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Bearing capacity of closed and open ended pipe piles installed in loose sand with emphasis on soil plug

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Present study investigates the behaviour of plug on pile load capacity and effect of plug removal. Different parameters are considered such as pile diameter to length ratio, type of installation in loose sand, removal of plug in three stages (50%, 75% and 100%) with respect to length of plug. Kerbala sand from Iraq, which is used as a foundation soil is poorly graded clean sand. It was concluded that the percentage of reduction in pile load capacity for open–ended pile increases with increase of the length of removal of the soil plug. Open-ended pipe pile behaves as a closed-ended if the soil plug formed inside piles is in state of partial plug or full plug. The failure of a pile to plug during driving does not necessarily mean that it will not plug during static loading, since inertia effects, which are present during driving are absent during static loading. This can be observed from the load-settlement curves where the open-ended piles exhibit large resistance to penetration due to mobilization of internal friction during static loading.

[Keywords: Pipe piles, open-ended, closed, bearing capacity, plug].

Introduction

Pile foundations are the part of a structure used to carry and transfer the load of the superstructure to the bearing ground located at some depth below ground surface. Piles are long and slender members, which transfer the load through weak compressible strata or water to deeper soil or rock of less compressibility and high bearing capacity avoiding shallow soil of low bearing capacity (Abeb and Smith, 2005).

Pipe piles can be either open-ended or close-ended. It has been documented that the behaviour of open-ended piles is different from that of closed-ended piles (Klos and Tejchman, 1981; Lee et al., 2003). According to the field test results of Szechy (1961), the blow count necessary for driving a pile to a certain depth in sands is lower for an open-ended pile than for a closed-ended pile. Thus, it is generally acknowledged that an open-ended pile requires less installation effort than a closed-ended pile under the same soil conditions. However, other research results (Smith et al., 1986; Brucy et al., 1991) have shown that the mode of pile driving is an important factor in driving resistance. If a pile is driven in a fully coring (or fully unplugged) mode, soil enters the pile at the same rate as it advances. On the other hand, if a pile is driven under plugged or partially plugged conditions, a soil plug finally attaches itself to the inner surface of the pile, preventing additional soil from entering the pile. A pile driven in the plugged mode behaves similarly as a closed-ended pile. Typically, a large-diameter pipe pile (such as used in off- shore piling) driven in sand will tend to be driven in a fully coring mode, while smaller diameter piles will be plugged, at least partially. Larger penetration depths and lower relative densities facilitate soil plug formation. Both the driving response and static bearing capacity of open-ended piles are affected by the soil plug that forms inside the pile during pile driving. In order to investigate the effect of the soil plug on the static and dynamic response of an open-ended pile and the load capacity of pipe piles in general, experimental pile load tests were performed on instrumented open- and closed-ended piles driven into sand. For the open-ended pile, the soil plug length was continuously measured during pile driving, allowing calculation of the incremental filling ratio for the pile. The cumulative hammer blow count for the open-ended pile was 16% lower than for the closed-ended pile. The problem is complicated by the fact that the pile may behave, as a closed-ended pile during static loading although it does not plug during installation.

Materials and Methods

This pile is a steel pipe, which is open at both ends and is driven into the ground with blows to the top of the pile. After the pile driving, the ground level is approximately the same both inside and outside the pile.

This pile is a steel pipe, which is open at both ends and is driven into the ground with blows to the top of the pile. On completion of the pile, driving the ground level is distinctly lower inside than outside the pile. The state of plugging of the pile is determined based on the difference between the ground levels inside and outside the pile. Normally, formation of the plug requires that the pile penetrates into the plugging soil layer not less than 10 x D length, where D is the diameter of the pile. Open-end pipe piles are driven in order to reduce driving stresses during driving; a soil plug can develop inside the pipe pile, Figure 1, (Paik et al., 2003).

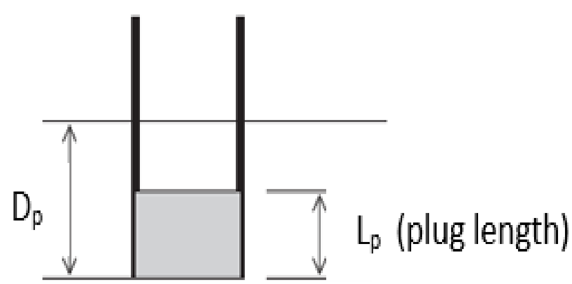

Figure 1: Plug length of open-ended pile (Paik et al., 2003).

Szechy (1961) showed that the degree of soil plugging and bearing capacity of two piles with different wall thicknesses do not differ in a significant way (with bearing capacity increasing only slightly with increasing wall thickness); only driving resistance depends significantly upon the wall thickness.

Klos and Tejchman (1981) carried out an experimental work on pile models of tubular steel of (69.9 and 128 mm) diameter, driven to 1.0 m depth in loose and dense sand where the relative density is equal to 41% and 70%, respectively . It has been indicated that, the height of soil core tends to decrease substantially with the pile driving depth. It was reported that, "a tubular pile when driven to a penetration depth equal to ten times it's inside diameter will behave as a solid –base one".

Abdullah and Al-Mhaidib (1999) studied the bearing capacity of tubular pile into sandy soil under axial loads. The effect of pile embedment length and soil plug length on the bearing capacity of open-ended piles was studies. The model pile used was steel pipe having 31 mm outside diameter, 27 mm inside diameter, 2 mm wall thickness and 380 mm length. The tests were performed with dense sand corresponding to a unit weight of approximately 18.9 kN/m^3. It was suggested that the reduction factor must be used for calculating the bearing capacity of open – ended piles by static formula, where it was equal to (0.49) for sandy soil used in the study.

