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Effect of Particle Size Distribution of Cohesionless Soil and Pile Diameter on the Behavior of Open Ended Pipe Piles

ABSTRACT-*Pipe piles are normally used in deep foundations to transfer the structure load to stronger layer beneath the ground or to rock formations. More popular applications of pipe piles are marine construction (offshore structures), bridge piers construction and building construction. This research is conducted to study the effect of grain size distribution of cohesionless soil (i.e. fine, medium and coarse sand) on the ultimate load capacity of pipe piles with different diameters under dry and fully saturated state through an experimental model. Also, Degree of soil plugging behaviors for different pipe pile diameters and saturation conditions (i.e. dry, fully saturated conditions) for different particle size distribution was studied. Karbala sand, were used as a natural soil in the present study, it is poorly graded clean sand of rounded particles. The sandy soil is sieved to obtain a fine, medium and coarse graded according to (ASTM D 422-02). The experimental model tests conducted on four open-ended steel pipe piles models with diameters of (25, 30, 35 and 41mm) embedded within different grain size distribution of sand prepared under dry and fully saturated conditions with relative density of 65%. The results shows that, the ultimate load capacity of open-ended pipe piles embedded within medium grain size exerted higher bearing capacity than the other grain size distribution and increased with increasing piles diameters. The increasing values of the ultimate load carrying capacity for different pipe pile diameters under dry conditions are almost greater than that of saturated conditions by about (1.95-2.4) times for fine sand, (2.36-3.04) times for medium sand and (1.62-1.97) times for coarse sand. Furthermore, Plug Length Ratio PLR (which is the proportion of a soil plug length to the pile penetration depth) was measured for different pile diameters, and it was found that the length of soil column increases gradually with the increasing of a piles diameter.*

KEYWORDS- *pipe pile, soil plug, particle size distribution, pile diameter.*

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1. Introduction

Steel pipe piles classified into two types open and closed ended, and according to the British standard for foundations [1], the close-ended pipe piles considered large displacement piles. However the open-ended pipe piles classified as small-displacement piles. Both of which became widely used in civil engineering works such as submerged area and offshore structures (marine construction) because of steel pipe piles are easy of handling, driving and its industry as compared with concrete piles, and can be driven to greater depths. As well as their high load bearing capacity, so many times used to support heavy structures, bridge piers and high buildings to ensure structural safety.

During the driving of open-ended pipe piles, the soil inside an open-ended pipe pile may form as unplugged mode (i.e. the soil enters in the pile at the same rate of pile penetration). Partial plugging mode refers to the state where the soil is still able to enter in the pile, but not as the same rate of the pile penetrates. On the other hand, if a pile is driven under plugged mode (i.e. preventing new soil from entering in the pile) the internal shaft friction is large enough to prevent the soil from entering and the pipe pile behaves similarly as a closed-ended pile. Degree of soil plugging often described by the incremental filling ratio (IFR) (which is defined as the increase of the plug length with respect to increase of the pile penetration depth) or by the plug length ratio (PLR) (which is defined as the proportion of a soil plug length to the pile penetration depth) [2].

Paik and Salgado [3] showed that the bearing capacity of open-ended piles is affected by the degree of soil plugging, which is quantified by the incremental filling ratio (IFR). This conclusion was based on model pile made of two very smooth stainless steel pipes with outside diameter of 42.7 mm, inside diameter of 36.5 mm, and length of 908 mm. The results of these tests showed that the IFR increases with

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increasing relative density and increasing horizontal stress. It can also be seen that the IFR increases linearly with the plug length ratio (PLR) and can be estimated from the PLR. The unit base and shaft resistances increase with decreasing IFR. Based on the results of the model pile tests, new empirical relations for plug load capacity, annulus loaded capacity, and shaft load capacities of open-ended piles were proposed. A comparison between predicted and measured load capacities showed that the recommended relations produce satisfactory predictions.

