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Effect of Pile Spacing on Group Efficiency in Gypseous Soil

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Abstract

As a matter of fact, the gypseous soil is usually considered as collapsible soil, such type of soil illustrates high resistance to settlement and high bearing capacity when it is dry, but it loses these characteristics when it is inundated and collapses excessively because of the sudden decrease in the volume of the surrounding soil mass. It is founded in the arid and semi-arid regions of the world in Asia, South Asia (Iraq, Syria, Jordan, Yemen, and Iran), North Africa, North America, moreover, it covers more than (31%) of the surface area in Iraq. Gypseous soil is one of the most difficult problems facing the process of building any project because of the difficulty of preventing leakage of water to the soil in practice. Deep foundation (piles) are one of the most common types used in collapsible soils which penetrating problematic soil layers and reaching more hard ones (end bearing piles) or transfers loads depending on skin friction (floating pile). The current work is directed to study the behavior of single and group driven pile of square pattern (4 piles) in case of floating pile (friction pile) with different spacing (2D, 4D, 6D) and length to diameter (L/D) ratio of (20) in this special medium dense soil (gypsum content 30% and 61%) under axial load condition. The investigation was carried out to measure the soil collapse before and after inundation. The results showed that the group efficiency for spacing 2D is less than one while for spacing 4D and 6D are more than that value. In addition, the spacing 4D was more efficient to carry 4 group pile in both dry and soaked cases, in addition, the result showed a high reduction in the bearing capacity at inundation state of group pile of (82% in gypsum content 30%) and (87% in gypsum content 61%) with respect to dry state.

Keywords: Gypseous Soil; Pile Spacing; Group Efficiency; Axial Load; Driven Pile.

1. Introduction

Large areas of the earth's surface, especially within the Midwest and Southwest U.S.A, some parts of Asia, and southern Africa, are covered with collapsible soil [1]. Gypseous soils is considered as one of the important types of collapsible soils. More insightfully, collapsible soils are defined as any unsaturated soil undergoes a radical rearrangement of particles and large decrease in volume when soaked with or without additional loads [2-4]. In addition, the major materials of collapsing soil are silt, sand, or any other material combinations [5, 6]. This type of soil covers about 31.7% in Iraq with different gypsum content ranging from 10-70% [7].

Actually, many of the problems that occur in foundation when such soils soaked by water are due to gypsum dissolution or submerging or leaching. However, these problems are usually have led to cracking, tilting and collapsing the related structure [8]. For example, the damage and collapse that occurred in the soil under the foundations reported in Mosul City [9]. When the soil is wetted, precipitated, or groundwater leaching is occurred, the problem appears clearly and the gypsum begins to be dissolved causing a consequent loss of bond between soil particles [10]. Deep foundations are commonly consist of piles, which are structural units set up by using driving or in-situ construction techniques.

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Foundation on collapsible soil usually suffers a sudden settlement, which may also have lead to extreme damage because of inundation, so the use of piles is considered one of the ideal solutions for transferring loads from soil surface penetrating weak layers into more stable layers and overcome the problem [11].

The pile group can be defined a group consists of a number of individual piles that have different embedding lengths and congested resistance of toe to a various degree. The group piles issue have two important outlines in general, firstly, they are jointed to the same solid cap of pile and secondly, the movement of all the pile heads is equally in addition, all piles must have been developed in neutral plane somewhere at the same depth in the soil [12].

Actually, the pile behavior in the group may be completely different of single pile if the piles are friction piles and this difference may not be so observed in bearing piles. Additionally, if the group of piles embedded in soil layer has adequate bearing capacity under the group piles, each pile of the group of pile carries the same load as in the single pile. If the layer below the piles group is compressible, the settlement of group pile may be so larger than the observed settlement of the single pile because of the overlap in the increasing pressure zone under the base of the bearing piles. In addition, the group of pile is probable to act as a unit. Finally, it is highly recognized that in large group of closely spaced friction piles, the actions of the piles overlap and the distribution of load to the various piles is not uniform, [13, 14].

When several piles are assembled, it is reasonable to expect that soil pressures resulting from lateral friction or point bearing will ideally overlap. The density of the accumulated pressure will depend on both the pile load and the pile spacing, and if the soil is sufficiently large, it will fail in the shear or expose to excessive settlement. Moreover, it is clear that the intensity of stress due to interference of stress zones will decrease with increasing the pile spacing. In practice, it possible to avoid the overlap by constructing the group piles at reasonable spacing. However, large spacing is often impractical because the cap of pile is cast over the pile group for the base of shaft and / or for dividing the load on multiple piles in the group, since it would result in bigger size of pile cap, which lead to increase in cost of foundation, [11, 15]. Furthermore, the spacing between a groups of pile relies on factors such as overlapping the stresses of adjacent piles, cost of foundation, and the group pile efficiency [15].

Actually, there is a considerable lack of information can be recognized through the literature regarding the response of single and group piles subjected to axial loadings in gypseous soil, most of the previous studies where dealt the issue of end bearing piles. The term "group efficiency" depends originally on such parameters as, type of soil, method of piles installation, i.e. either cast-in-situ or driven piles and pile spacing.

A parametric numerical analysis is studied of 3×3 bored pile groups (1.5m in diameter of pile and Length to diameter ratio of 46) for different pile spacing (3D, 4.5D and 6D) (D=diameter of pile) embedded in clay with their tips resting in sand. The results showed that the efficiency factor is slightly smaller than one for a pile spacing equal to 3D and increases to values greater than one for larger pile spacing [19].