Paik and Salgado (2003) stated that during the driving of open-ended pipe piles, some amount of soil will initially enter into the hollow pipe. Depending on the soil state (dense or loose) and type (fine-grained or coarse grained), diameter and length of pile, and the driving technique, the soil inside the pile may or may not allow further entry of soil into the pipe. If soil enters the pipe throughout the driving process, driving is said to take place in a fully coring mode and the behaviour is more like that of a non-displacement pile. However, if the soil forms a plug at the pile base that does not allow further entry of soil, then driving is said to be done in a fully plugged mode. If a pile were driven in the plugged mode during all of the driving, its load response would approach that of a displacement pile. In real field conditions, the behaviour is generally in between the fully plugged and coring modes. Further, depending on whether a pipe is jacked or driven into the ground, the behaviour is different.

Paik et al., (2003) described the driving response and static bearing capacities of open-ended piles affected by the soil plug that forms inside the pile during pile driving. In order to investigate the effect of the soil plug on the static and dynamic response of an open-ended pile and the load capacity of pipe piles in general, field pile load tests were performed by Paik et al. (2003) on instrumented open- and closed-ended piles driven into sand. For the open-ended pile, the soil plug length was continuously measured during pile driving, allowing calculation of the incremental filling ratio for the pile. The cumulative hammer blow count for the open-ended pile was 16% lower than that for the closed-ended pile. The limit unit shaft resistance and the limit unit base resistance of the open-ended pile were 51 and

32% lower than the corresponding values for the closed-ended pile. It was also observed, for the open-ended pile, that the unit soil plug resistance was only about 28% of the unit annulus resistance, and that the average unit of frictional resistance between the soil plug and the inner surface of the open-ended pile was36% higher than its unit outside shaft resistance.

Lehane et al., (2005) incorporated plugging into design practice in the ICP-05 and UWA-05 design approaches, for piles in sand, which are included in the commentary of the latest American Petroleum Institute (API) design code. The most significant effect of plugging for piles in sand is the increase in base resistance, with a five to seven-fold increase in the ultimate base resistance mobilized as a pile moved from the coring to fully plugged condition in sandy soil. In general, the base resistance amounts to a much smaller proportion of the total capacity of closed-ended piles in clay. This may explain the historical lack of research examining the effects of plugging on the resistance of piles in clay.

A case study was carried out by Matsumoto and Kitiyodom (2005) on soil plugging of two large diameter open-ended steel pipe piles, which were constructed in Tokyo Bay. Analysis of the load-displacement relationships of these piles were carried out using a hybrid numerical program KWAVE. Good agreement was found between the analysis results and the measurement values were found. Then a parametric study was carried out to investigate possible methods to increase the bearing capacity of the pipe piles due to the increase in the soil plugging effect. It was found that the pile/soil modelling which was employed in the study can simulate the behaviour of the pile, the soil and the soil plug during static loading, if adequate soil parameters were selected. From the parametric study, it was found that two methods are effective to increase the bearing capacity of the pile due to the increase in the soil plugging effect. One of them is to increase the length of the fully drained section in the soil plug. The other is to attach the cross steel brace inside the pipe pile.

White et al. (2007) concluded that pressing pile is an alternative method for installing an open-ended tubular pile, which can penetrate in an unplugged or a plugged manner. During unplugged penetration, the pile moves downwards relative to the internal soil column, in the manner of a sampler tube.

Penetration is resisted by shaft friction on the inside (Q_{si}) and outside (Q_{so}) of the pile and by base resistance on the annulus of pile wall (Q_w). During plugged penetration, the internal soil column is dragged downwards, and the pile exhibits the characteristics of a closed- ended pile (Paikowsky et al., 1989). Penetration is resisted by shaft friction on the outside of the shaft (Q_{so}) and by base resistance on the pile wall (Q_w) and the soil plug (Q_p). When a tubular pile is being installed by the press- in method, (or is being loaded to failure- these events are analogous), penetration will occur by whichever mechanism is the weakest. If the shaft friction on the inside of the pile (Q_{si}) (plus the weight of the soil column) is greater than the base resistance of the soil column (Q_p), the pile will penetrate in a plugged manner.

Kikuchi et al., (2010) described the mechanism of plugging phenomenon at the toe of vertically loaded open-ended piles. The behaviour of the surrounding ground at the pile toe on the observation of the movement of iron particles, which were mixed with sand to form layers in the model ground, extracted from visualized X-ray CT data. The CT images of the experimental results showed that the condition of wedge formation below the open-ended pile was clearly different from that below the closed-ended pile. Although the penetration resistance of the open-ended pile and closed-ended pile was similar, the movement of soil inside the open-ended pile was not stopped but was restricted, as shown by intermittent increase and decrease in penetration resistance during pile penetration.

Although the penetration resistance of the open-ended pile and closed-ended pile was similar, the movement of soil inside the open-ended pile was not stopped but restricted, as shown by intermittent increase and decrease in penetration resistance during pile penetration. As a result, a plugging mechanism.

The present study focuses on the determination of effect of soil plug on the ultimate compression capacity of single open – ended steel pipe pile compared with closed-ended pipe pile driven or pressed into loose sandy soil. Axial compression load tests were performed on model piles embedded in loose sand.

Results and Discussion

Description and details of the material properties, foundation soil preparation, loading frame and apparatus, testing program techniques, and manufacturing of the setup required to perform the pressed and driven model piles under static loading are presented in this section. Twenty steel pipe piles (open-ended and closed ended) were used to carry out static compression loading tests on loose sandy soil.

Kerbala sand from Iraq, which is used as a foundation soil in the present study, is poorly graded clean sand. The sand is sieved on sieve (No. 4) to remove the coarse particles. Standard tests were performed to determine the physical properties of the sand. Details of these properties are listed in Table 1.

Laboratory tests carried out on soil used included the following:

1. Specific gravity.
2. Grain size distribution.
3. Maximum and minimum dry unit weight, and
4. Direct shear test.

Sieve analysis was performed in general accordance with ASTM D422 – 2001, the grain size distribution of the sand used is shown in Figure 2. Maximum and minimum index density tests were performed in general accordance with ASTM D 4253-2000 and ASTM D 4254-, respectively.

