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Bearing Capacity of Driven Open-Ended Pipe Piles in Weak Soil Formations

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***Abstract*- Steel pipe piles have been increasingly used as deep foundations for offshore or onshore structures in weak soil formations. These piles are usually open-ended and installed to their final level using suitable hammers or vibrators relying on the subsurface conditions. Simultaneously, the soil plug (SP) forms inside the employed pipe pile during driving or installation. Moreover, it affects bearing behavior and total pile resistance. The experimental tests have been performed on a single tube pile. All tube piles were tested using the well-graded sand collected from the Egyptian desert, and the sand was prepared at medium density using a raining technique. The outcomes of the model pile tests showed that the value of plug resistance in open-ended pipe pile (OEPP) is typically on the order of 50% to 70% of the total pile load of OEPP, and it is influenced by pile thickness, pile diameter, pile length, and submerged state. Simultaneously, the plugging influence of OEPP increased with increasing pile thickness and embedded pile length. However, the plugging influence decreased with increasing pile diameter. The total pile load of OEPP increased with increasing the embedded pile length. It must be noted that the influence of pile length on the total pile load is greater than the influence of pile diameter; this refers to the pile length having a significant effect on the total pile load. This is due to an increase in the influence of SP.**

Keywords- Steel pipe pile; Open-ended; Soil plug; Pile resistance; Single pile.

I. INTRODUCTION

Open-ended pipe piles (OEPPs) have been increasingly utilized as deep foundations for onshore structures or offshore structures in cohesionless (sandy) soil. These piles are usually open-ended and installed to their final level using suitable hammers or vibrators relying on the subsurface conditions. Such piles' capacity is gained from a combination of the external friction, the internal friction, end bearing on the annulus, and the end bearing due to soil plug (SP). The SP will be formed during the pile installation or driving process. In this research, laboratory studies will be performed and integrated to study SP formation's influence on the total pile capacity of this type. The outcomes of the analyses will be thoroughly studied and compared to correlations published in such literature. Based on the study outcomes, recommendations for estimating the capacity of such pile types will be given. Nevertheless, a few types of research and experimental work have been raised to cover this topic, and there were limited trials to analyze the conduct of OEPP.

Murthy [1] and Mahmood [2] conducted a series of experimental tests to investigate the total pile capacity of rigid model piles in the sand. In this research, an experimental study is performed to quantify the total pile capacity of driven open-ended tube piles due to external friction, internal friction, and end bearing load due to the pile's SP and thickness. The study will extend to cover the influence of the submerged conditions, pile length, pile diameter, and pipe thickness on the SP formation and bearing resistance of a tubular pile.

II. LITERATURE REVIEW

Piles are structure elements in a foundation that transfer load from the superstructure through a mostly weak compressible layer or the water onto the stiffer layer. They may be required to carry uplift loads when used to support high structures subjected to overturning forces from winds or earthquakes T. MJ [3]. The steel tube pile has already been performed as deep foundations for the offshore structure. These piles are usually open at the end and installed to their final level using suitable hammers or vibrators relying on the subsurface conditions. So, the conduct of OEPP has already been the focus of many studies within the last years. The two main types of steel tube piles may be driven either closed or open-ended. OEPPs include open-end plugged piles, open-end unplugged piles. Open-end plugged piles are suitable when the SP develops inside the employed tube pile due to the influence of friction, and the pile acts like a closed-ended tube pile.

To a great extent, the plug can increase the tube pile tip resistance. Open-end unplugged piles do not occur because pile driving is less laborious, and the stresses passing through the shaft are small compared to closed-ended driven piles. In general, the expression soil is plugging mentions the status where the soil into the pipe pile has mobilized enough frictional resistance to overcome the lower end resistance and avoid the additional soil from getting into the pile. The mechanism for redistribution of stresses within a soil body has been shown by Paikowsky [4] to include the arching mechanism in cohesionless (sandy) soil. During the installation of OEPPs, the pile walls move relative to the soil body as passive arching. The passive tube pile arching causes the formation of concave soil at the tube pile tip level. In this case, an arching mechanism can transfer axial stress acting on the internal soil column at the toe of the pile to the pile walls in the form of horizontal (normal) stress, giving rise to increased internal shaft friction and plug resistance. The forming of a plug relies on various factors, like the diameter of the pile and the installation method. There are various measurable parameters to understand the plug inside the tube pile. A measurable parameter is the so-named Incremental Filling Ratio (IFR) presented by Bruce et al. [5]. The function is expressed in Eq. (1)

$$IFR = \Delta h / \Delta L \quad (1)$$

Where Δh: Incremental plug length inside the pipe pile for each x meters of penetration. ΔL: Incremental pile embedded length inside a soil for each x meters of penetration.

Three different situations come to rise, as presented in the following. IFR equals zero, IFR lower than one, and IFR equals one. IFR is equivalent to zero. It indicates that the tube pile is already closed, with no SP inside the employed tube pile. IFR is equaled to one. It indicates that the SP is not moving already downwards into the tube pile. Moreover, there is already no plug, and therefore Δh equals ΔL. While IFR is lower than one, indicating that the tube pile already has partial plugging. Paik et al. [6] presented the so-named Plug Length Ratio (PLR). It is well-defined like an IFR but that PLR is not an incremental value, and it is only once measured at the end of the installation of the pile at a selected depth. The function expressed in Eq. (2).

$$PLR=h/L \qquad (2)$$

Determining the end bearing capacity and the shaft friction of the steel tube pile is a challenging task. Various approaches to explain this phenomenon are documented. A few of those are based on on-site testing, some on numerical simulations.

Szechy [7] exhibited that there is no significant difference in the quantity of plugging for the ultimate load of two piles with different wall thicknesses (when the pile thickness increases, the pile capacity will increase only slightly); the driving resistance has already been affected significantly by the wall thickness.

However, Heerema and De Jong [8] distinguished SP throughout driving and testing and reported that if a pile does not plug or is partially plugged during driving, it may plug solidly and behaves as a closed-toe pile during static loading.

Klos and Tejchman [9] executed experimental research of steel tubular pile models with were driven in loose sand and dense sand. The height of a soil column was indicated to decrease significantly with the increased embedded pile length inside the soil. It was stated that a tube pile would behave like a closed-base one while driving to an embedded length equal to 10 times inside pile diameter.

Paikowsky [4] stated that, throughout the first stage of installation of a tube pile in the sand, soil enters inside the employed pipe pile at a ratio equivalent to the pile penetration inside a soil. As pile penetration continues inside a soil, the interior SP cylinder may develop enough resistance to deny moreover soil entered, and it causes the soil to become plugged.

A. P. I. [10] showed that this type of deep foundation is mainly utilized for offshore foundation design; the total pile load can only be estimated for either the unplugged mode or the fully plugged mode of embedded length. In practice, most tubular piles are driven into sand soil in a partially plugged mode.