A serious tests of 3×3 group pile driven in sand subjected to axial load are investigated to study the behavior of group interaction effect. The results show that load carrying capacity of group pile is increased with narrower spacing of 3D due densification of soil among the neighbouring piles. The effect of pile–soil–pile interaction is positive at large spacing of 4D and 5D in pile capacity due to large increasing in shaft friction, whereas the capacity of pile remained constant at narrow spacing of 3D and less [20].

Gogoi et al. (2014) Reported model test results of group efficiency of micro piles in sand. The group of micro piles consist of four-bored concrete pile as square group with spacing of 2D, 4D and 6D with Length/Diameter (L/D) ratios of 30, 50 and 70 for each of the spacing conditions. The results showed the efficiency increased with increasing pile spacing up to 4D then slightly decreased with the increasing pile spacing. It is observed that the maximum efficiency occurs at 4D pile spacing [21].

Zhang et al. (2015) Studied non-linear analysis of the load-displacement behavior of single pile and pile groups. In addition, a parametric study is conducted to study the effect of pile spacing and number of piles on the load-settlement response of the pile groups connected to a rigid cap. The results show that the settlement of group pile is decreased with increasing pile spacing at the same loading level. Moreover, the group resistance ratio (group efficiency) is increased with increasing pile spacing. Furthermore, the results show that the group settlement ratio is decreased with increasing pile spacing and increased with increasing number of piles [22].

Tehrani et al. (2015) studied the group efficiency calculated by semi-analytical solution in multi-layered elastic soil. The circular pile having diameter of 0.5m and 12m in length with slenderness ratio (L/D) of 20 .The results showed that the group efficiency is increased with increasing pile spacing about (0.28, 0.35, 0.4, 0.45 and 0.50) of pile spacing of (2D, 4D, 6D, 8D and 10D) respectively. I addition, the group efficiency is increased as the decreasing of slenderness ratio (L/D) [23].

Tuan (2016) conducted numerical analysis for analysis group efficiency of frictional piles in granular soils. The group piles of 3×3 embedded in multi-layered fine sand are used in study, the results show that the group efficiency are (0.52, 0.63, 0.75, 0.95 and 1) for spacing of (1.5D, 2D, 3D, 6D and 8D)respectively. In addition, the results show that the group efficiency is tend to be one at pile spacing of 8D and more [24].

Choi et al. (2017) investigated the model test to study the response of group driven pile in sand, the model piles are stainless steel closed-ended pipe piles. The outer diameter, wall thickness, and length of the model piles are 30, 2, and 1200 mm, respectively. The results showed that the overall value of group efficiency is slightly less than one for the model piles driven in dense sand, while it is greater than one for the model driven piles in medium dense and loose sand [25].

Sales et al. (2017) reported a testing program in a large calibration chamber involving individual piles and pile groups of four piles (2×2) embedded in sand, Tests on driven piles are evaluated to study the effect of the pile installation process on pile load-settlement response and pile spacing of (2D, 3D and 4D). It found that pile spacing has minimal effect on group capacity if pile spacing exceeds 2B. In addition, the result showed that the group efficiency is more than unity for loose to medium dense sand, while in dense sand the group efficiency is less than unity. Moreover, the result showed that the driving effects had an impact on the load-settlement response of the groups for spacing of 2D and 3D, whereas for 4D spacing, installation effects are negligible [26].

Gowthaman and Nasvi (2018) Reported three-dimensional analysis to study the effect of pile spacing (2D, 4D and 8D) on the load-settlement of pile group of (2×2). The results showed that the group efficiency is increased with increasing pile spacing up to 8D and approach to unity, beyond this range, the failure mechanism gradually changes to the “single pile” mode [27].

Sharma et al. (2019) investigated experimental tests of group behavior in sand under axial compression. Twelve micro pile groups with each group arranged in a square pattern of four piles, with center-to-center spacing of (2D, 4D, and 6D) and with L/D ratio of (20, 35, 50, and 65) are installed in sand bed having relative density of (30%, 50% and 80%). The results show the group efficiency is to be higher in 4D spacing in loose to medium dense state of sand. In addition, the observation showed positive group effect in loose to medium, while negative group effect is observed in dense state (relative density of 80%). Moreover, it found that the L/D ratio, pile spacing, relative density are most importantly effect on group efficiency [28].

Aksoy et al. (2016, 2018) proposed a new economic design chart method to estimate the interface friction angle. It found that the conformity between literature and skin friction chart over (90) % in the obtained δ value which make more economic for design piles instead of ($\delta = 2\phi/3$). Figure 1 shows the proposed chart to determine the interface friction angle value for steel and FRP (Fiber-Reinforced Polymer) Piles [29-30].

Schanz (2018) investigated the properties of Tikrit soil (71% gypsum content) in dry and soaked state. The results showed that the angle of internal friction are decreased slightly as 12.2% and 9.2% after soaking for 6 and 24 hours respectively. In addition, the results showed that the cohesion has a large reduction as 91.5% and 94.2% after soaking for 6 and 24 hours respectively with respect to dry case [31].

The objectives of the current work are to investigation the performance of single and group pile in a collapsible soil in both dry and soaked. In addition, to find how much settlement occurs due to immersion in case of floating pile. In addition, to find the optimum spacing that give more efficiency in-group pile. Does the driven pile method is capable for gypseous soil? This fact necessitates the need for laboratory research study that fills the lack of knowledge on this subject. A summary of group efficiency test data in literature as shown in Table 1.