Luking and Kempfert [4] investigated the influence of different factors on the plugging effect and the change in the load-bearing behavior, mainly in non-cohesive soils using experimental, numerical and statistical methods during jacking an open-ended displacement pile. The soil is entering through the pile toe into the profile; this plug can close up the pile toe completely. Because of such reason, the pile can be treated approximately as a fully closed-ended displacement pile and can mobilize an additional base resistance. Indeed, the soil-mechanical processes and the different factors of influence on the plugging effect are mostly unknown. All investigations showed that a fully plugged soil inside the pile could not be identified and disproved the classical model representation of a fully plugged pile toe. The load transfer in the plug takes place by compression arches, which are mainly influenced by the pile diameter and the soil density. Finally, based on these results a practical calculation method is suggested.

Shighait [5] investigated the effect of plugging on the load carrying capacity of close and open ended pipe piles embedded in sandy soil. It was found that the behavior of open-ended pipe piles and close-ended piles where similar, whether the soil plug formed inside piles is in a state of partial plug or full plug. Length of the soil plug is based on the type of installation and relative density, whether open-ended piles are driven or pressed in the fully unplugged mode or in the partially plugged mode, the plug does contribute to static pile base capacity. When a pipe pile is driven to a depth equal to fifteen times of its inside diameter, it behaved as a solid base and the load carrying capacity of a fully plugged open ended pipe pile was equal or greater than that of the closed-ended pile.

Hassan [6] investigated the load carrying capacity of the single and group pipe piles foundation embedded within unsaturated cohesionless soils. It was found that the changes of soil plug length and incremental filling ratio IFR with penetration depth during pile driving showed that the open-ended pile reached a fully plugged state (at which IFR would be equal to zero) for all tested models. And the results of analysis showed that the ultimate loading capacity increases with decreasing in the plug length ratio PLR.

The main objectives of this research are evaluating the bearing capacity and degree of soil plugging behavior of single pipe piles under dry and fully saturated conditions, also investigating the effect of pile diameters and particle size distribution of cohesionless soil (i.e. fine, medium and coarse sand) on the ultimate load capacity of pipe piles and degree of soil plugging.

2. Soils and Materials Used

1. The soils

Poorly graded clean sand were used as a natural soil the present work, most particles of the sand used are rounded. The sandy soils are sieved to obtain a fine, medium and coarse sand according to (ASTM D 422-02) [7]. Physical soil properties are presented in Table 1. Grain size distribution curve presented in Figure 1, and according to the Unified Soil Classification System (USCS), the sandy soils is classified as poorly graded sand with symbol SP.

2. Model Pipe Piles Used

Four steel open-ended pipe piles with different in diameters were used to achieve the objective of this study as shown in Plate 1. Properties of piles are summarized in Figure 2. Properties of the pipe piles used are summarized in Table 2. Diameter to thickness ratio (D/t) of 18.7 were used, which is within the range of (15-45) recommended by (Jardine and Chow, 2007) [8].

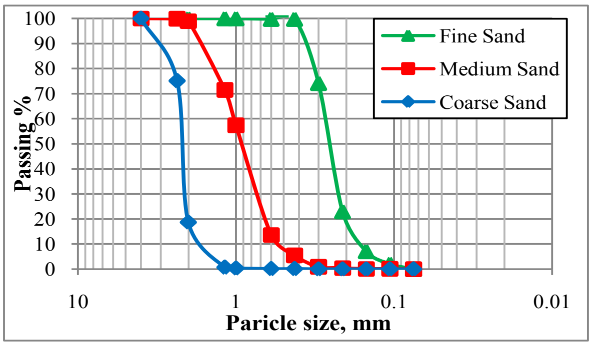

Figure. 1: The grain size distribution for the soils used.

