has a wider extent than the bulb of vertical strain. The influence area in which the vertical deformation occurs due to pile installation will increase with an increase in the embedment length depth as shown in Fig. 7. This phenomenon may be attributed to the area affected by the vertical movement of the soil as a result of the agglutination of the grains with each other to compensate for the size of the inserted pile.

The contour lines distribution of the soil deformation in the vertical direction is presented by random figures as mentioned above in the horizontal directions. In contrast, the expansion in the contour's lines in the horizontal deformation approximately is the same at the pile base and the pile head, while in the vertical deformation, the expansion in the contour lines is extra at the pile base than in the pile head. The soil particle will change the deformation direction as the length of the pile increase. This implementation supports the reasons for the expansion of the contour lines in the vertical direction. Also, the observed vertical deformation of soil due to the pile installation is closed to the theoretical assumption [19].

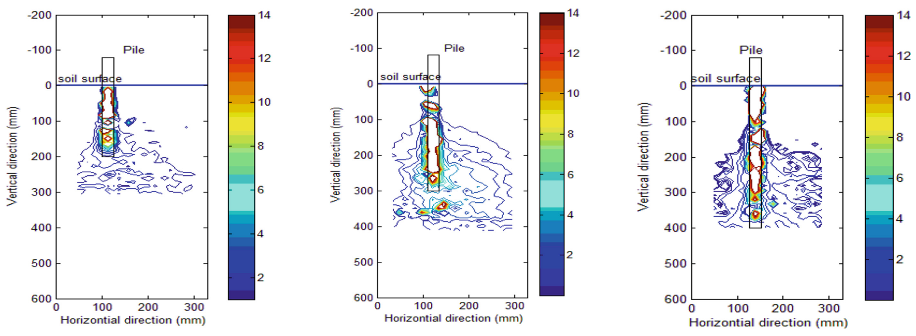


Fig. 7. Vertical displacement due to the installation of a single pile.

3.6 The Direction of Soil Deformation Due to Loading of Single Pile

A series of experimental setups were prepared and tested as described in chapter three under two types of loading, lateral and inclined compression. The pile tested at three lengths to diameter ratios (8, 12, and 16) and the soil deformation under these variables are discussed. The experiments were repeated at least three times to ensure the reality of the results achieved. The vector of movement during the penetration process is shown in Figs. 8 and 9. The piles loaded constantly to reach the angle between the verticals about 15 degrees. This angle is enough because the pile is failed under strain, as recommended by many researchers. The results show that the increase in the length to diameter ratio for the laterally loaded cases produces that the shallow and surface soil will gradually move out in a round motion and increase at the surface of the soil at shallow depth.

Figure 8 refers to the single piles under the inclined compression loading. The round motion is significantly lower than that in Fig. 9. The motion of the particles is affected by the direction of loading. Some wild vectors that appear in the figures mentioned above represent the noise during the video recording during the experimental work. The horizontal influence zone and sand displacement for the (L/D = 16) are larger than those at (L/D = 8) when comparing the pattern in Figs. 8 and 9. This shows that the horizontal influence zone and sand displacements around the lateral loaded long pile will increase. The displacement trajectory around the pile ranged between (120–180 mm), (190–200 mm), and (290–300 mm) for the length to diameter ratio equal to (8, 12, and 16), respectively. These observations support the findings that the maximum rotation at the soil surface is influenced by the depth of the embedded pile [20]. The studied embedment ratios have different behaviors. This conclusion indicates that the rotation points are approximately 67 percent of the embedded length. This observation is supported by many researchers [12, 17].

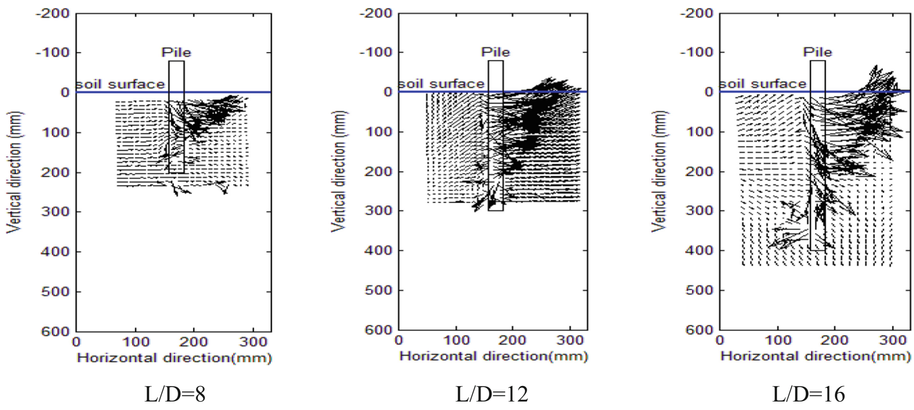


Fig. 8. Particle movement trajectory due to laterally loading of a single pile.