Direct shear box test was performed in general accordance with ASTM D 3080-90. The value of the angle of friction (ϕ) for the loose sand was found to be 31^{o}.

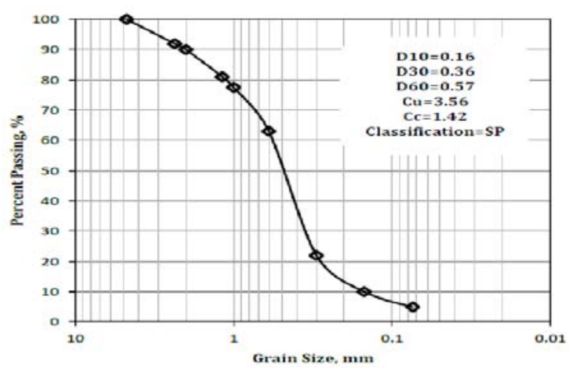

Figure 2: Grain size distribution for the sand used.

To simulate the pile load test in the field, a new apparatus was manufactured. It consists of the following parts:

1. Steel container.
2. Steel base.
3. Steel loading frame.
4. Axial loading system.
5. Raining frame.
6. Impact hammer device.
7. Mechanical jack.
8. Load cell.
9. Digital weighing indicator.
10. Gear box.
11. AC Drive (speed regulator).
12. UPS (universal power system).
13. Pile driving system –pressing system installation.
14. Soil plug removal and measurement devices.

The steel container was 0.75 m in length, 0.75 m in width, and 0.75 m in height. It was made from five separated parts, one for the base and the others for the four sides. Each part of the container was made of 4 mm thick steel plate. At the internal sides of the container, a steel bar with 1 cm^2 cross sectional area was welded along three *si*des and the front side was kept free. A steel base was manufactured to support the container and the loading frame weight. The box was rested on two channels with the ability of lateral movement.

A steel loading frame was manufactured to support the mechanical jack, axial loading system and gear box motor, as shown in Figure 3.

Figure 3: Steel loading frame and axial loading system.

Table 1: Physical properties of the sand used in the present tests.

Index property	Value	Specification
Grain size analysis		ASTM D 422-2001
D10 ,(mm)	0.35	
D30 ,(mm)	0.6	
D60 ,(mm)	0.9	
Coefficient of uniformity (Cu)	2.57	
Coefficient of curvature (Cc)	1.42	
Soil classification (USCS)	SP	
Specific gravity (Gs)	2.66	ASTM D 854-2005
Dry unit weights		
Maximum dry unit weight (kN/m3)	18.5	ASTM D 4253-2000
Minimum dry unit weight (kN/m3)	15.2	ASTM D 4254-2000
Maximum void ratio	0.41	
Minimum void ratio	0.71	

USCS = Unified soil classification system.

The load is applied through a mechanical jack connected by a gear box motor and AC Drive (speed regulator), which in turn controls the speed of the gear box motor (see Figure 3). The maximum load that can be applied is about 2 tons. The loading rate wais kept constant at 1 mm/min as recommended by Bowels (1978) for triaxial test.

A compression/tension load cell "SEWHA, Korea" model S-beam type: SS300 is used to measure the load. A digital weighing indicator is used for displaying the load amount "SEWHA, Korea" model SI 4010, with an input sensitivity of 50 gm. AC drive device (speed regulator) is connected directly to (gear box) to control the speed of rotation by inserting the value of the required speed.

The raining frame consists of two columns with changeable height. It was designed to achieve any desired elevation. This configuration of raining frame helps get a uniform density by controlling the height of fall. The rolled beam and the screw that is connected with the cone ensure that each particle drops in equal height and uniform intensity. An impact hammer was used for soil tamping, it consists of square aluminum plate (250 mm × 250 mm) and 10 mm in thickness. The plate is tied to a rod of length (500 mm) and diameter (30 mm), the weight of the group is (2.0) kg.

The central displacement of the footing is read by one dial gage of 0.01 mm sensitivity. The load increments are continued until the applied load became constant while the increments of the settlement measured continued.

Pile driving –pressing system installation.

The pile installation system consists of a base plate with dimensions of (85 cm × 20 cm) and 20 mm in thickness. This plate involves three holes (32 mm) in diameter; these holes are considered as focus place to penetrate the piles the soil in the box. Two columns are fixed vertically (28 mm) in diameter to support two beams designed from aluminum. These parts are shown in Figure 4.

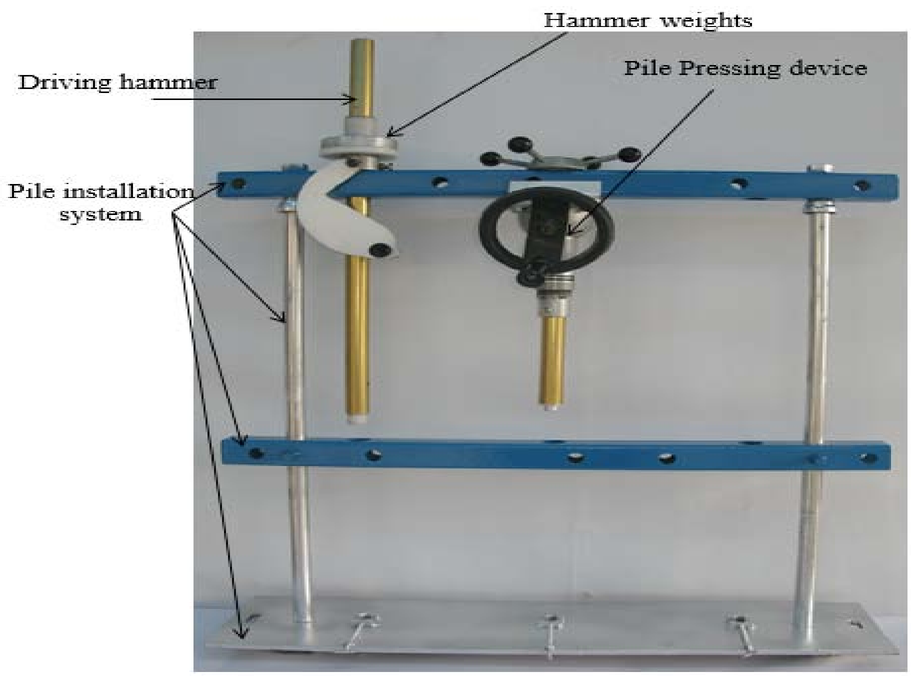

Figure 4: Pile driving –pressing system installation.