Tomlinson and Woodward [11] suggested that for OEP driven in cohesion fewer materials, the ultimate bearing capacity can be taken as the sum of the skin friction along the external perimeter of the shaft and the ultimate base resistance, i.e., ignoring the internal friction between SP and pile. The skin friction and ultimate base resistance can be determined as if the pile were closed-ended, but a reduction factor of 0.8 and 0.5, respectively, should be applied. The tip end resistance must be calculated utilizing the gross area of the pile.

Al-Mhaidib [12] studied the total pile load of a tube pile driven inside the sand under axial compression loads. The influence of pile penetration depth inside a soil and plug length inside the employed tube pile on the total pile capacity of tube piles has already been studied. It was recommended that the reduction factor should be utilized for computing the total pile capacity of tube piles by static formula, where the reduction factor was already equal to 0.49 for cohesionless soil that was utilized in such study.

Lehane and Randolph [13] Calculated the min tip resistance for driven tubular piles in sand soil and made a presumption, which exhibits that the base pile capacity for a steel tube pile that has been installed in plugged coring or partially plugged mode is already exactly similar as for closed-ended tubular piles.

Paik and Salgado [14] described that the static total pile load of a tube pile was influenced by the conduct of SP that formed inside the employed tube pile during the installation or (driving) process. The field tube pile load test was done on instrumented tubular and closed-ended tube piles driven inside sandy soil. For the tubular pile, the plug length inside the employed tube has been continuously measured during the installation or (driving) process, letting the calculation of IFR for the tube pile. Noted that the cumulative hammer number blow count to installing a tube pile was 16% lesser than that for a closed-ended tube pile. The shaft resistance and base resistance for a tube pile were 51% and 32% lesser than the resultant values for a closed-ended tube pile.

Kikuchi et al.[15] Defined the conduct of the plugging at the base of tubular piles. The experimental test results exhibited that the mode of soil formation at the tube pile tip for the tube pile was various from that below a closed-ended tube pile. In comparison, the penetration resistance of a tubular pile and a closed-ended tube pile has already been similar. Moreover, the movement of SP inside the employed tube was not stopped but was limited.

In Fattah and Al-Soudani [16], the small-scale experimental tests contain 36 tests performed on single tube piles. Various parameters are already considered, like the method of installation, pile length to diameter (L/D) ratio, relative density, and removal of SP. Strain gauges are already utilized to already divide skin friction with two components from and end bearing resistance. It was concluded that the pile capacity of a closed-end tube is slightly larger than that of open-ended in loose and medium sands (by about 10%). In dense sands, the capacity of OEPP with fully plugged was found substantially larger than that of closed-ended tube piles (by 42% and 50%) for the same lengths and diameters. The removal of SP from inside the tube piles caused a lowering in tube pile capacity due to the removal of two components, the internal friction and the confining, at the end bearing zone due to the forming of SP.

Mahmood [2] concluded that the ultimate load-carrying capacity of tube piles embedded within partially saturated soils is more significant than those embedded within saturated soil. The higher pile capacity was given in fine sand more than the coarse sand. Nevertheless, the coarse sand gives a reduced resistance at various saturation conditions. Under a fully saturated state, the coarse sand gives a lower resistance, while medium sand gives a higher resistance. The increment ratios in the ultimate carrying capacity for smaller pile diameters are more significant than larger ones.

Many approaches have already been developed through the years to determine the tube pile capacity, e.g., from De

Nicola and Randolph [17] and Paik and Salgado [14]. Recent approaches are A. P. I. [10]. API method Hannigan et al. [18]. FHWA method, FinnRA method, and (China's Code). A comparison of some methods can be found in Y. Guo and X. B. Yu [19].

III. EXPERIMENTAL SET-UP

This section demonstrates a complete characterization of an experimental program, testing procedure, and measurement technique to evaluate the ultimate capacity of driven OEPP in weak soil formations and different parameters that affect pile capacity. The tests were already performed in the geotechnical engineering research lab at the faculty of engineering at Ain Shams University.

A. Soil Properties

The soil type used in this research was medium sand; this medium sand was collected from the Egyptian desert. This type of soil was selected in such a study because it's widely used for many research purposes and has well-known properties presented by [2-16-24-25]. The sand sample was sieved on a sieve (No. 4) to separate sand particles and remove the coarse particles. Standard laboratory tests were already performed to determine the engineering and physical properties of the medium sand sample, as illustrated in Table 1.

Table 1. Physical properties of the used soil

Parameters	Symbol	Medium Sand
The effective diameter (mm)	D_{10}	0.194
The coefficient of curvature	C_c	0.884
The coefficient of uniformity	C_u	2.41
Specific gravity	G_s	2.62
Dry unit weight (kN/m^3)	γ_{dry}	16.50
Maximum dry unit weight (kN/m^3)	γ_{max}	18.80
Minimum dry unit weight (kN/m^3)	γ_{min}	14.30
Relative density (%)	D_r	55
The angle of internal friction in a dry state (degree)	Φ	34.80°
The angle of internal friction in the submerged state (degree)	Φ'	32.00°

B. Model Pipe Piles

In such a study, six steel OEPPs were used as a pile of 50cm length, as shown in figure 1. Three types of different pile diameters of (32, 38, and 42) mm were used in this research, with two different pile thicknesses of (1.5 and 2) mm to achieve the main objective of this study. The embedded length of the model piles and diameter of the pile were selected according to the ratio between pile length/diameter (L/D) to achieve the ratio suggested by Klos and Tejchman [9], which states that the ratio between (L/D) must not be less than ten times diameter of the pile to form the SP inside the employed tube pile. Also, The pile thickness was selected according to the ratio between pile diameter and thickness ratio (D/t) to achieve the ratio suggested by Jardine and Chow [20], which states that the ratio of pile diameter and pile thickness (D/t) ranged between (15 and 45) for safety design and economical.

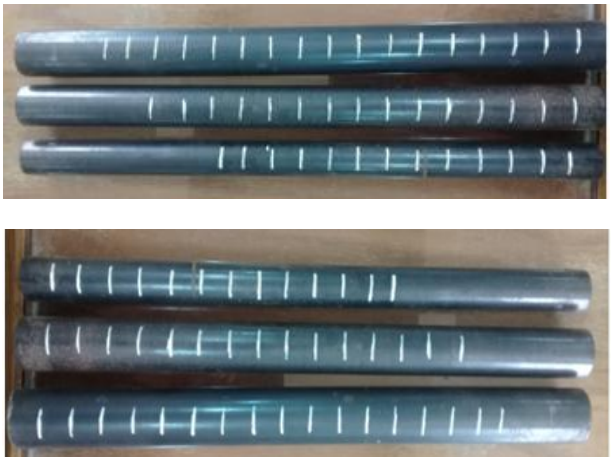

Figure 1. Models of steely tube piles with two different pile thicknesses of (1.5 and 2) mm and pile diameters (32, 38, and 42) mm.