Table 1: Physical properties of the soils used

Physical properties	Fine Sand	Medium Sand	Coarse Sand	Specification
Effective size $D_{10,}$ (mm)	0.17	0.54	1.88	
D30, (mm)	0.22	0.77	2.19	
D60, (mm)	0.27	1.03	2.26	ASTM D 422 [7]
Coefficient of curvature, C_c	1.08	1.06	1.02	
Coefficient of uniformity, C_u	1.58	1.87	1.20	
Soil classification (USCS)	SP	SP	SP	
Specific gravity, $G_{s,}$ @20°C	2.69	2.65	2.60	ASTM D 854 [9]
Maximum dry unit weight γ_{max}, (kN/m^3)	16.6	17.4	16.4	ASTM D 4253 [10]
Minimum dry unit weight $\gamma_{min,}$ (kN/m^3)	13.6	14.8	13.8	ASTM D 4254 [11]
Dry unit weight (γd) (kN/m^3) at R.D. = 65%	15.4	16.4	15.4	
Maximum void ratio, e_{max}	0.93	0.75	0.84	-
Minimum void ratio, e_{min}	0.58	0.49	0.58	-
Coefficient of permeability, K @20°C (cm/min)	0.96	2.36	5.75	ASTM D 2434 [12]
Angle of internal friction(Ø°) at R.D. = 65%	36.0°	38.7°	35.8°	ASTM D 3080 [13]

Table 2: Model pipe piles dimensions and properties used in the tests

No.	Pile Outside diameter, D (cm)	embedded length of pile, L (cm)	L/D ratio	Pile Thickness t (cm)
1	2.5	40	16.0	0.15
2	3.0	40	13.3	0.15
3	3.5	40	11.4	0.20
4	4.1	40	9.80	0.20

Plate 1: Pipe piles models.

3. Model Setup Formulation

The apparatus and other accessories were designed and manufactured to achieve the requirements of this study. The apparatus consists of, namely; steel loading frame with axial loading system, steel container, load cell with digital weighing indicator, dial gauges, steel tamping hammer, soil plugs measurement device and piles installation equipment, as shown in Plate 2.The steel loading frame was manufactured to support the piston of the axial loading system, and allows to move the piston horizontally to simplify measuring the degree of soil plugging without moving the container.

Load cell model S-beam type (SS300) with a maximum capacity 0.5 ton used to measure the applied load by linking with digital weighing indicator model SI 4010 is used for displaying the load amount with an input sensitivity of 0.2 µN/Digit. Steel base plate were used as a pipe piles holder with a dimensions of (70cm × 20cm) and 15mm thickness associated with four circular collar of different diameters depending on the pipe pile diameter used for fixing the pile through an embedment stage in soil without tilting. Then two dial gauges reading with an accuracy of (0.01 mm/division) have been used for measuring the displacement of the pipe pile during the pile load test, installed by two magnetic stand base holders, these apparatus are shown in plate 3.

Plate 2: Axial loading system and general view of the apparatus.

Plate 3: The apparatus of testing and pile guideline.

4. Model Preparation and Testing Program

The experiments tests were conducted in a cubic steel container of internal dimensions of (600 × 600 ×700) mm. The dimensions of the steel container were chosen to achieve fully mobilized pressure within the soil media during loading the models. Each part of the container was rigid enough and not affected by the lateral deformation during the preparation of the soil bed and during the test. This container sits on a moveable frame base which has four small wheels to allow moving a steel container to the loading frame after the soil bed preparation is completed. The container has a water supply valve used to control the amount of water suppling when saturation of the soil sample.

The sandy soil was poured into the test container in layers of thickness of 100 mm to maintain a uniform condition. Depending on the dimensions of each lift, and with the knowledge the value of the dry unit weight corresponding to the required relative density of 65% which is used in this research, the weight of the dry soil placed in each lift can determine. A steel tamping hammer was used for compacting the soil lifts by uniformly distributed blows to get the required relative density.