The main part in the driving hammer is the aluminum rod, it contains steel helmet in the rod head and steel cylinder which is used as a base for dropping the hammer weight. The steel helmet was manufactured with different holes that are suitable for all model pile sizes that are used in the tests. These grooves were designed to ensure the fixity of piles as possible to reserve the vertical direction for pile penetration without tilting during the driving process, these parts are shown in Figure 4. Mechanical jack was used for pressing pile into the soil at a constant rate. This jack is fixed to the pile installation system, these parts are shown in Figure 5.

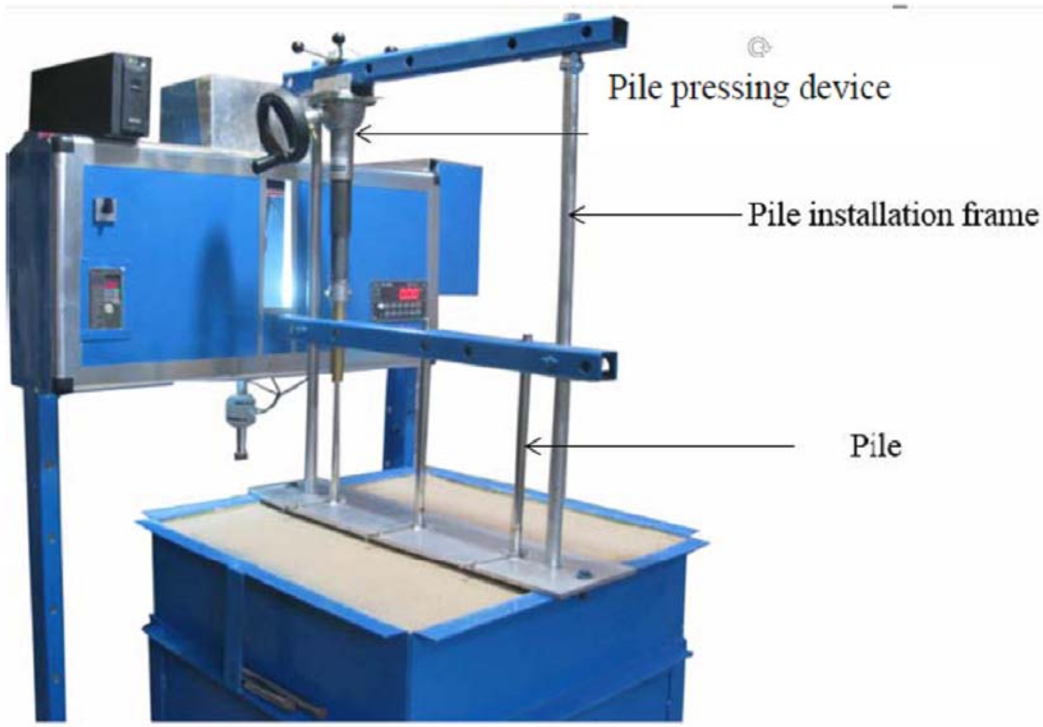

Figure 5: Pile pressing system installation.

Soil plug removal and measurement

In this study, the soil plug was removed by a device manufactured to remove the soil column entrapped inside the pipe piles during installation by driving and pressing device. This tool consists of aluminum tube 400 mm in length and 15 mm in diameter, inside a steel tube rod 470 mm in length, 8 mm diameter, and spring of 70 mm length, in the bottom of aluminum tube. A drilling device, which usually includes a rotating helical screw blade to act as a screw conveyor was used to remove the drilled soil out. The rotation of the blade causes the soil to move out of the hole being drilled. These parts are shown in Figure 6. The aluminum tube has been marked by small grooves every 10 mm to assist measure the plug length as shown in Figure 6.

Sand deposit preparation

The sand deposit was prepared using the sand raining technique. Six trials were performed to control the density of sand by raining. The sand was poured from different dropping heights 10, 20, 30, 40, and 50 cm to fulfill the same volume. The results showed that the weight of sand required to fill the computed volume increases with increasing falling height, as a result, the sand density has a direct proportion with dropping height at specific boundaries. After completing the final layer, the top surface was scraped and leveled by a sharp edge ruler to get as near as possible a flat surface. The height of drop was chosen to be 20 cm which maintains to a placing unit weight of 15.8 kN/m^3, void ratio of 0.65 and relative density of 25%.

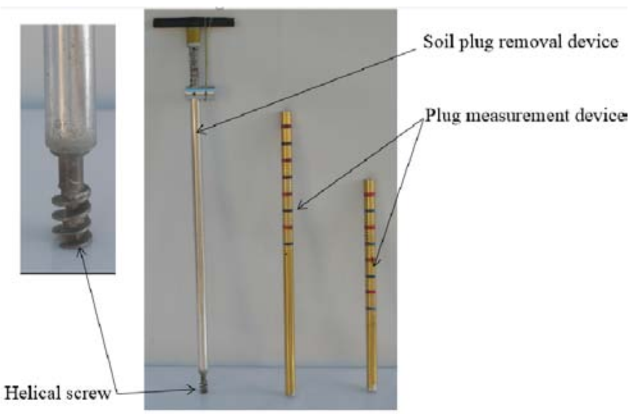

Figure 6: Soil plug removal and measurement instruments.