C. Model Set-up Formulation

The main parts of the model comprise the following parts: a steel tank, loading frame, axial loading system in compression, axial loading system in tension, raining soil system, compaction hammer, pile installation system, pile driving system, and Soil plug removal device. Figures From (3) to (4) illustrate the model components.

I. Steel tank

Dimensions of the steel tank are 1000 mm in length, 1000 mm in width, and 750 mm in depth. However, these dimensions were chosen to achieve the boundary conditions for piles. The steel tank is composed of five steel plates with a thickness equal to 4 mm, four steel plates were used for sides, and one steel plate was used for the base. Moreover, the side plates of the steel tank were welded with the base plate, and steel angles were added to the side plates to prevent the sides buckling during compaction of the soil to prepare for the test.

II. The Loading System

The loading system has consisted of the following: the loading frame was manufactured to support the axial loading system, and it was designed from steel sections as presented in figure 2. Moreover, the loading frame consists of four columns of 1500 mm height were bolted with the steel tank and three horizontal beams of span 1000 mm; two beams are fixed in the columns. While the other moves horizontally forward and backward. The second components are an electrical motor and the screw jack; both are fixed on the moving horizontal beam with two plates to allow this electrical motor and screw jack to move to any point on the steel tank, as indicated in figure 2 figure 3. The applied load on the pile will be transmitted through a screw jack connected to an electric motor equipped with a variable speed drive for reducing shaft speed to 60 rpm. The maximum load of a screw jack is 500 kg in compression load and tension load. The load rate is kept constant to 1 mm/min, as recommended by Bowles [21] for the triaxial test.

A proving ring, a sensitive balance, and a vertical loading rod were used to transmit the load from the screw jack to the pile sample. Two vertical loading rods were used to carry the load to the pile, one of them is used to transmit the compression load from a proving ring to the pile, and the other is used to transmit the tension load from the pile to a Sensitive balance to measuring the external friction of pile. Moreover, the two vertical loading rods were manufactured to reach different loading levels of piles, as shown in figure 4.

A proving ring has been employed to measure the applied load transmitted to the pile model. Employed proving ring has a capacity of 500 kg. At the top side of the axial loading system, a proving ring was directly connected to the mechanical screw jack, while its bottom side was directly connected to the vertical loading rod, as depicted in figure 4. A proving ring is jointed with a dial gauge with an accuracy of 0.002 mm.

Also, a sensitive balance has been employed to measure the resistance of external friction of pile. At the top side of the axial loading system, the sensitive balance was directly connected to the mechanical screw jack, while its bottom side was directly connected to the vertical bar that connected with the pile during the test, as depicted in figure 4. Employed Sensitive balance has a capacity of 50 kg with an accuracy of 0.001 kg.

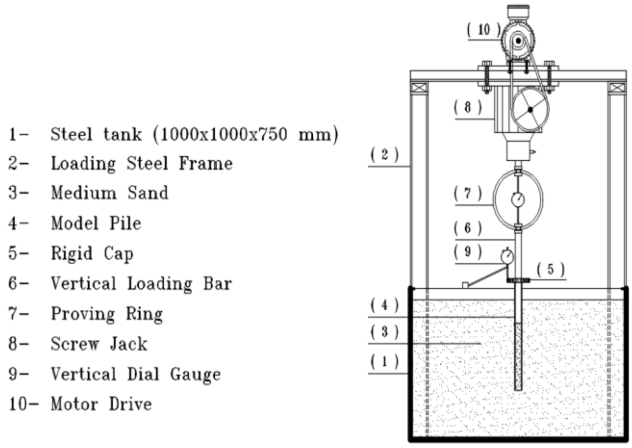

Figure 2. Schematic Diagram for the Model Components.

Figure 3. Test model components

Figure 4. Proving ring with dial gauge 0.002 mm accuracy and a Sensitive balance.

A vertical dial gauge was used to record the vertical displacement of the pile during the pile loading, as shown in figure 4. A vertical dial gauge has been located at the top of the pile cap at a specific distance. The compression of the Vertical loading rod is neglected because of its high rigidity. Also, a vertical dial gauge has been located at the screw jack to record the vertical displacement of the pile while measuring the resistance to external friction of the pile.

D. Soil Preparation

Sand-bed was prepared in the fabricated steel-framed experimental cubic tank. The sand sample was sieved on a sieve (No. 4) to separate sand particles and remove the coarse particles. A standard cone was used to fill the tank from a known height. The moving horizontal beam was designed to carry the steel cone used to pour the sand. This raining frame configuration helps get a uniform density by controlling the height of the fall of 30 cm as recommended by Fattah and Al-Soudani [16] to achieve medium relative density (Dr). The moving beam and the screw are jointed with the cone to ensure each particle drops at equal height and uniform intensity. A mesh steel piece (diameter of the opening is 10 mm) is already put into the cone to decrease the influence of particles.

Based on the considered relative density, the required volume of sand was placed in six layers. The continuous filling was used so that a uniform density was ensured. The sand cone test was performed at the upper layer of the tank to ensure that the obtained medium density matches the required one. The top surface of the upper sand layer was leveled with a straight edge to produce a smooth surface. For the tests, where a submerged state was needed, water was provided from the bottom of the sand bed by hose pipe. A layer of aggregate with 6 cm thickness was prepared in the bottom of the tank as a filter to enter the water, and a Plastic mesh with small holes was laid at the top level of this layer to prevent sand particles from passing through it, as indicated in figure 5. Sand-bed was prepared to the final level; after that, the water was entered from the bottom of the steel tank by a hosepipe, as indicated in figure 5. The rate of entry of water was very slow, and it was left for three days before testing to ensure sand grains were deposited to avoid soil disintegration during the water entered the tank.

Figure 5. Water was provided from the bottom of the sand bed

Table 2. The testing program for the single piles of different dimensions.

Test Designation	Submerged	Pile Outside Diameter D(mm)	Embedded length of pile L(mm)	The thickness of pile t(mm)	L/D ratio	D/t ratio
P-1	Dry State	32	320	1.5	10	21.3
P-2		38	380	1.5		25.3
P-3		42	420	1.5		28
P-4		32	320	2		16
P-5		38	380	2		19
P-6		42	420	2		21
P-7	Dry State	32	320	1.5	10	21.3
P-8			384		12	
P-9			448		14	
P-10	Submerged State	32	320	1.5	10	21.3
P-11			384		12	
P-12			448		14	

E. Configuration of the Testing Program

In total, (12) experimental tests were conducted in such a study, including the tests performed on OEPPs in a dry state and submerged state; table 2 illustrates the testing program for the OEPPs of different dimensions. With the dimensions previously presented in this section. The main parameters considered in such study were pile diameter, pile thickness, the ratio between pile length/pile diameters, submerged condition.

F. Steel pipe-pile Preparation

The capacity of OEPP is gained from a combination of the external friction, the internal friction, end bearing on the annulus of the pipe, and bearing resistance on SP. Hence, four tests are already performed for the model pile to get the total pile capacity and all components of pile capacity.