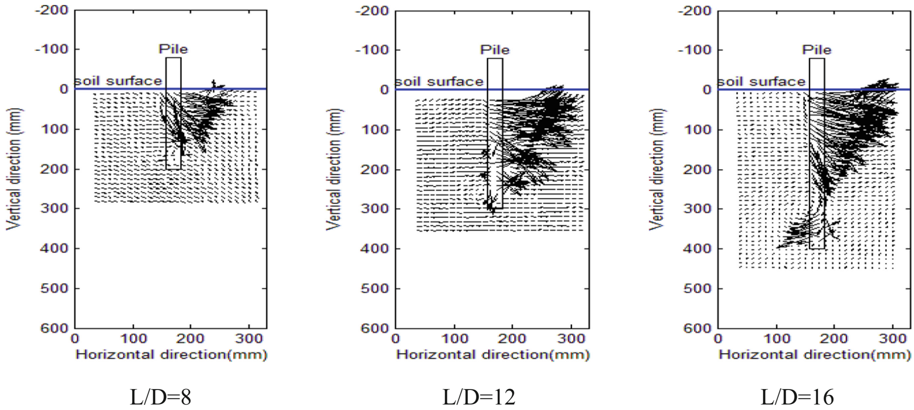
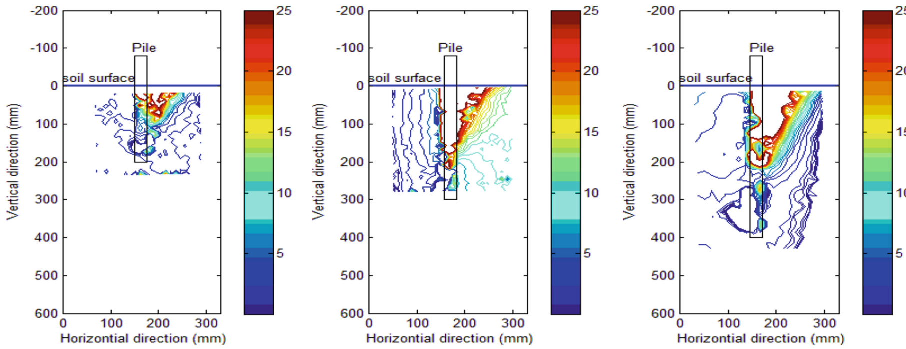


Fig. 9. Particle movement trajectory due to inclined loading of a single pile.

3.7 Soil Deformation in the Horizontal Direction Due to Loading of Pile

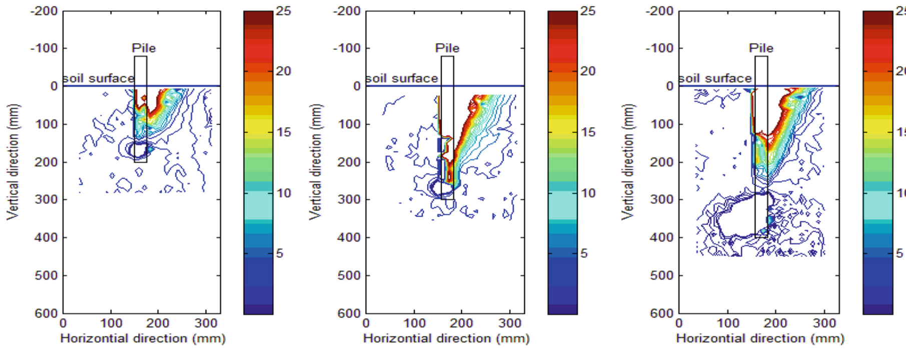
A series of experimental tests are conducted on the three lengths to diameter ratios (8, 12, and 16), under two types of loading lateral and inclined compression. The applied load direction pulls the pile head is being pulled to the right by the applied load direction. A triangular wedge is formed to the side of the displaced pile. A passive zone is created in front of a laterally loaded pile. The horizontal soil displacement and triangular wedge during the loading process are shown in Figs. 10 and 11. The soil deforms mainly in the passive zone, and this zone extended to depth about 67 percent of the pile embedding length. After this depth, the passive zone will change to the other side of the pile to rotate the pile about the rotation points 67 present the embedding length. The passive zone established in front of a laterally loaded pile is almost conical in shape in three dimensions when redrawn in a 3D figure as that observed by Hajialilue-Bonab et al. [17]. The rotation of the soil near the bottom of the inclined loaded piles as that appear in Figs. 10 and 11, are clear than that for the laterally loaded pile. Also, when increasing the length to diameter ratios, the rotation of the pile due to the laterally and inclined compression loads will appear.