Details of Model Piles

Eight open-ended and two closed-ended steel pipe piles of 20 mm diameter and 1 mm thickness were used as model piles in the experimental program of the compression static loading as shown in Figures 7 and 8 . The length (embedment length) of the model piles, which was considered in the experimental programs of the tests, depends on the ratio of embedment length to pile diameter, (L/d) ratio. Details of model piles are shown in Table 2.

In order to simplify the notation used for piles, each model is given identification symbol as indicated in Table 3. ID for each pile is identification of model pile according to length of pile to diameter ratio, type of installation and type of pile.

Table 2: Model piles types and dimensions used in the tests.

Pile No.	Pile type	Soil plug situation	Diameter D (mm)	Length (mm)	
				L/d=15	L/d=20
1	Closed-ended	-	20	300	400
2-a	Open-ended	Fll Plug			
2-b	Open-ended	50 % Plug			
2-c	Open-ended	25 % Plug			
2-d	Open-ended	0 % Unplugged			

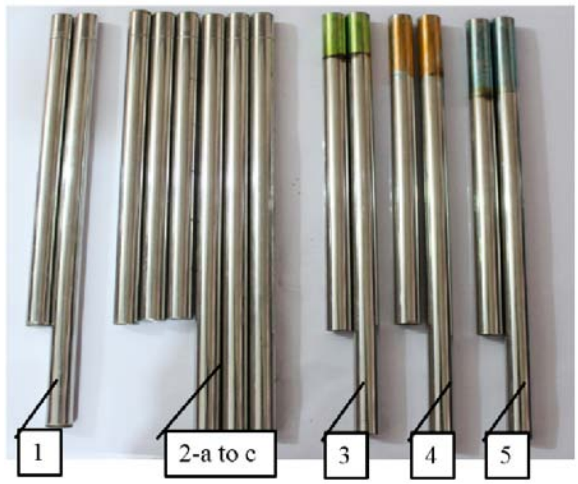

Figure 7: Pile models used in testing program.

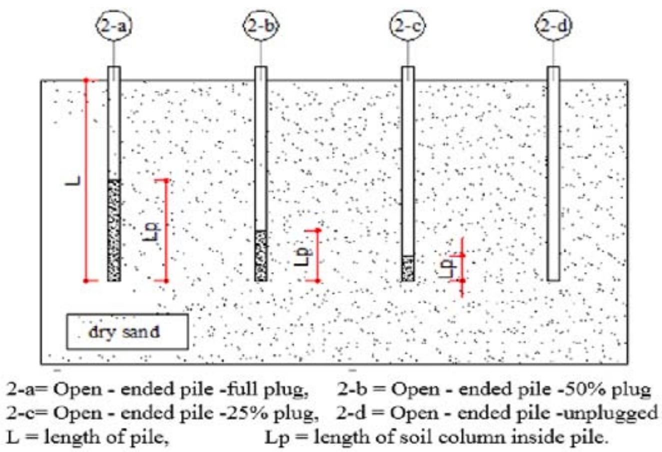

Figure 8: Development of plugs in pile models (open type) used in testing program.

Installation of model driven and pressed piles

The driving hammer was fixed to the box to penetrate the model piles to the required length. The weight that is used to drive the model piles was calculated approximately. The weight is taking into consideration many factors that affect pile capacity.

The model piles are vertically installed in specific hole that is being in the hammer plate and the rod of hammer was lowered to the model piles until the pile helmet will be in contact with the model pile. After the model pile head enters inside the helmet, the driving process begins with dropping a certain weight from a specified height, and the results of the number of blows are recorded each 25 mm of model pile length until reaching the final required length of penetration.

Table 3: Identification of open and close-ended piles.

No.	L/d ratio	Type of installation	Type of pile	ID of pile
1	15	Driven	Open-ended-Full plug	15DOF
2	15	Driven	Open-ended-Un plug	15DOU
3	15	Driven	Open-ended-25% plug	15DO25%
4	15	Driven	Open-ended-50% plug	15DO50%
5	15	Pressed	Open-ended-Full plug	15POF
6	15	Pressed	Open-ended-Un plug	15POU
7	15	Pressed	Open-ended-25% plug	15PO25%
8	15	Pressed	Open-ended-50% plug	15PO50%
9	20	Driven	Open-ended-Full plug	20DOF
10	20	Driven	Open-ended-Un plug	20DOU
11	20	Driven	Open-ended-25% plug	20DO25%
12	20	Driven	Open-ended-50% plug	20DO50%
13	20	Pressed	Open-ended-Full plug	20POF
14	20	Pressed	Open-ended-Un plug	20POU
15	20	Pressed	Open-ended-25% plug	20PO25%
16	20	Pressed	Open-ended-50% plug	20PO50%
17	15	Driven	Closed-ended	15DC
18	15	Pressed	Closed-ended	15PC
19	20	Driven	Closed-ended	20DC
20	20	Pressed	Closed-ended	20PC

The weight of ram used to drive the model piles equals 0.8 kg. This weight was chosen to obtain the best driving energy depending on the weight of pile to hammer ratio (P/W) where P is the weight of pile and W is the weight of hammer. The hammer masses used in the tests were circular in shape and formed of steel material. They have holes in the center to enable lifting and lowering along the hammer rod. The hammer mass which was lifted to a specified height by means of half- plastic plate with handle was fixed to small steel cylinder where the weight of ram drops on it; it helps the hammer to be lifted and dropped with the weights at a constant rate (Fattah et al., 2016).

For installation of model pressed piles, the mechanical jack was used and fixed in the installation frame on the box to press the model pile to penetrate the required length as shown in Figure 5.

Some of during test photos are shown in Figures 9 to 11.

Figure 9: Removing of soil plug

Figure 10: Piles installed in the model.