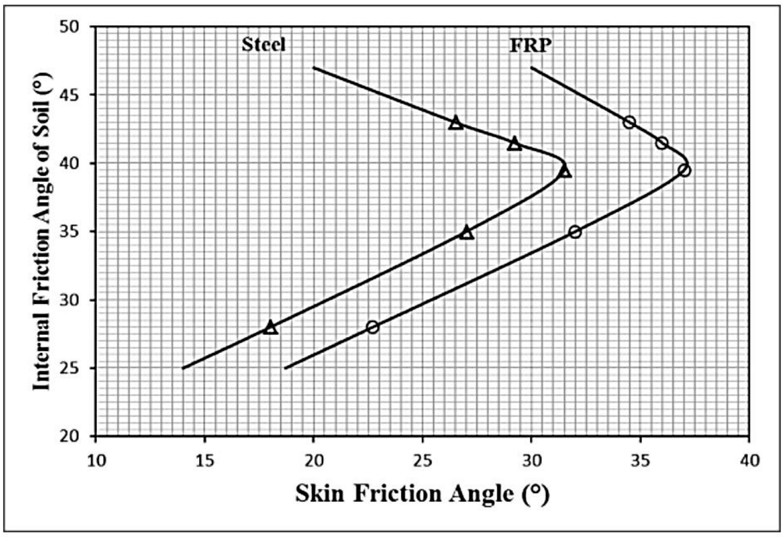


Figure 1. Proposed chart for estimation the (δ) value [29, 30]

Table 1. Summary of some researches about test data of pile group efficiency

Reference	Group size	c/c pile spacing	η	Type of test	Pile type	Soil type	Deflection (dia.)
Comodromos et al. (2003) [19]	3x3 3x3 3x3	3D 4.5D 6D	0.94 1.02 1.17	Numerical analysis	1.5 m in dia. concrete bored pile	Soil layers of clay, silt, bearing layer of sand and gravel	0.1D
Lee and Chung (2005) [20]	3x3 3x3 3x3 3x3	2D 3D 4D 5D	1.2 1.34 1.06 1.05	Experimental model test	32 cm in dia. Aluminium pipe pile	Dr=70% sand	0.15D
Gogoi et al. (2014) [21]	2x2 2x2 2x2	2D 4D 6D	0.91 0.97 0.98	Experimental model test	1.2 cm in dia. steel pipe pile free head (L/D=30)	Dr=50% Sp	Two tangent method
Zhang et al. (2015) [22]	2x2 2x2 2x2 2x2	3D 4D 6D 10D	0.86 0.87 0.89 0.93	Non-linear hyperbolic model	0.3 m in dia. steel pipe pile free head	Multi-layered soils Sandy silt, silty clay	0.13D
Tehrani et al. (2015) [23]	3x3 3x3 3x3 3x3 3x3	2D 4D 6D 8D 10D	0.28 0.35 0.4 0.45 0.50	semi-analytical solution	0.5 m in dia. free head	Multi-layered Dense soil	Not reported
Tuan (2016) [24]	3x3 3x3 3x3 3x3 3x3	1.5D 2D 3D 6D 8D	0.52 0.63 0.75 0.95 1.00	Numerical analysis	0.6 m in dia. free head	Multi-layered Fine sand	0.05D
Choi et al. (2017) [25]	2x2 2x2 2x2	2D 3D 4D	1.10 1.12 1.07	Experimental study	30 mm in dia. driven steel pipe pile free head	Dr=59% SP Medium dense	0.15D
Sales et al. (2017) [26]	2x2 2x2 2x2	2D 3D 4D	1.1 1.13 1.02	Experimental study	30 mm in dia. driven steel pipe pile free head	Medium dense sand	0.15D
Gowthaman and Nasvi (2018) [27]	2x2 2x2 2x2	2D 4D 8D	0.73 0.87 0.93	Numerical simulation	1.5m in dia, bored concrete circular sec.	Multi-layered Silty sand Medium dense Very dense	0.1D
Sharma et al. (2019) [28]	2x2 2x2 2x2	2D 4D 6D	0.88 1.05 0.99	Experimental study	15 mm in dia. bored concrete pile	Dr=50% sand	Two tangent method

2. Materials and Methods

2.1. Soil

Gypseous soil used in the current study with gypsum content (G.C 30% and G.C61%) taken from Tikrit city center of Salah Al-Deen Governorate north of Baghdad city (Iraq) as shown in Figure 2. These soils are used to study the effect of pile spacing on group efficiency subjected to axial loading. The properties of engineering, chemical and physical of gypseous soil are carried out as shown in Tables 1 and 2. Moreover, Figures 3 and 4 revealed the results of the laboratory tests conducted on the soils used in current study. In addition, the test of relative density is not applicable for these soils (ASTM D4254-00). Furthermore, the initial water content test is obtained under the temperature at (40-50) °C to avoid losing crystal of gypseous soil [16]. The two samples of gypseous soil of S1 (G.C30%) and S2 (G.C61%) are classified as Moderate and Moderately severe respectively (ASTM D5533-2003) as shown in Figure 3.