Firstly: Sand-bed was prepared by the procedures described previously. The Pile installation system is one of the most critical steps for correctly driving a pile. Ensure and install the pile in a vertical direction and avoid tilting during the pile installation. So, the pile installation system comprises two base plates with a thickness of 4 mm and dimensions of (1000 mm x 100 mm). Each plate contains three holes with a diameter of 44 mm for an installation pile diameter of 42 mm. moreover, for the second pair of plates, a diameter of the three holes is 40 mm for an installation pile diameter of 38 mm. finally, for the third pair of plates, a diameter of the three holes is 34 mm for an installation pile diameter of 32 mm. These holes are considered concentrated places to allow piles to penetrate the soil, and the whole diameter was selected to allow piles to move inside it without any obstruction. Two steel columns are fixed vertically with a diameter of 10 mm and were used to support two plates, as indicated in figure 6.

The three models for the one pile were driven by using a hammer through the holes of the templates. A drop hammer is a device that was manufactured to drive the model piles inside a soil to the required length. This hammer consisted of a steel cylinder, the rod of the hammer, and the hammer weight. A steel cylinder is used as a pile helmet and a base for the hammer weight. The drop hammer was vertically installed on the pile head; after that, the driving process beginning with dropping a weight of hammer from a fixed height of 30 cm as recommended by Murthy [1], with a constant rate, and The outcomes of the number of blows are recorded each 25 mm of model pile length until reaching the final required length of penetration. The hammer utilized to drive a tube pile is presented in figure 7.

A steel measuring rod has been employed to measure the plug length inside the employed tube pile during the pile driven in soil. The measuring rod has a length of 600 mm and a diameter of 10 mm; this diameter has been selected according to pile diameter.

To measure the external friction for OEPP, the SP has been removed using three Soil plug removal devices manufactured to eliminate the soil entrapped inside the employed tube piles during the pile installation. This device consists of a steel rod with a diameter of 10 mm and a length of 600 mm. the lowest part of the steel rod is a spiral part with different three diameters of (40, 36, and 30) mm this diameter has been selected according to piles diameters that allow being removed the soil from inside the employed tube pile as presented in figure 8 and figure 11. The rotation of the auger causes the auger to be inserted to the required depth inside the employed tube pile. After that, the auger is pulled gently to avoid any pile movement. The templates were then released from the piles using the screws on their sides. Finally, three tests are performed for three models to get the ultimate pile capacity, the end bearing on the annulus, and the external friction are as follows:

Test (1): the first test was performed on the first pile model to get the ultimate pile capacity. A proving ring and the vertical loading rod were fixed in their positions. The vertical dial gauge was set in their position, as indicated in figure 9. The readings from the dial were taken; to construct the necessary calculations for the drawing of load-displacement curves. The compression load was applied to the pile through the screw jack, where the screw jack was rotated at a constant rate; the load was continuously applied until failure occurs, which is a great settlement with a constant load for pile and a continuous settlement with increasing the load to form a nearly linear relation for the pile.

Figure 6. Pile system installation.

Figure 7. Driven the pile models.

Figure 8. Steel pipe-pile after installation

Test (2): the second test was performed on the second pile model to get the end bearing on the annulus. The influence of the thickness of the pile model with 0.1 mm thickness at the pile tip is minimal. So, the influence of thickness was neglected, as shown in figure 10. A proving ring and the vertical loading rod were fixed in their positions. The vertical dial gauge was set in their position, as indicated in figure 9. The compression load was applied to the pile through the screw jack, where the screw jack was rotated at a constant rate; the load was continuously applied until failure occurs, which is a great settlement with a constant load for pile and a continuous settlement with increasing the load to form a nearly linear relation for the pile. The readings from the dial were taken; to construct the necessary calculations for the drawing of load-displacement curves. Finally, the end bearing on the annulus = the results get from the test (1) - the results get from the test (2).

Test (3): the third test was performed on the third pile model to get the external friction. The SP has already been removed utilizing an industrialized device to remove a soil column entrapped into the tube piles through installation by driving as previously described. The vertical dial gauge and a Sensitive balance were set in their position as indicated in figure 11. The tension load was applied to the pile through the screw jack, where the screw jack was rotated at a constant rate in the reverse direction; the tension load was continuously applied until failure occurs, which is a great movement with a constant load for pile and a continuous movement with increasing the load to form a nearly linear relation for the pile. The readings from the dial were taken; to construct the necessary calculations for the drawing of load-displacement curves.

*Secondly***:** the push-up load test for sand plug inside an open-ended tube pile was performed to get the internal friction as recommended by Thongmunee et al. [22]. After performing the test (1), the pile has been removed from the soil while maintaining the same soil formation inside the employed tube pile. The model tube pile with the rigid plate inside its bottom was set up to control the specified initial conditions of the sand plug. A proving ring was placed between the screw jack and the loading plate to measure the push-up force (internal friction), as indicated in figure 12. Finally, the dial gauge was installed at the top loading plate to measure the push-up displacement. The push-up load was applied using the screw jack. Push-up loading was determined when the push-up displacement reached about 50% of the inner pile diameter. The readings from the dial were taken; to construct the necessary calculations for the drawing of load-displacement curves.

Figure 9. Pile loading for the test (1) and test (2).

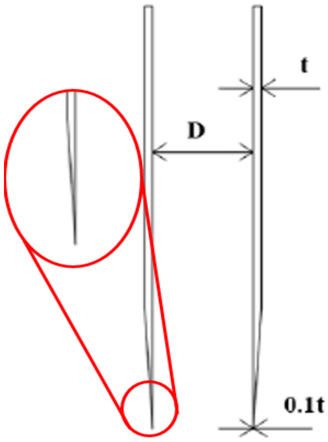

Figure 10. The model pile is set in the test (2).

Figure 11. Pile loading for the test (3) and Soil plug removal tool.

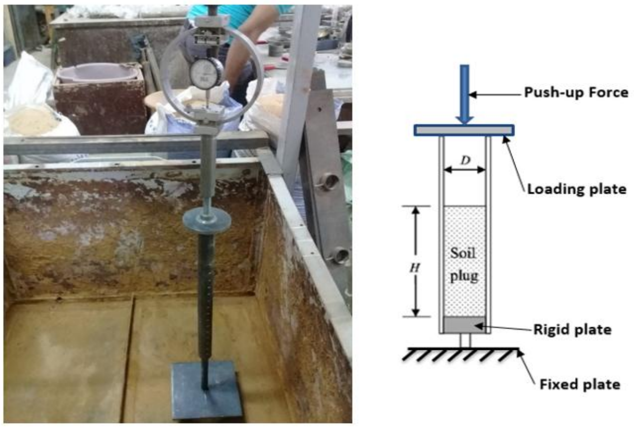

Figure 12. Push-up loading to determine the internal friction for the tube pile.