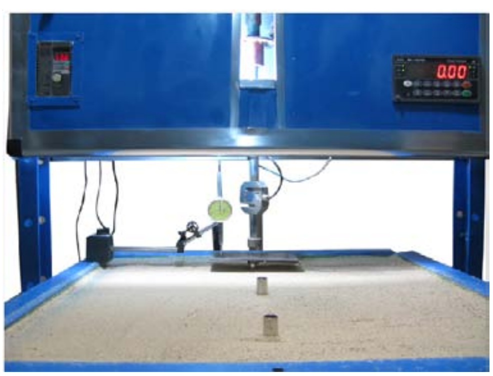

Figure 11: Testing of a pile.

Predicting of Pile Load Capacity (Ultimate Pile Capacity in Compression).

In this section, the pile capacity equation of the American Petroleum Institute, API (1993) is used to calculate the predicted pile load capacity (P_{pre}).

According to API method (API, 1993), the total load capacity of piles Q_t can be determined by the equation:

- For driven piles :

$$Q_t = Q_1 + \text{Inf}\left[Q_{p1}, Q_{p2}\right] - w \quad \text{..........(1)}$$

- For drilled and grouted piles :

$$Q_t = Q_1 + Q_p - w \quad \text{................(2)}$$

where:

a) $Q_1 = \sum_{z=z0}^{L} f_o \, \Delta A_o$ = external shaft friction capacity, equal to the sum of the external shaft friction forces over the pile penetration depth, after detection of the depth z_o along which skin friction is ignored.

L = pile length,

W = weight of pile,

Z_o = length of pile above soil,

f_o = external unit shaft friction, and

ΔA_o = external lateral contact area with the soil for layer in which f_o is applied.

b) $Q_{p1} = q_p \, A_p$ = end –bearing capacity of a pile assumed to be plugged.

q_p = unit end bearing capacity,

$A_p = A_{wp} + A_{sp}$ = total cross-sectional area at the tip,

A_{wp} = annular cross-sectional area of the tip, and

A_{sp} = cross-sectional area of the internal soil column at the tip.

c) $Q_{p2} = q_p A_{wp} + \sum_{z=z0}^{Lo} f_i \Delta A_i$ = end–bearing capacity of an open- ended pile without a plug , corresponding to the sum of the end-bearing capacity of the annulus and the shaft frictional capacity of the internal soil column

f_i = internal unit skin friction,

ΔA_i = internal surface area of soil-to-pile contact for the layer where f_i is applied,

L_o = length of pile along in which the internal soil column may have been removed.

d) $w = \sum_{z=z0}^{L} A_{wp} (\gamma_p - \gamma)\Delta L$ = weight of pile,

A_{wp} = annular cross-sectional area of the pile,

γ_p = specific weight of steel (77 kN/m^3),

γ = total unit weight of soil, and

ΔL = Length of pile sections along which the tubular cross –sectional area A_w and γ are constant.

e) For open- ended driven piles, the end-bearing capacity is limited by the bearing capacity of the internal soil column, in other words, it is taken as the lower of the two values Q_{p1} and Q_{p2} :

- If $Q_p = Q_{p1}$, the pile is said to be "plugged".
- If $Q_p = Q_{p2}$, the pile is said to be "unplugged".

An open-ended pile behaves under static condition as an "unplugged" pile as long as the internal skin friction $\sum_{z0}^{L} f_i \Delta A_i$ remains lower than the end-bearing capacity of the internal soil column $(q_p A_{sp})$:

- Unplugged open-ended pile: $\sum_{z0}^{Lo} f_i \Delta A_i < q_p A_{sp}$.
- Plugged open-ended pile: $\sum_{z0}^{Lo} f_i \Delta A_i > q_p A_{sp}$.

For pipe piles in cohesionless soil, the skin friction may be calculated using the equation (API, 1993):

$$f = K \sigma_v' \tan \delta \qquad \ldots(3)$$

where:

K = coefficient of lateral earth pressure (ratio of horizontal to vertical normal effective stress),

σ_v' = effective vertical overburden pressure at the point in question, and

δ = friction angle between the soil and pile wall.

The unit end-bearing (tip resistance) of pile in cohesionless soil may be computed using the equation (API, 1993):

$q_p = \sigma_v' N_q$ ……………..(4)

where:

σ_v' = effective overburden pressure,

and

N_q = dimensionless bearing capacity factor.

The API method illustrated in the previous section is used here to calculate the pile bearing capacity for different plug conditions. Table 4 shows the predicted bearing capacity values obtained from the theoretical API method in addition to values measured during the tests. The failure load in experimental result is considered as the load at which the settlement continues under constant load. It can be noticed that the API method underestimates the pile bearing capacity for all pile and soil conditions.

Table 4: Measured pile load capacity (P_m) and predicted pile bearing capacity values obtained from the theoretical API method , pile length = 40 cm.

Type of Installation	Type of Pile	Measured Pile Load Capacity (N)	Predicted Pile Load Capacity , API method (N)
Driven	20DC	148	81.6
	20DOF	140	58.3
	20DO50%	137	54.5
	20DO25%	80	52.6
	20DOU	77	50.75
Pressed	20PC	156	81.6
	20POF	155	52.6
	20PO50%	142	51.7
	20PO25%	104	51.2
	20POU	64	50.75

Interpretation of Pile Load Capacity

Several methods (criteria) are used to define the failure load from load-settlement curves; some of these methods are Davison, Chin Konder, Fuller and Hoy, De Beer, Terzaghi Criteria and constant load vs. increase of settlement according to Civil Engineering Code of Practice No.4, 1954). Throughout the pile load test, the pile is loaded to failure, the settlement continues at fixed load (failure), and this load is considered as the failure pile load capacity **(P_f)**.

According to the Civil Engineering Code of Practice No.4, (1954), the ultimate load capacity is that load at which the rate of settlement continues at a constant rate. Table 5 shows the interpretation of pile load capacity for 40 cm long of closed and open-ended piles driven into loose sand.

Presentation of Load Settlement Curves.