After dry soil bed was prepared for saturation test, the water supply valve was opened; the water table was raised slowly from the base of a container through the filter layer. This technique facilitated of air escape gradually from soil porous layers in the container to ensure a fully saturated condition. Water supplier (water tank)was connected to the lower valve of the container by a thin plastic tube to provide the water under a controlled head, used for saturation of soil bed models. The tests of the fully saturation condition were conducted after 24 hours from saturation the dry soil bed to ensure the equilibrium conditions in the soil were achieved according to Reference [14]. The pipe pile model was installed using a manual hydraulic jack having a maximum loading capacity of (100 kN) to penetrate required length of 400mm. A constant loading rate has been adopted in the insertion of pipe piles models. Aluminum measuring tube of 20mm diameter was used to measure the plug length inside the pipe piles at each (25 mm) intervals during installation.

A series of laboratory model tests were conducted using the quick test method according to (ASTM D1143M-07) [15] by applying the test load with an increases of 5% of the anticipated failure load, and keep the load constant for a time interval of 10 min during each increment in load. The test was continued until the recorded settlement exceeded 15% of the pile diameter. The displacement of the pile was measured by taking a rate of two dial gauges reading with an accuracy of (0.01 mm/division). Plate (4) illustrates the main steps of the sand deposit preparation and testing procedure.

Plate 4: Preparation of soil bed and testing procedure.

5. Results and Discussion

1. Effect of pile diameter and Soil Particle Size on the ultimate load capacity

To examine the effect of pile diameter and soil particle size on the ultimate load capacity under different degrees of saturation, open ended model piles with diverse diameters are (2.5, 3, 3.5, 4.1) cm were installed in the various soil beds (i.e., fine sand, medium sand and coarse sand) and prepared with the relative density of 65%.

Load settlement curves for test result of pipe piles models are shown in Figures (2 to 5). (ASTM D1143–07) [15] criterion was adopted in determining the ultimate loads for all piles models carried out in this study. The ASTM method defines the ultimate load as "the test load at which rapid continuing of pile settlement, or the test load at which the total axial movement of the pile exceeds (15%) of the pile width or diameter". The figures shows that the ultimate bearing capacity for dry state exerts higher values than that of fully saturated state and the medium grain size distribution of sand exert higher bearing capacity in dry and fully saturated condition than that of the other grain size distributions of the sand used and for all the different pie piles diameters.

Figures (6 and 7) show the trend of the effect of grain size distribution and pipe pile diameter on the ultimate load capacity under dry and fully saturated conditions. The figures clearly indicated that the pile load capacity increases regularly with increasing the pile diameter, and the relationship seems to be linear or quasi-linear between the diameter of pipe pile and ultimate load capacity for pile diameter greater than 3cm. This may be attributed to the increase in both internal and external friction forces. These results agree with Awad [16] who investigated the dependence of bearing value on the diameter of driven steel piles in sand.

The results also, demonstrated that, at dry and fully saturated states the ultimate load capacity of pipe piles models in medium sand greater than fine sand and coarse sand respectively, these differences in the ultimate load capacity attributed to the gradual variation of the external and internal ultimate skin resistance (due to the influence the interface friction angle (δ) between soil and pile material), angle of internal friction, overburden pressure along the pile shaft friction and finally effect of the lateral earth pressure coefficient as recommended by Kulhawy [17].

Moreover, the ultimate load capacity of pipe piles models under dry conditions is greater than that in fully saturated conditions for the same pipe pile diameter and soil type as shown in the proportions described in Table 3. It shows the ratio of an increase in the ultimate pile load capacity in dry conditions compared with fully saturated conditions. This may be attributed to the reduction in both internal and external friction forces, in addition to the decreases of shear strength parameters in the fully saturated state as was found by Hamid and Miller [18], who focused their study on the shear strength of a fully and partially saturated soil interfaces (where in contact with structures).

General note can be deduced from Table 3, for the same soil grain size with different saturation conditions, the differences in ultimate load capacity for smaller piles diameters were greater than that of the larger pile diameter.