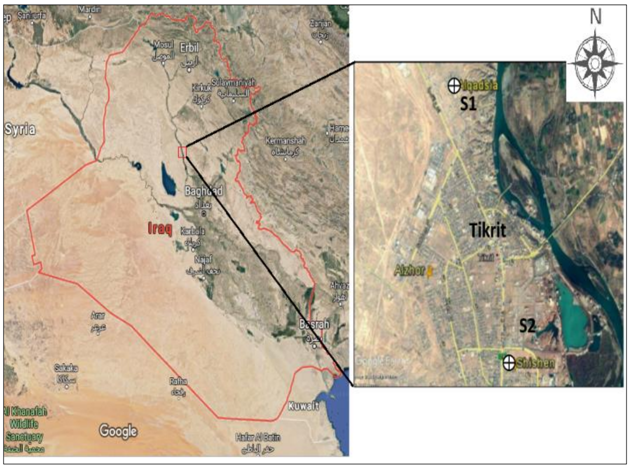


Figure 2. The location of the soil samples

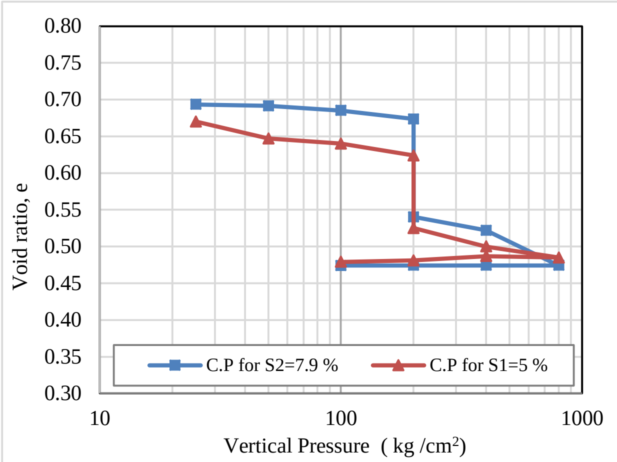


Figure 3. Results of single Oedometer collapse test for two samples of soil used

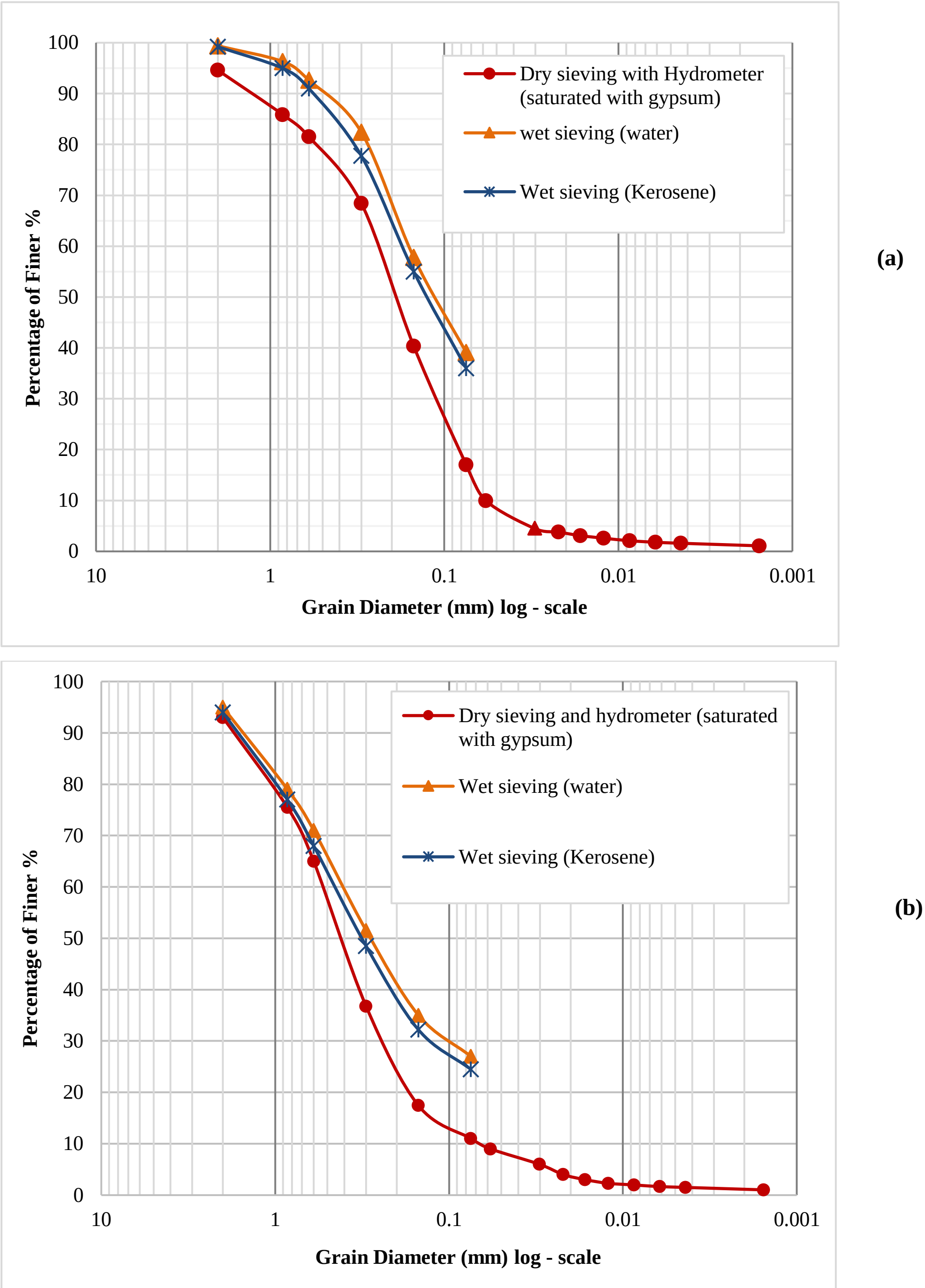


Figure 4. Grain size distribution for gypseous soil, a) S1 (G.C30%), b) S2 (G.C61%)