IV. EXPERIMENTAL RESULTS

A. *Discussion on results for Steel pipe-pile*

Figure 13 and Figure 14 illustrate the complete details of the bearing capacity for a single pile with internal and external friction components, end bearing load resulting from the SP, and thickness of pipe values when the pile was driven in the sandy soil. Based on the different pile thickness, different pile diameter, different pile length, and submerged conditions. It can be concluded that the influence of SP resistance on the ultimate pile load is highly more significant than the other pile components. The value of plug resistance in an open-ended tube pile is typically on the order of 50% to 70% of the ultimate load capacity of open-ended tube piles and is influenced by pile thickness, pile diameter, pile length, and submerged conditions.

The results are in good agreement with Fattah and Al-Soudani [16], which states that the participation ratio for end bearing ranged between 54.7% to78.3% for fully plugged cases. From the table mentioned adown, it can be noted that the value of internal unit shaft resistance in open-ended tube pile is typically on the order of 45% to 55% of the exterior unit shaft resistance and is influenced by pile thickness, pile diameter, and pile length in the dry state.

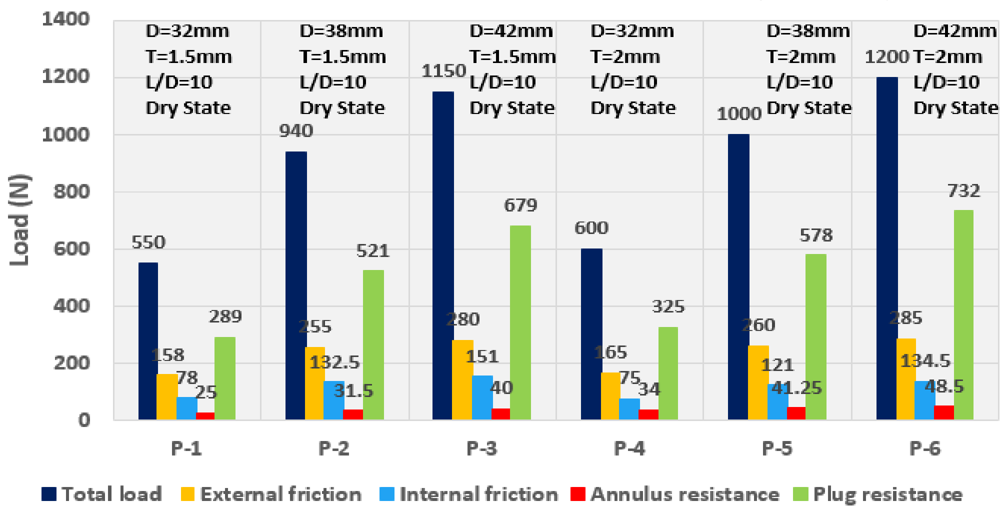

Figure 13. The total pile load with both components is in a dry state.

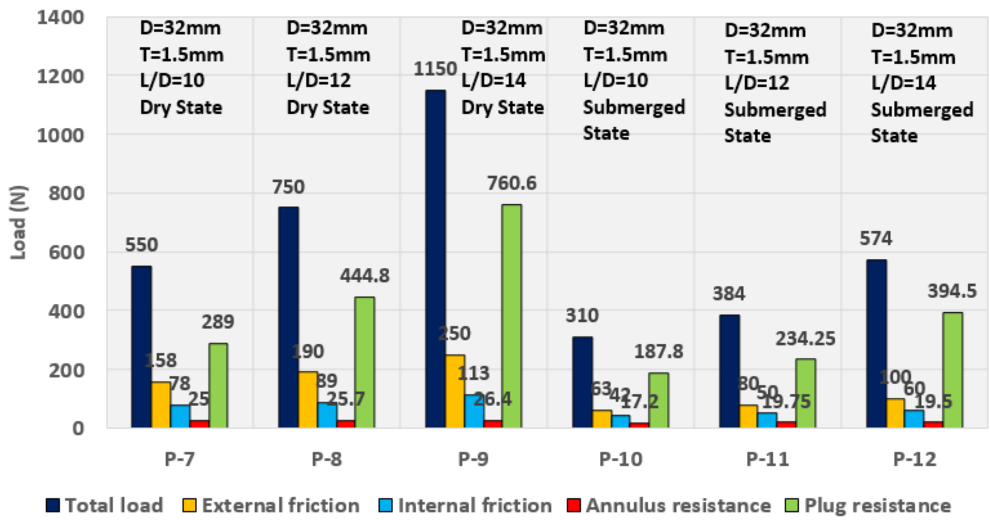

Figure 14. The total pile load with both components is dry and submerged.

Table 3. Ratios for pile external friction, internal friction, and end resistance to ultimate carrying single tube pile capacity.

Test Designation	Submerged	Percentage of Ratios for pile capacity components			
		external friction (%)	internal friction (%)	annulus Resistance (%)	Plug Resistance (%)
P-1 P-2 P-3 P-4 P-5 P-6	Dry State	28.73 27.13 24.35 27.50 26.00 23.75	14.20 14.00 13.15 12.60 12.10 11.20	4.55 3.35 3.50 5.65 4.10 4.00	52.55 55.40 59.00 54.25 57.80 61.00
P-7 P-8 P-9	Dry State	28.73 25.33 21.75	14.20 11.90 9.80	4.55 3.45 2.30	52.55 59.30 66.14
P-10 P-11 P-12	Submerged State	20.35 20.80 17.45	13.55 13.00 10.45	5.30 5.15 3.40	60.58 61.00 68.73

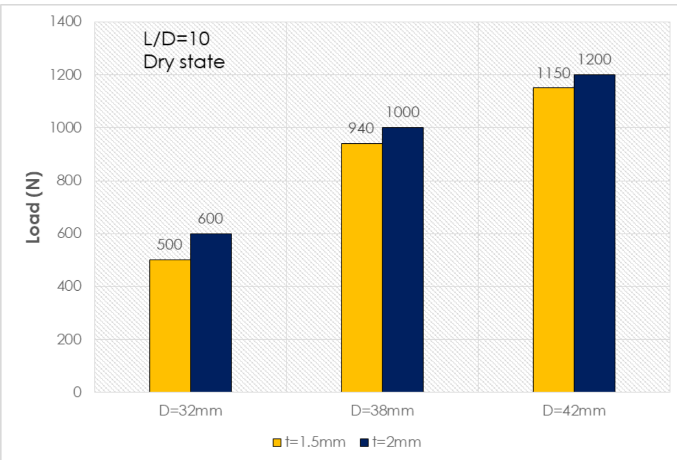

Figure 15. The ultimate pile capacities embedded length (L/d) =10, dry state.

There is also a good agreement between the obtained results and Hannigan et al. [18], which states that the value of internal friction in an open-ended tube pile is usually 1/3 to 1/2 the external friction. The value of internal shaft resistance in an open-ended tube pile is typically on the order of 60% to 70% of the exterior unit shaft resistance in the submerged state. This is due to the plugging influence of open-ended tube pile decrease. Finally, Table 3 illustrates the contribution ratios for internal and external friction components and the end resistance to the total pile capacity of tube piles tested.