This phenomenon may appear due to the effects of the passive pressure on the soil will lead to moving the soil in the area near the base of the pile in a circular manner and prevent the soil from scattering on the side of the base. The soil displacement due to the laterally loaded pile will be accompanied by the rotation and exit of the soil from the side of the pile head. This rotation of the soil in circular paths is greater than in a pile inclined compression loaded pile. The horizontal displacement that occurred due to moving the soil due to laterally load pile will be greater than that for the same pile loaded inclined compression.



L/D=8 L/D=12 L/D=16

Fig. 10. Horizontal displacement due to laterally loading of a single pile.



L/D=8 L/D=12 L/D=16

Fig. 11. Horizontal displacement due to inclined loading of a single pile.

3.8 Soil Deformation in the Vertical Direction Due to Loading of Pile

Experimental tests are conducted on the three lengths to diameter ratios (8, 12, and 16). These results are shown in Figs. 12 and 13. The pile head is being pulled to the right as achieved in Sects. 4.7 and 4.8. The vertical deformation of the soil surrounding the pile begins when the pile head is pulled laterally and inclined compression. Observing the patterns of deformations in the cases of the piles, it turns out that the vertical displacement in the soil does not take a specific pattern and does not depend on the length or the type of horizontal loading only or the inclined compression. The variation of cases for the vertical movement of the soil may be due to the structures of formation of each case and the amount of compaction and presence of coarse and fine grains below and on the sides of the pile.

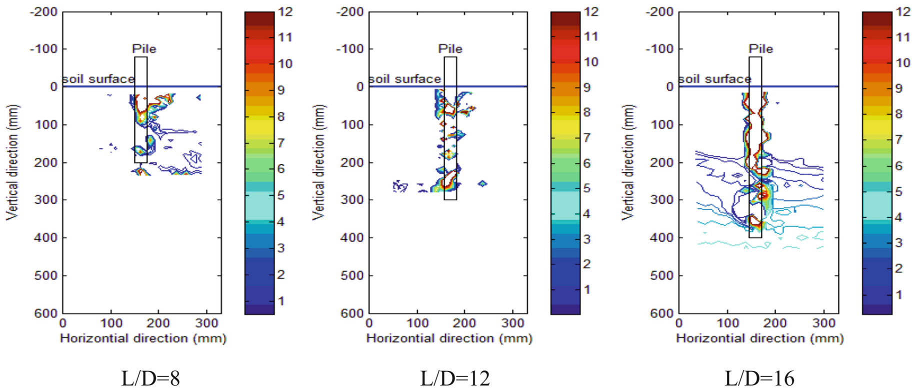


Fig. 12. Vertical displacement due to laterally loading of a single pile.

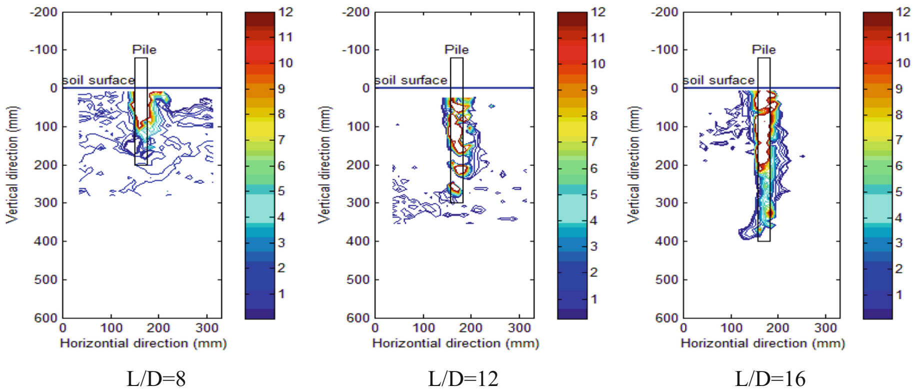


Fig. 13. Vertical displacement due to inclined loading of a single pile.

4 Conclusions

It can be concluded that depending on the extensive review of previous studies on the "The soil deformation near the laterally loaded a single pile by using the PIV techniques," all the researchers have been observed the PIV technique to estimate the deformation near a single pile under only lateral load or only axial load except some researchers [11]. They used the PIV technique to observe the soil deformation near only lateral loaded of the thin pile. They test several thin piles. These tests are subjected only to lateral loading, and the pile head in the group is a hinged type. Also, the pile installation is conducted before remolding the sandy soil raining the sand from a specific height in the testing box. The present work focuses on studying the effect of the factors that are not studied in the previous study and makes the way to install the pile and load the pile more reliable than other the previous study. Some of these factors are: Pushing the pile continuously in the previously remolded soil; The pile used in this study have the same shape that used in the field; The single piles are loaded actually as it is loaded in the field either only horizontal or vertically and horizontally load; Effect of number of images processed in PIV on the deformation; and Effect of pile length to diameter ratio;

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