Table 1. Results of chemical properties of gypseous soil used for testing (BS 1377: 1990, Part 3)

Composition	Magnitude %	
	S1	S2
Total soluble salts (T.S.S.) %	33	67.2
Sulphate content (SO3) %	13.9	30.4
Gypsum content %	30	61
Organic matters (O.M)%	0.2	0.21
Chloride content (CL) %	0.055	0.061
pH value	7	8.4

Table 2. Physical properties of gypseous soil used for testing

Property		Value		Specification
		S1	S2	
Grain size analysis	D10 (mm)	0.06	0.07	ASTM D422-02
	D30 (mm)	0.07	0.14	
	D60 (mm)	0.18	0.35	
	Coefficient of uniformity, Cu	3	5	
	Coefficient of curvature, Cc	0.45	0.8	
	Passing sieve No. 200 (%) (using kerosene)	37	24	
	Classification of soil based on (USCS)	SM	SM	
	Specific gravity, Gs	2.49	2.43	ASTM D 854 (2006)
Atterberg's limits	Liquid limit (L.L)%	22	19	ASTM D4316-84
	Plastic limit (P.L)%	N.P	N.P	
	Plasticity index (P.I)	---	---	
Direct Shear Test	Angle of Internal Friction (Ø) in dry	34	38	ASTM D 3080-98
	Soil Cohesion (C) (KN/mm^2) in dry	9	14	
	Angle of Internal Friction (Ø) in soaked	31	34	
	Soil Cohesion (C) (KN/mm^2) in soaked	4	5	
	Initial void ratio , $\boldsymbol{e_{test}}$	0.64	0.72	
	Initial water content %	0.7	0.5	ASTM D2216-02
Compaction characteristics	Max. Dry unit weight (kN/m^3)	17.96	16.63	ASTM 698-00
	Optimum Moisture content (%)	14.12	11.20	
	Test unit weight (kN/m^3), $\gamma_{d\ test}$	15.26	14.13	
	Field density ((kN/m^3), γ_{field}	15	14.06	ASTM D1556-07
	Collapse Potential	5	7.9	ASTM D5533-2003

2.2. Model Pile

The pile's model used in the current study is made of steel circular pipe having outer diameter of 15 mm and inner diameter of 12.2 mm. The slenderness ratio (L/D) length to diameter of piles is 20, the pile tip is cone-shaped of 1.5 cm in length and cone angle of 60°. The properties of used piles are illustrated in Table 3 and results of interface friction angle between soil and pile are shown in Table 4. The results of interface friction of soil-pile is approximately the same as in proposed chart design [29-30] as mentioned earlier.

Table 3 Properties of steel piles used

Properties	Value	Specification
Length of pile cm	35	
Embedded length of pile (L)	30	
Diameter of pile (D) cm	1.5	
L/D ratio (embedment)	20	
Wall thickness of pile (mm)	1.4	
Poisson ratio	0.3	
Compressive yield strength (MPa)	135	ASTM A36
Tensile strength (MPa)	207	
Type of steel pipe pile	Mild steel	

Table 4. Results of interface shear test between gypseous soil and steel pile

Sample	S1 (G.C 30%)		S2 (G.C61%)		**Specification**
Status	Dry	Soaked	Dry	Soaked	
δ, deg.	23	21	26	22	ASTM D5321 / D5321M – 17
δ/ϕ	0.703	0.70	0.72	0.69	

3. Experimental Program

Figure 5 shows the experimental program proposed for the current study. The tests are carried out in the laboratory of civil engineering in the faculty of Engineering in Diyala University using a self-design laboratory model as shown in Figure 4, which is fabricated with a steel plate 4mm in thickness. The steel tank is square with diameter equal to 500mm and height of 650mm. The inner face of the steel tank is painted to reduce the friction. The effective zone of influence that affected by the installation and loading of pile specified by a many of researchers about 3-8 times piles diameter as shown by [17], and [18]. Consequently, the dimensions for the steel tank are chosen to provide a clear distance between the perimeter and tip of piles to tanks internal to satisfy the requirements.

For axial loading test, the apparatus is designed in such a manner that the applying compression in the pile head by mean of 4 tons hydraulic jack as shown in Figure 6. The sliding piston is moveable in x-direction and the mechanical jack can move the steel tank in z-direction to desired distance of pile spacing as revealed in Figure 6.