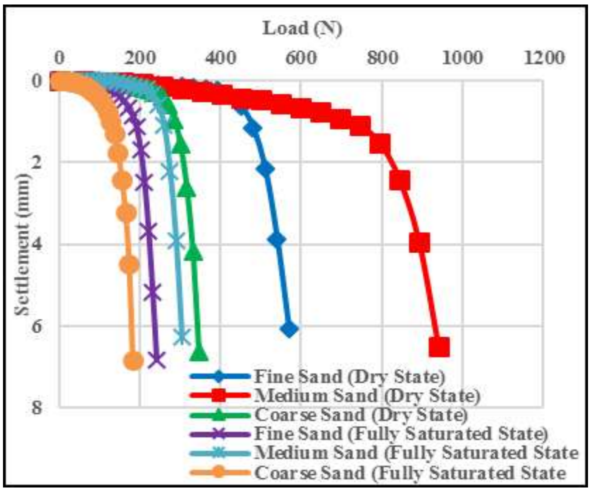

Figure 2: Load-settlement curve for pipe pile diameter 2.5cm embedded in different types of soils under dry and fully saturated state.

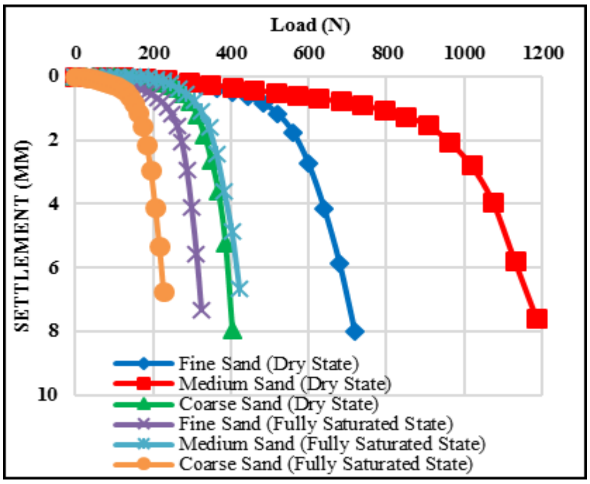

Figure 3: Load-settlement curve for pipe pile diameter of 3cm embedded in different types of soils under dry and fully saturated state.

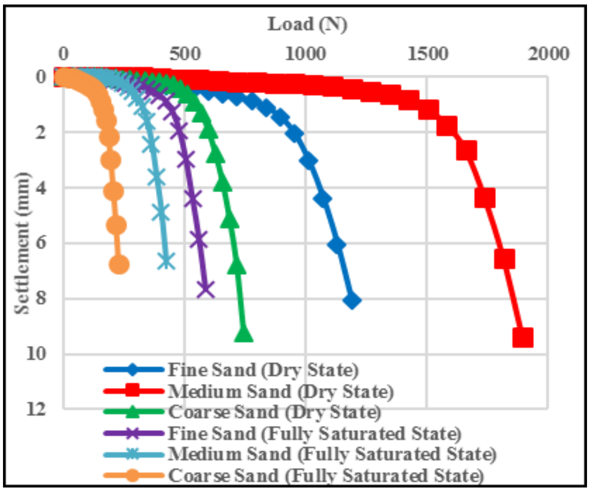

Figure 4: Load-settlement curve for pipe pile diameter of 3.5 cm embedded in different types of soils under dry and fully saturated state.

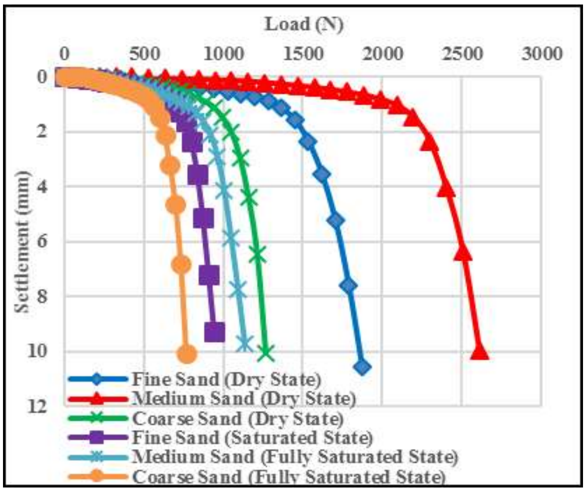

Figure 5: Load-settlement curve for pipe pile diameter of 4.1 cm embedded in different types of soils under dry and fully saturated state