B. Effect of Pile Thickness on the Ultimate Pile Capacity

Figure 15 represents the Load-settlement curves for tube pile of diverse diameters are (32, 38, 42) mm, respectively, with two different pile thicknesses are (1.5, 2) mm, and the figures show the ultimate bearing capacity for the dry state. It is clear that when the pile thickness increases, the ultimate pile capacity increases; this is in good agreement with Polukoshko and Zagulins [23].This means that the base area of the tube pile is increased. It is shown from these figures that the higher effect of pile thickness on ultimate pile capacity is observed for smaller pile diameters. This refers to an arching action effect of sandy soil on the piles, increasing SP's influence. When the pile thickness is increased by 33.33%, the percentage of increase in total pile load is 9.00%, 6.38%, and 4.35% for pile diameters of 32, 38, and 42mm, respectively. Table 4 illustrate the outcomes of single pile capacities for different pile thickness.

Table 4. The ultimate pile capacities embedded length (L/d) =10, dry state.

Pile		The ultimate pile capacity(N)		Percentage of increasing (%)
Diameter (mm.)	Length (L/D)=10 (mm.)	The pile thickness (mm.)		
		1.5	2	
32	320	550	600	9.00
38	380	940	1000	6.38
42	420	1150	1200	4.35

C. Effect of Pile Diameter on the Ultimate Pile Capacity

Figure 16 and figure 17 represent Load-settlement curves for tube piles of diverse diameters (32, 38, 42) mm respectively, with two different pile thicknesses of (1.5, 2) mm, and the figures show that the ultimate bearing capacity for the dry state. When the diameter of the pile increases, the ultimate pile capacity increases at the same pile length/pile diameter ratio; this is due to the forming of SP and the increase in skin friction area. These results agree with Awad [24]. It is shown from these figures that the influence of pile diameter on ultimate pile capacity decreases with a large pile diameter. This refers to the influence of SP is decrease. When the pile diameter is increased by 18.75 and 31.25%, the percentage of increase in total pile load is 70.91% and 109%, respectively, for 1.5mm pile thickness. Also, when the pile diameter is increased by 18.75 and 31.25%, the increase in total pile load is 67.67% and 100%, respectively, for 2.00mm pile thickness.

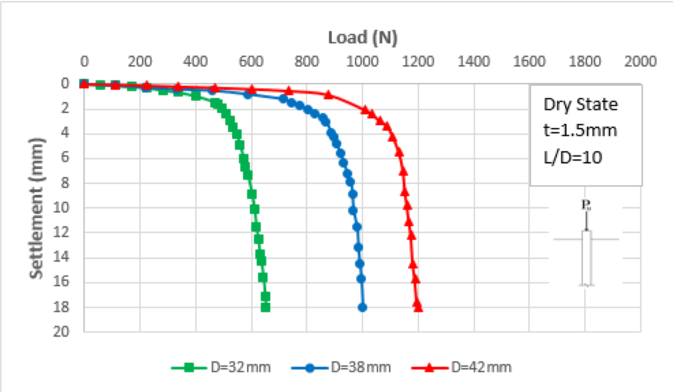

Figure 16. Load-settlement curves for tube piles of 1.5-mm thickness in a dry state.

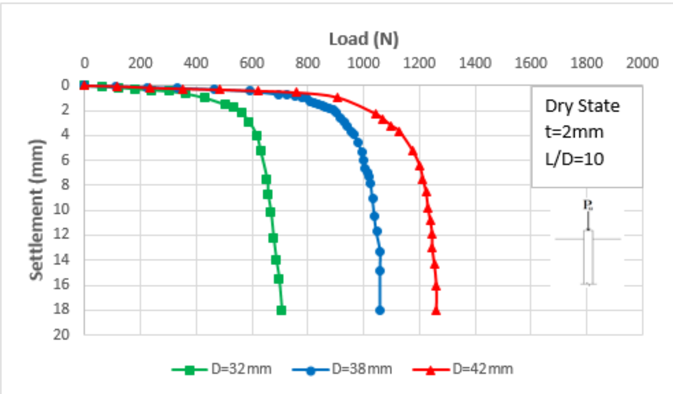

Figure 17. Load-settlement curves for tube piles of 2-mm thickness in a dry state.

D. *Effect of Embedded Pile Length on the Ultimate Pile Capacity*

Figure 18 and figure 19 represent Load-settlement curves for tube piles of 32-mm diameter, with different embedded pile lengths, 320, 384, and 448 mm for 10, 12, and 14 pile length/pile diameter ratios, respectively. The figures show the ultimate pile capacity for dry and submerged states. The ultimate pile capacity for 448 mm pile length is more significant than 320 and 384 mm. When the pile length increases, the ultimate pile capacity increases at the same pile diameter; this is due to an increase in the influence of SP, and the relative density is increased at the tube pile tip. The increase in pile length is constant, but the increase in ultimate pile capacity is considerable. It must be noted that the influence of pile length on the ultimate pile capacity is greater than the influence of pile diameter; this refers to the pile length having a significant effect on ultimate pile capacity. Table 5 demonstrates the outcomes of the experimental tests of single pile capacities for different pile lengths. When the embedded pile length increases by 20% and 40%, the percentage of increase in total pile load is 36.36% and 109%, respectively, for 32mm pile diameter in a dry state.

E. *Effect of Submerged State on the Ultimate Pile Capacity*

Figure 20 demonstrates the relationship between the ultimate pile capacity and settlement for a tube pile of 32-mm diameter, with the same embedded pile length. The figures show the ultimate pile capacity for dry and submerged states. It is shown from these figures that the higher ultimate pile capacity is observed for the dry state.

Table 5. The ultimate pile capacities for different embedded lengths (L/d).

Pile			Submerged	The ultimate pile capacity (N)
thickness (mm.)	Diameter (mm.)	Length (L/D)		
1.5	32	10	Dry state	550
		12		750
		14		1150
1.5	32	10	Submerged state	310
		12		384
		14		574

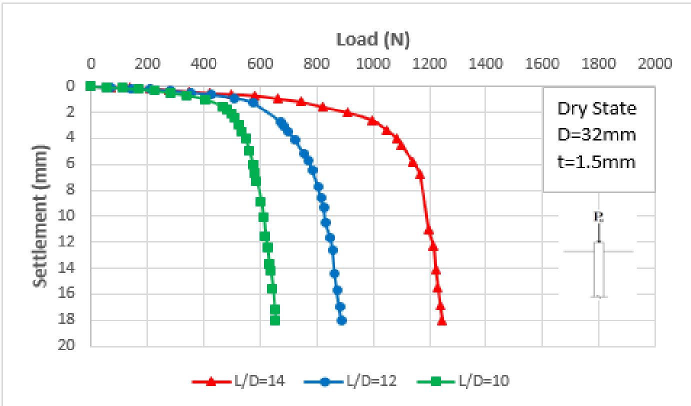

Figure 18. Load-settlement curves for tube piles of different embedded pile lengths, dry state.