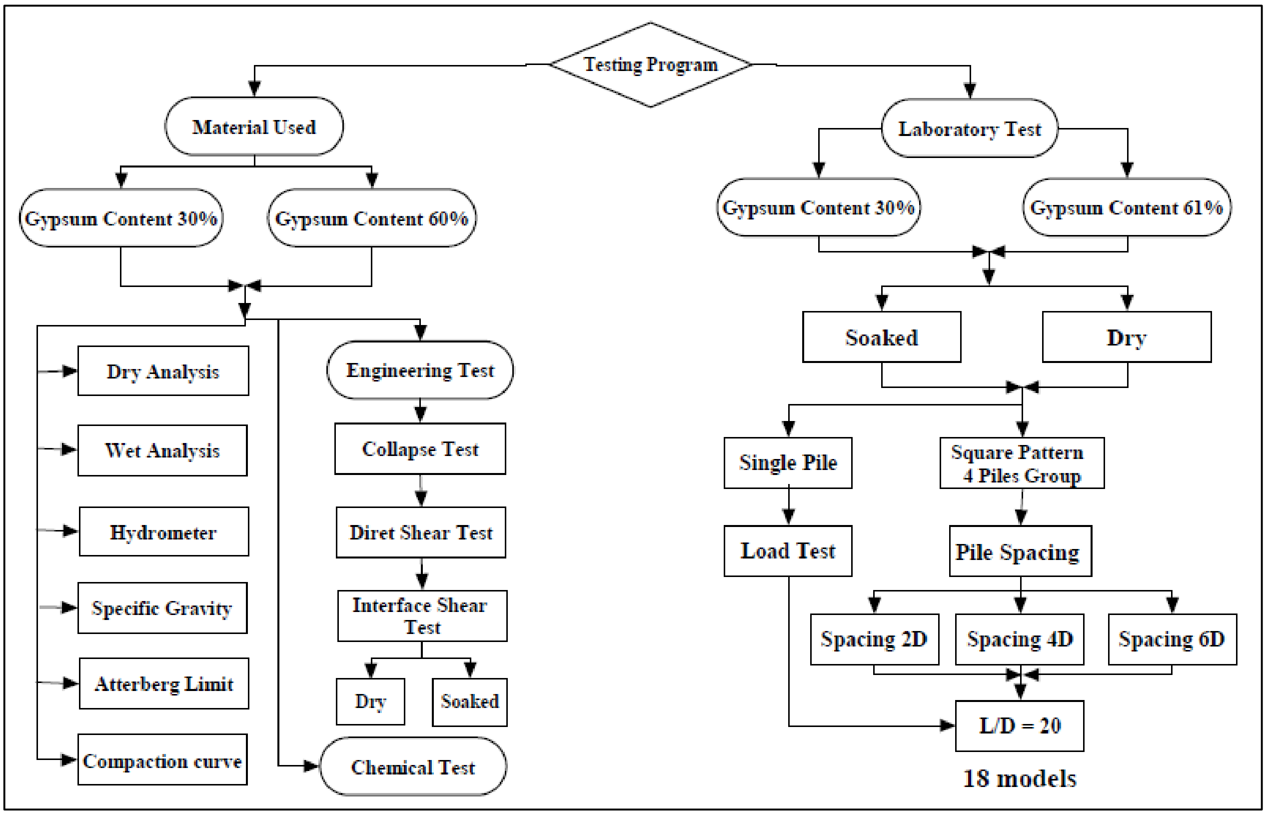
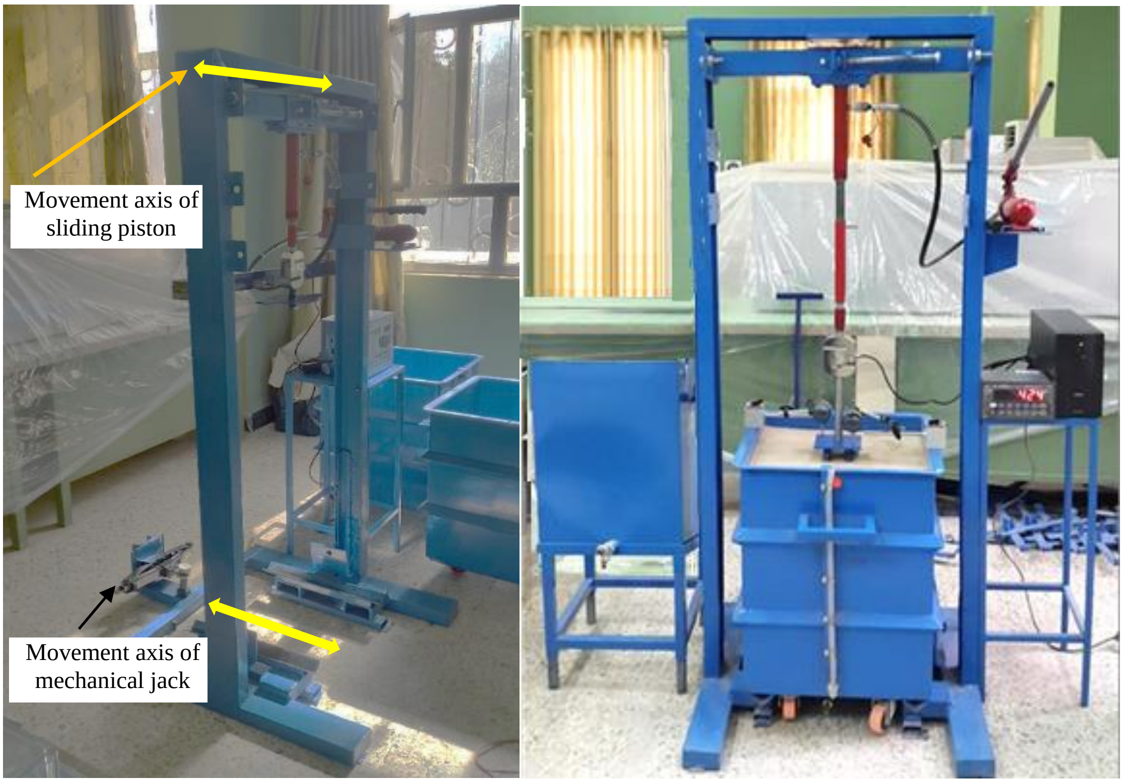