Open – ended pipe pile was chosen as a reference pile to compare all other types of model pile ultimate capacity, settlement and failure pile load capacity. This pile was chosen for each model installed in loose sand, type of installation and length of pile.

Open- ended piles.

Sixteen open-ended piles have been tested and these piles are divided into four groups:

I. Open –ended piles with full plug: in this type of piles, the soil column inside the pipe is not removed before pile test.

II. Open –ended with 50% plug: in this type of piles, 50% of the total length of the soil column inside the pipe is removed before pile test.

III. Open –ended with 25% plug: in this type of piles, 75% of the total length of the soil column inside the pipe is removed before pile test.

IV. Unplugged open –ended piles: in this type of piles, 100% of the total length of the soil column inside the pipe is removed before pile test.

Table 5: Interpretation of driven pile load capacity in loose sand (N).

No.		Civil Engineering Code of Practice No.4, (1954)	Measured Failure Load
1	20DC	146	148
2	20DOF	140	142
3	20DO50%	137	140
4	20DO25%	80	83
5	20DOU	77	80

Figures 12 to 15 present the load- settlement curves for model open-ended piles (full plug, 50% plug, 25 % plug, and unplugged) and show the effect of removing of the soil column inside the pile. It can be noticed that all load-settlement curves exhibit punching shear failure.

Closed ended piles

Four models of closed ended pile were tested in compression static load. The piles were installed by two types of installation system (driving and pressing) in loose sand. The observed load-settlement relations are described in Figures 16 and 17.

Table 6 presents the pile load capacity according to Civil Engineering Code of Practice No.4, 1954 for driven and pressed piles of 40 cm and 30 cm length closed and open-ended driven or pressed into sand of different densities.

According to Szechy (1961), the settlement of an open-ended pile is greater than that of a closed-ended pile under the same load and soil conditions. This means that, if ultimate load capacity is defined with reference to a standard settlement of 10% of the pile diameter, for example, the load capacity of open- ended piles is typically lower than that of closed-ended piles. However, the difference in load capacities varies within a wide range, depending on the degree of soil plugging during driving. This is compatible with the findings of Szechy (1961).

According to Paik and Lee (1994), the difference between the load capacity of closed- and open-ended piles decreases with increasing driving depth, as the soil plugging effect increases.

Pile driving results in densification of all sands immediately below the pile tip, regardless of their initial relative density (Szechy, 1961). This densification extends within the first few diameters of the soil core. Densification is an important ingredient in the formation of an arch and promoting plugging (Iskander 2010, Fattah and Al-Soudani, 2016).

Table 6: Pile bearing capacity according to the Civil Engineering Code of Practice No.4, (1954).

Type of installation	Type of pile	Measured pile load capacity (N)
Driven	20DC	148
	20DOF	140
	20DO50%	137
	20DO25%	80
	20DOU	77
Pressed	20PC	156
	20POF	155
	20PO50%	143
	20PO25%	104
	20POU	64
Driven	15DC	132
	15DOF	150
	15DO50%	128
	15DO25%	112
	15DOU	55
Pressed	15PC	103
	15POF	112
	15PO50%	91
	15PO25%	61
	15POU	59

On the other hand, the length of pile plays an important role in controlling the pile load capacity in pressed piles. When L/d = 20, there is greater increase in pile capacity due to mobilization of skin friction, while when L/d = 15 , the improvement in load carrying capacity is due to dilation effect in the latter type.

During the driving of open-ended pipe piles, some amount of soil will initially enter into the hollow pipe. Depending on the soil state (dense or loose) and type (fine-grained or coarsegrained), diameter and length of pile, and the driving technique, the soil inside the pile may or may not allow further entry of soil into the pipe. When the open-ended pile is fully plugged, its load carrying capacity is close to closed ended pile as shown in Table 6.

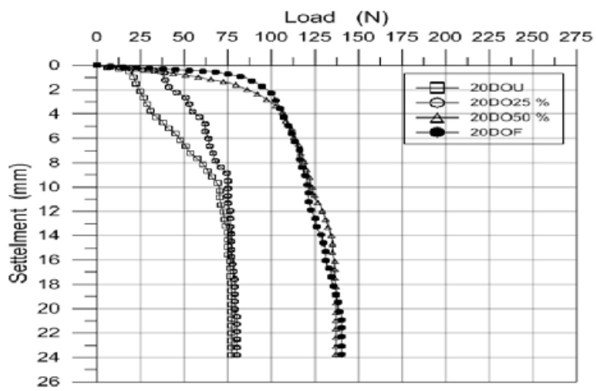

Figure 12: Load- settlement relations for open-ended driven piles in loose sand, L=40 cm.

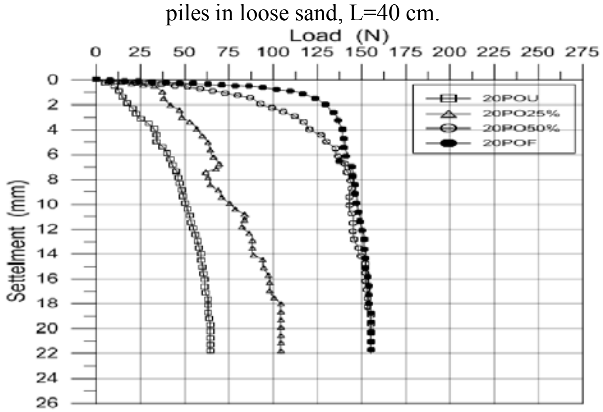

Figure 13: Load- settlement relations for open-ended pressed piles in loose sand, L=40 cm.