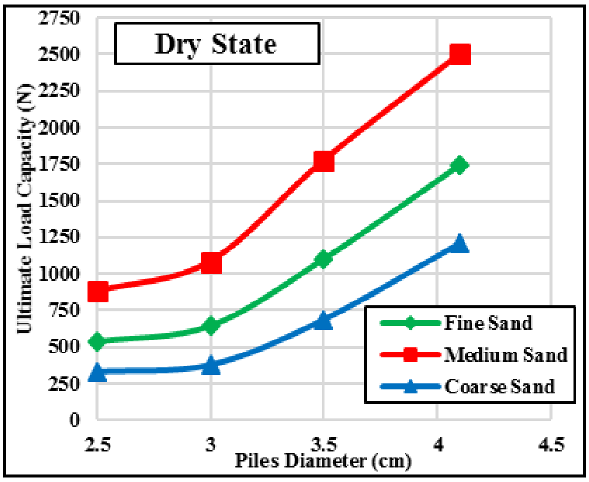

Figure 6: Effect of grain size distribution and pipe pile diameter on the ultimate load capacity at dry states.

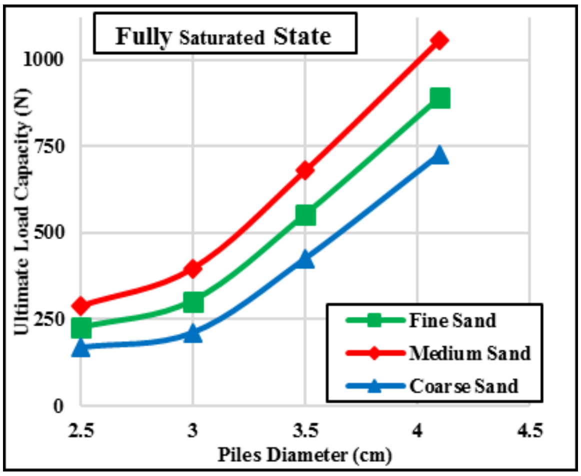

Figure 7: Effect of grain size distribution and pipe pile diameter on the ultimate load capacity at fully saturated states.

Table 3: The ratios of an increase in the ultimate pile load capacity in dry conditions compared with fully saturated conditions.

Pile Diameter (cm)	The ratios of an increase in the ultimate load capacity		
	for fine sand	for medium sand	for coarse sand
2.5	2.40	3.04	1.97
3.0	2.13	2.72	1.80
3.5	1.99	2.61	1.62
4.1	1.95	2.36	1.67

2. Effect of Pile Diameter and Soil Particle Size on the Plug Length

The increment of soil plug length was measured for each (25mm) interval during installation of pipe pile models, then the soil column inside the open ended pile (plug length) measured in the end of piles installation for all the studied cases. The best indicators of the degree of soil plugging are

Plug Length Ratio (PLR) (which is known proportion of a soil plug length to the pile penetration depth) and an Incremental filling ratio (IFR) (that is defined as the proportion between increments of soil plug length to the increment of pile penetration depth).
The effect of particle size distribution and pile diameter on the plug length ratio at dry and fully saturated condition is shown in Figures 8 and 9.