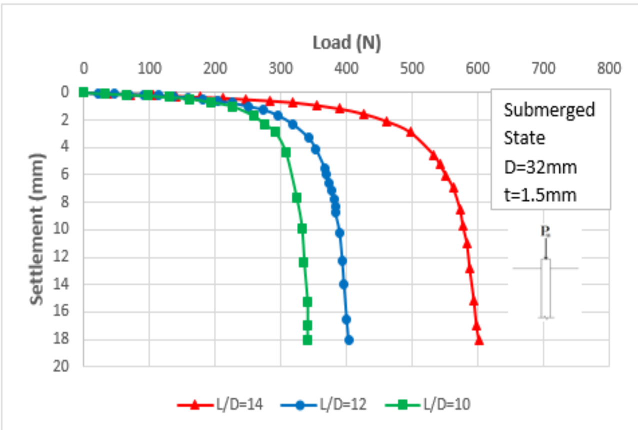

Figure 19. Load-settlement curves for tube piles of different embedded pile lengths, submerged state.

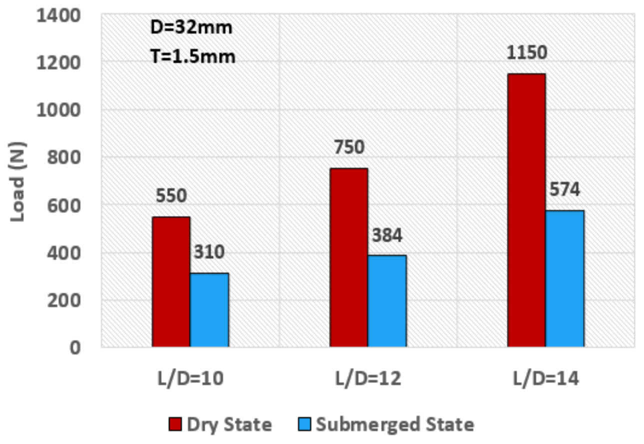

Figure. 20. Effect of Ground Water Table on the Ultimate Pile Capacity for pile diameter 32mm and pile thickness 1.5mm.

This refers to an arching action effect of sandy soil on the piles, and the influence of SP is increased. It must be noted that the influence of the submerged state decreases the ultimate pile capacity to equal from 50% to 60% of ultimate pile capacity in the dry state; this refers to the submerged state having a significant effect on the ultimate group capacity.

F. Effect of Pile thickness, Pile Diameter, and penetration depth on the plug length ratio

The one most widely utilized indicator of soil plugging, plug length ratio (PLR), has been estimated utilizing the following relationships as mentioned earlier in previously. Figure 21 represent the relationship between the diameter of the pile and the plug length ratio (PLR) for the dry state, with different pile diameter and different pile thickness. It is shown from these figures that a higher plug length ratio (PLR) is observed for a bigger pile diameter and smaller pile thickness. This means that when the diameter of the pile increases, SP's influence decreases, and the plug length inside the employed tube pile will increase; this is in good agreement with Islam et al. [25]. SP's influence increases when the pile thickness increases and the plug length inside the employed tube pile will decrease.

Figure 22 demonstrates the relationship between the pile length/pile diameter ratio (l/d) and the plug length ratio (PLR) for the dry state, with different saturated cases and different pile lengths at the same pile diameter. When the pile length/pile diameter ratio (l/d) increases, the plug length ratio (PLR) decreases. This means that the influence of SP increases and the plug length inside the employed tube pile will decrease. Also, the lower plug length ratio (PLR) is obtained for a dry state. This means that the influence of SP increases. The test results from 12 tests with estimated PLR are summarized in Table 6 and figure 23.

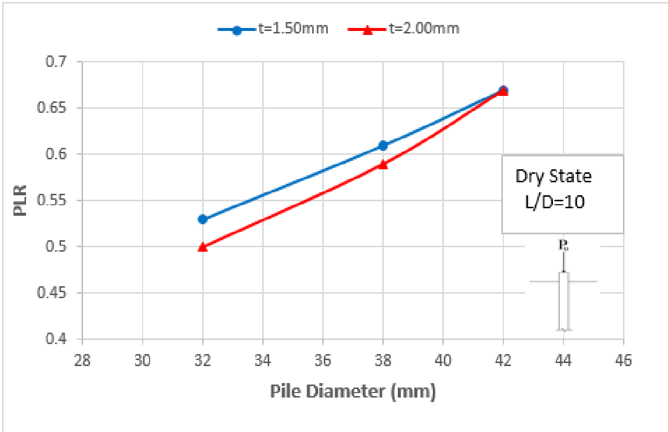

Figure 21. The relation between pile diameter and plug length ratio (PLR) for the dry state, with different pile diameters and different pile thickness.

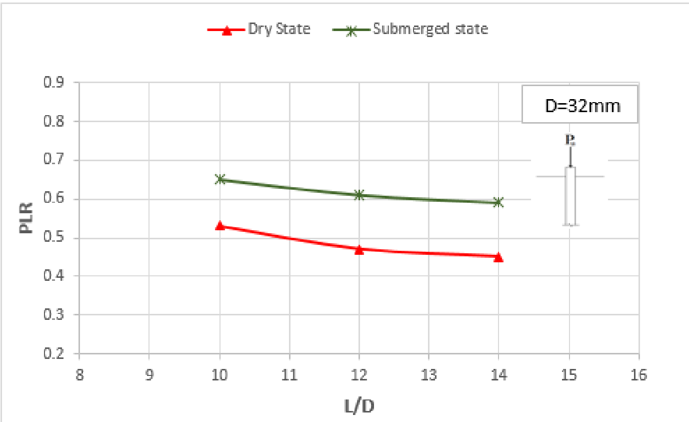

Figure 22. The relation between embedded pile length and plug length ratio (PLR) for dry and submerged states

Table 6. PLR values for the dry state, submerged state, different pile diameters, and different pile thicknesses.