Figure 5. Flow chart of testing program

3.1. Ancillary Equipment

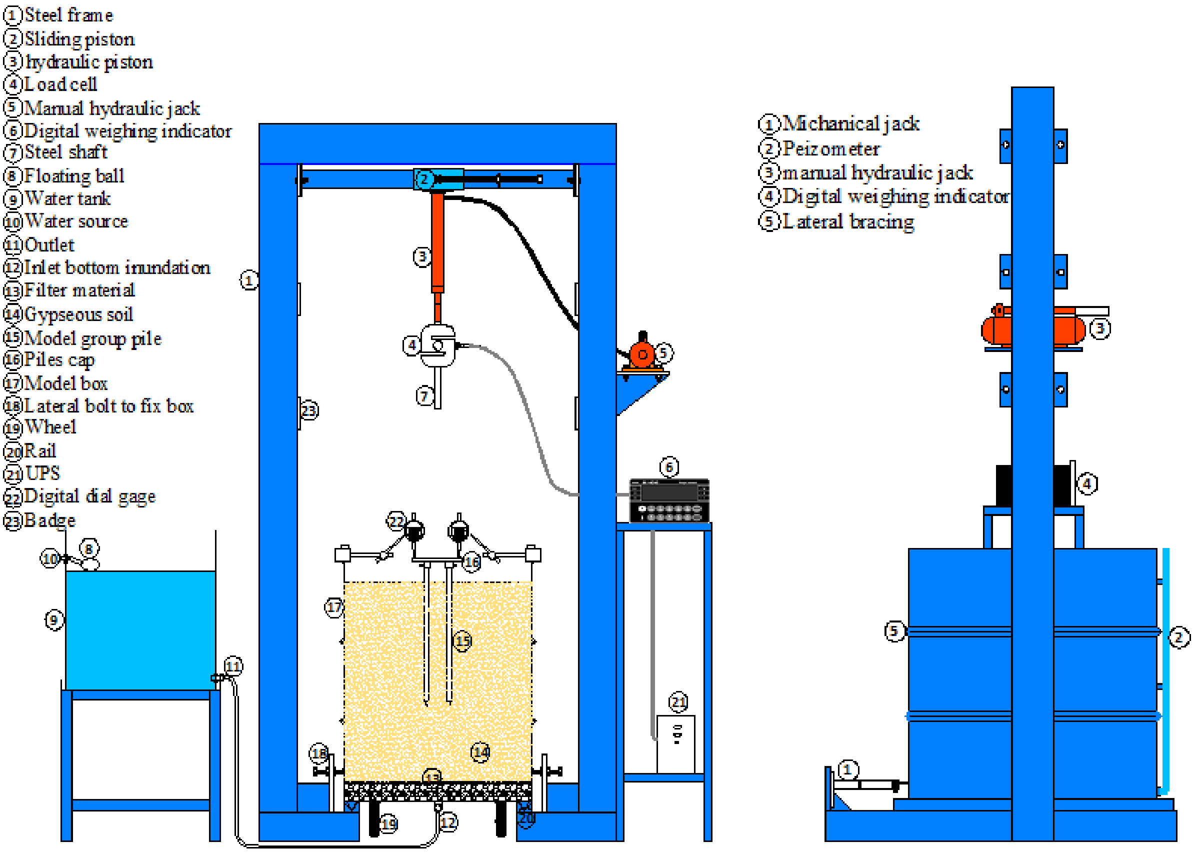
Numbers of ancillary equipment are attached with the apparatus, as described below:

- Compression Load Cells: To measure the axial load applied on the model pile during test in progress, a load cell with 3 tons capacity. Calibration for load cells are performed using mode "load cells' max load "and "Rated output value (mV)".
- Two Digital Dial Gauges: To measure the pile head deflection in the axial direction with sensitivity 0.001mm.
- Digital Indicators: A digital indicators are used to display and record the Load Cell reading as shown in Figures 6 and 7.



(a) (b)

Figure 6. Manufactured testing equipment, a) An arrangement of the sliding piston and manual jack, b) An overview



(a) (b)

Figure 7. Schematic diagram of manufactured testing equipment, a) Front view, b) Side view

3.2. Group Configuration of Piles and Piles Cap

A steel pipe piles are fabricated with constant diameters and different spacing and length, forming six configurations of four piles (2x2) as square pattern. These configurations are arranged to achieve the testing program of the laboratory study. The piles are bolted to rigid steel plate pile cap. The cap of single and pile group is made from steel plate having a thickness of (10 mm), the piles cap is rigid to keep the load transferred equally to each pile. In addition, the cap is free of 5cm above the soil and kept of 2D minimum edge distance from face of piles as shown in Figure 8.