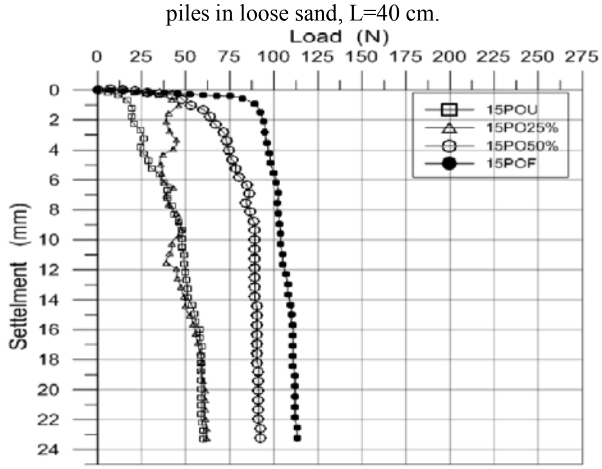

Figure (14): Load- settlement relations for open-ended driven piles in loose sand, L=30 cm.

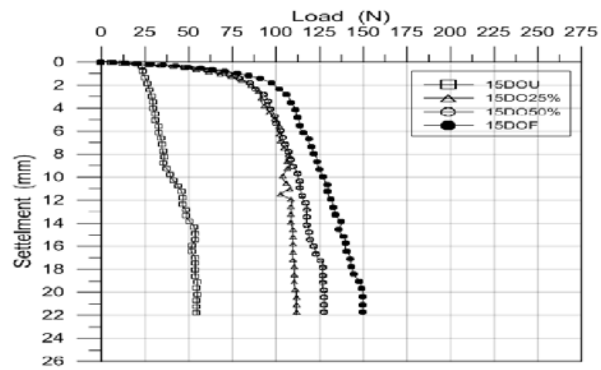

Figure (15): Load- settlement relations for open-ended pressed piles in loose sand, L=30 cm.

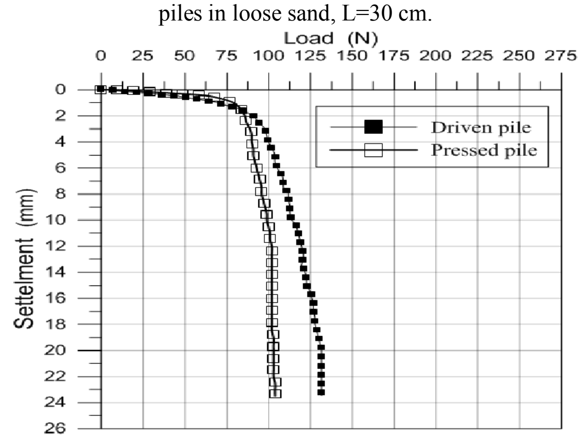

Figure (16): Load- settlement relations for closed – ended driven and pressed piles in loose sand, L=40 cm.

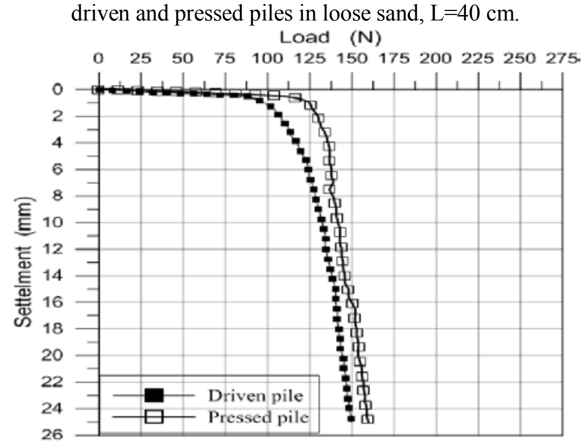

Figure (17): Load- settlement relations for closed – ended driven and pressed piles in loose sand, L=30 cm.

Klos and Tejchman (1977) concluded that a tubular pile when driven to a penetration depth equal to ten times its inside diameter will behave as a solid –based one. In this study, it was concluded that when L/d ≥ 15, the load carrying capacity of fully plugged open-ended pipe pile may be equal or grater than that of closed-ended pile.

Piles, which plug during static loading may, nevertheless, have smaller tip bearing capacities than their closed-end counterparts. On the other hand, the inside skin friction may contribute considerably to the load carrying capacity.

The failure of a pile to plug during driving does not necessarily mean that it will not plug during static loading, since inertia effects, which are present during driving are absent during static loading. This can be observed from the load-settlement curves where the open-ended piles exhibit large resistance to penetration due to mobilization of internal friction during static loading.

The driven pile mobilizes all of its internal and external friction intermittently during penetration and, as a result, the soil core advances up the pile. As penetration progresses, the soil core inside the pile may develop sufficient frictional resistance along the inner pile wall to prevent further soil intrusion, causing the pile to become plugged. Larger penetration depths and lower relative densities facilitate soil plug formation. Previous studies showed that a short open-ended pile has lower load capacity than an equivalent closed-ended pile. The present study proved that if the pile is embedded in loose sand, the fully plugged open-ended pile reveals a load carrying capacity equal or may be greater than closed-ended pile.

Conclusions

Open-ended pipe piles behave as a closed-ended if the soil plug formed inside piles in state partial plug or full plug. Length of soil plug depends on the type of installation. The driven pile mobilizes all of its internal and external friction intermittently during penetration and, as a result, the soil core advances up the pile. Whether open-ended piles are driven or pressed in the fully coring -fully unplugged mode or in the partially plugged mode, the plug does contribute to static pile base capacity. The settlement of an open-ended pile is greater than that of a closed-ended pile under the same load and soil conditions. This means that, if ultimate load capacity is defined with reference to a standard settlement of 10% of the pile diameter, for example, the load capacity of open- ended piles is typically lower than that of closed-ended piles. However, the difference in load capacities varies within a wide range, depending on the degree of soil plugging during driving. When a pipe pile is driven to a penetration depth equal to fifteen times its inside diameter, it will behave as a solid–based and the load carrying capacity of fully plugged open-ended pipe pile may be equal or grater than that of closed-ended pile. The failure of a pile to plug during driving does not necessarily mean that it will not plug during static loading, since inertia effects, which are present during driving are absent during static loading. This can be observed from the load-settlement curves where the open-ended piles exhibit large resistance to penetration due to mobilization of internal friction during static loading.

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