Test Designation	submerged	Pile Outside Diameter D(mm)	Pile thickness t(mm)	Embedded length of pile L(mm)	Plug length Inside the tube pile (mm)	Plug length ratio (PLR)
P-1	Dry State	32	1.5	320	170	0.53
P-2		38	1.5	380	230	0.61
P-3		42	1.5	420	280	0.67
P-4		32	2.0	320	160	0.50
P-5		38	2.0	380	225	0.59
P-6		42	2.0	420	280	0.67
P-7	Dry State	32	1.5	320	170	0.53
P-8				384	180	0.47
P-9				448	203	0.45
P-10	submergd State	32	1.5	320	210	0.65
P-11				384	235	0.61
P-12				448	265	0.59

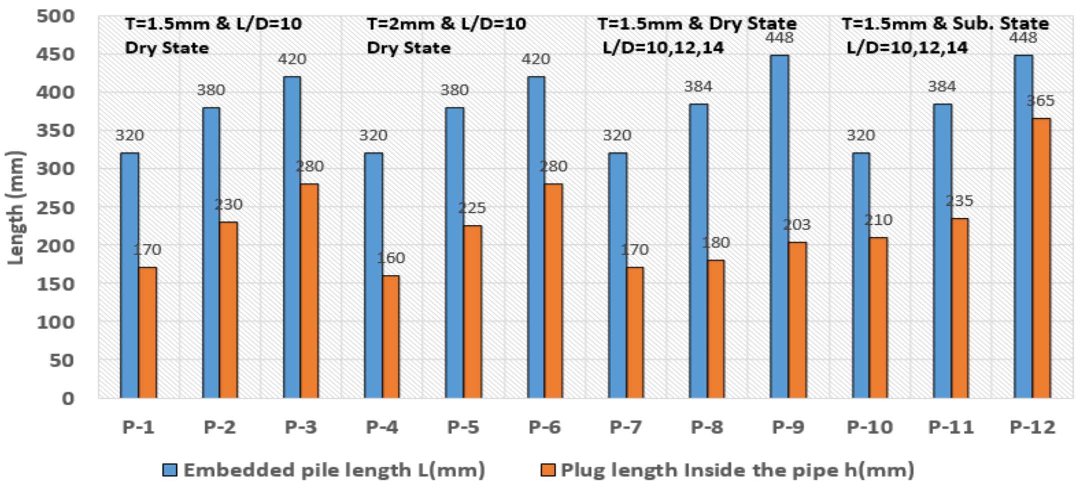

Figure 23. The relation between embedded pile length and plug length inside the pipe

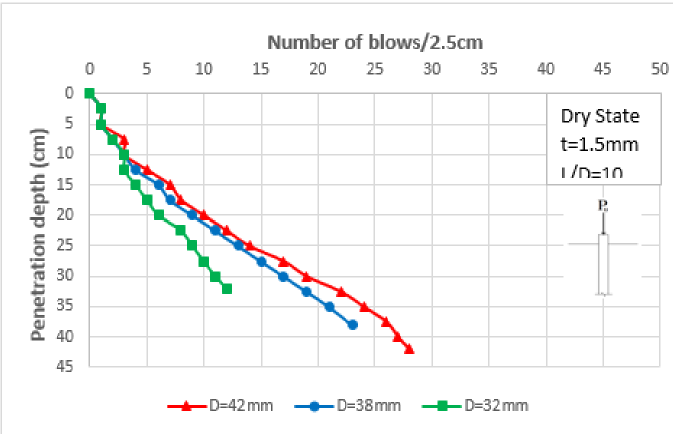

Figure 24. The relation between the number of blows and embedded pile length for different pile diameters at the same pile thickness.

G. *Effect of Number of blows on pipe pile during installation*

As previously mentioned, while driving the open steel tube pile inside a soil, the drop hammer was used to install the pile. Figure 24 indicates the relationship between the number of blows and embedded pile length for different pile diameters at the same pile thickness. The number of blows was recorded at a depth of 2.5 cm. When the length of the pile inside soil increases, the number of blows increases. This means that the ultimate pile capacity increases due to the increase in the shaft resistance and end bearing resistance. It must be noted that the curve is divided at depth equal to 3.5D into two parts, the first part of the curve is linear, and the second part is nonlinear. It indicates that the influence of the formation of SP occurs after the tube pile enters inside a soil to a distance not less than 3.5D. This is in good agreement with the ("China's Ministry of Construction. Technical Code for Building Pile Foundations. Beijing, JG J94–2008 (in Chinese)," n.d.).

V. CONCLUSIONS

The experimental tests, developed and discussed throughout this research work stages, has given the possibility to draw out some conclusion, which is summarized in the subsequent sections:

- The value of plug resistance in an open-ended tube pile is typically on the order of 50% to 70% of the ultimate load capacity of open-ended tube piles and is influenced by pile thickness, pile diameter, pile length, and submerged conditions.
- The value of internal unit shaft resistance in an open-ended tube pile is typically 45% to 55% of the exterior unit shaft resistance. It is influenced by pile thickness, pile diameter, and pile length in the dry state.
- The value of internal unit shaft resistance in an open-ended tube pile is typically 60% to 70% of the exterior unit shaft resistance. It is influenced by pile thickness, pile diameter, and pile length in the saturated state. This is due to the plugging influence of open-ended tube pile decrease.
- The plugging influence of open-ended steel tube piles increased with increasing tube pile thickness and penetration depth. However, the plugging influence decreased with increasing tube pile diameter.
- The ultimate load capacity of open-ended tube piles increased with increasing pile thickness; the higher effect of pile thickness on ultimate pile capacity is already observed for smaller tube pile diameter.
- The ultimate load capacity of open-ended tube piles increased with increasing pile diameter, at the same pile length/pile diameter ratio. The influence of pile diameter on the ultimate pile capacity decreases with a large pile diameter.
- The ultimate pile capacity of open-ended steel tube piles increased with increasing the penetration tube pile depth. This is due to an increase in the influence of SP. It must be noted that the influence of pile length on the ultimate pile capacity is greater than the influence of pile diameter; this refers to the pile length having a significant effect on ultimate pile capacity.
- The ultimate load carrying capacity for tube piles under dry conditions is almost more significant than those of saturated conditions. It must be noted that the influence of the submerged state decreases the ultimate pile capacity to equal from 50% to 60% of ultimate pile capacity in the dry state for the same pile diameter and pile length; this refers to the submerged state has a great effect on ultimate group capacity.
- The higher ultimate group capacity is observed for the dry state. It must be noted that the influence of the submerged state decreases the ultimate group capacity to equals from

48% to 60% of the ultimate group capacity in the dry state. The group efficiency is decreased by increasing the submerged state at the same spacing/diameter ratio.

- The ultimate group capacity is increased with increasing the pile embedded length, and the group efficiency is decreased with increasing the pile embedded length. It may be due to an arching action effect of sandy soil on the piles.
- The higher plug length ratio (PLR) is observed for a bigger pile diameter and smaller pile thickness. This means that when the diameter of the pile increases, SP's influence decreases, and the plug length inside the employed tube pile will increase. Also, when the pile thickness has increased, the influence of SP increases and the plug length inside the employed tube pile will decrease.
- The plug length ratio (PLR) decreased with increasing the pile length/pile diameter ratio (l/d). This means that the influence of SP increases and the plug length inside the employed tube pile will decrease. Also, the lower plug length ratio (PLR) is obtained for a dry state. This is due to the influence of SP increases.
- While driving the open steel tube pile inside a soil, the drop hammer was used to install the pile. The number of blows increased with increasing the embedded pile length.

These conclusions are limited to the considered materials and the boundary conditions.

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Conflicts of Interest:
The authors declare that there is no conflict of interest.

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