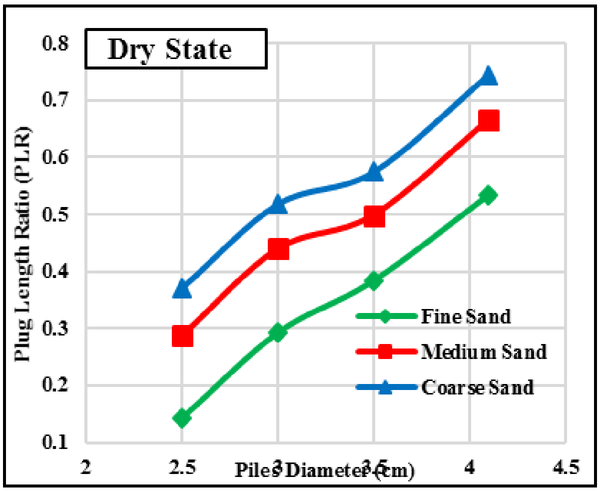

Figure 8: Effect of pipe piles diameter on the plug length ratio for the different types of soil under dry condition.

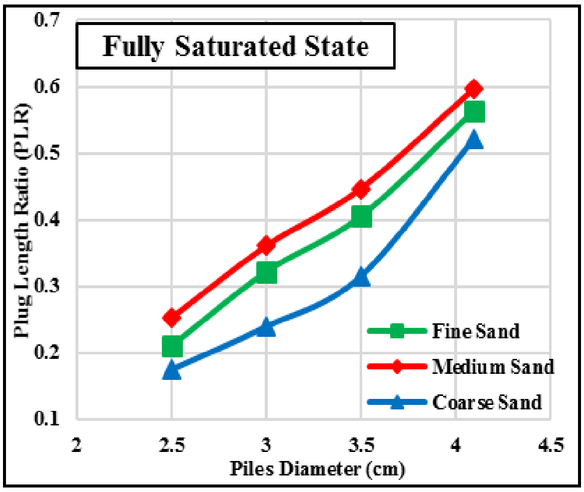

Figure 9: Effect of pipe piles diameter on the plug length ratio for the different types of soil under fully saturated condition.

The Figures shows that, the plug length ratio (PLR) increases gradually with the increasing of piles diameter. In dry conditions, the soil plug length ratio increases gradually from fine to coarse sand for the same pile diameter. This is attributed to the effect of median grain size (D_{50}) on the interface friction angle (δ) between soil and pile material which decreases with increasing average particle size (D_{50}) according to Lehane et al. (2005)[19]. On the other hand, in a fully saturated conditions, the friction force between soil and pile material decline due to decreases of skin resistance parameters to the presence of water, which leads to lubrication of soil particles, and the plug length is mainly depends on the friction along the inner pile wall to resist the load-bearing capacity of the ground. Therefore, the soil plug length ratio increasing steadily with ultimate pile load capacity for the same pile diameter.

6. CONCLUSIONS

From the experimental work results and data analysis the following conclusions can be drawn:

1) The ultimate load capacity of open- ended piles increased with increasing pile diameters.
2) The ultimate load carrying capacity for pipe pile under dry conditions is almost greater than those of saturated conditions and depends on grain size distribution of the soil. The increment ratios of the ultimate pile load capacity in dry condition compared with fully saturated condition for different pipe pile diameters are about (1.95-2.4) times in fine sand, (2.36-3.04) times in medium sand, (1.67-1.97) times in coarse sand.
3) By comparing between the results of fine, medium and coarse sand under dry condition, it is found that, the ultimate carrying capacity of pipe piles embedded within medium sand shows higher bearing capacity than that other grain size distribution, while pipe piles embedded within the coarse sand shows lower bearing capacity.
4) It was found that for the same pile diameter, the Plug Length Ratio (PLR), in dry conditions increases gradually from fine to coarse sand, and in a fully saturated condition increases with increasing the ultimate load carrying capacity of pile.
5) All the tests results, show that the length of soil column inside the open ended pipe pile (plug length) increases gradually with the increase of piles diameter, and the pipe piles with a smaller diameter exhibited more tendency to plug (i.e. IFR=0) than larger diameter.
6) In a fully saturated condition for the same pile diameter the penetration depth for access to the fully or partially plugged mode increases with decreases the median grain size of soils (D_{50}), contrary to the dry conditions.

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