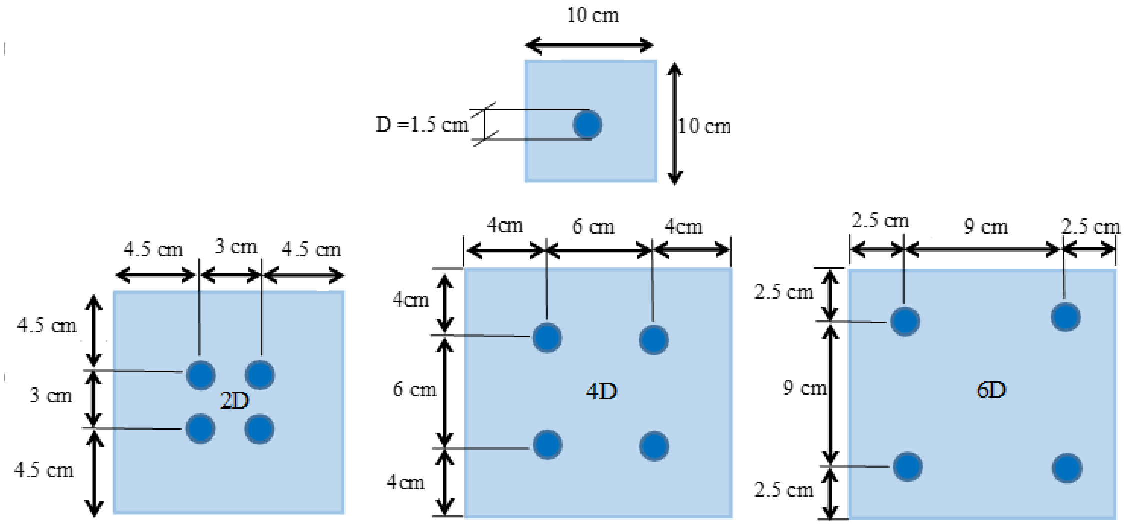


Figure 8. Model piles cap and configuration of group piles

The steel holder used to allow the movement of the piles in axial direction (vertical direction) during the process of installation, and prevent any side movement of piles, which can effect on the test results. The holder is made of a 4 mm steel plate and bolted with screws on top edges of the test box.

4. Test Procedure

4.1. Soil Bed Preparation

The soil bed used is gypseous soil prepared to fill the model box with (500 in high*500 in width*500 in length) mm in volume which has divided into (10) layers. Each layer has dimensions of (50*500*500) mm. The weight of total volume of soil is calculated depending on dry in place unit weight of soil (15.26 kN/m^3 for S1 (G.C30%) and 14.13 kN/m^3 for S2 (G.C61%)). The weight of each layer is determined based on calculated volume and dry unit weight of soil used, and then compacted the soil layer via electrical compactor to the desired depth. Plastic thick layer is cover the base of the electrical compactor to avoid crashing the soil particle. Each layer are leveled after compacted before adding the next layer, the compaction effort and time are fixed in all prepared soil layers to get a uniform density of all layers. In case of soaking state, the filter material of 5cm is placed in the base of steel tank to allow the water to move freely in all direction, a mesh is placed over the filter material and then the same procedure as in dry state to bored the soil.

4.2. Installation of Model Group Piles

When the soil bed preparation process is completed, the steel tank is installed inside the steel frame by which pulling manual jack is established at the back base. The holder is installed by bolt at the top edges of the test box, the piles is placed in a vertical shape through the center hole of the holder. The insertion of piles is done by the compression load cell (S shape) which is installed at the lower part of piston of jack. The piston of jack is lowered by using the manual handle of the jack until to be in contact with the piles. The load is applied on piles resulting downward axial movement to insert pile into the soil bed. The cap is bolted on the single or group of piles after make sure the piles in same level. The pressure load applied on cap of piles is measured by the digital weighing indicator every 2cm of embedment length of pile (strain control of speed 0.2 cm/sec) until achieving the desired depth of each test cases.

In loading cases, the vertical load is applied to a single or group pile through a 3-ton load cell (S-shape) with a constant load penetration rate of 1 mm/min in the full test program [14] and ASTM D1143. The test is going on until recorded a continuous displacement of the single or group piles of 20 mm embedded depth. The load is measured by a digital weight indicator, which is installed to the load cell. The central settlement of the single or group is read by two digital dial gauge with 0.001 mm sensitivity, and the stress is read in the pile from the load indicator.

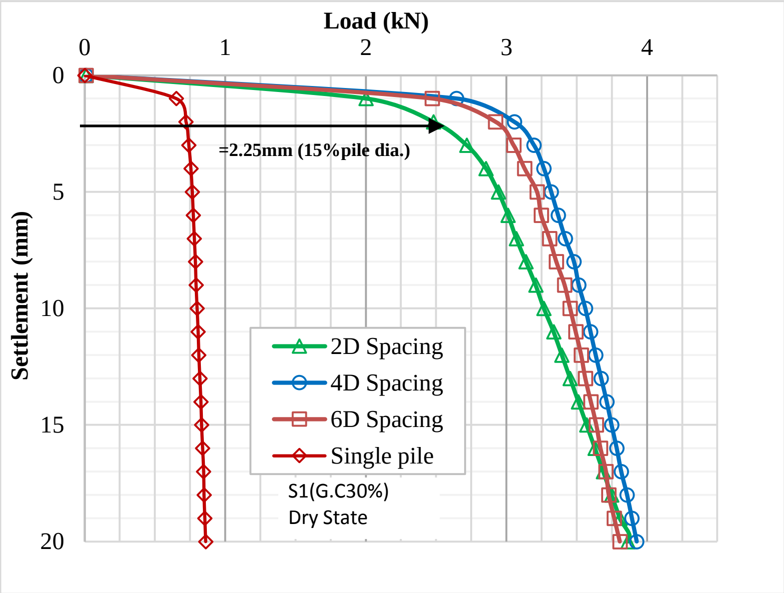
In soaked state, the graduated piezometer tube is used to make sure of fully saturated of soil. A piezometer tube was installed on the valve at the end base of the steel box. The valve is opened to allow water flow through the soil bed from bottom of test box. In addition, the soaked state duration is about 16 hours in S1 and 12 hours inS2, so the degree of saturation is 100% until the water is appeared and covered surface of soil bed, then the same procedure of axial pile load tests as denoted in dry state is carried out after 24 hours of soaking state.

5. Results and Discussion

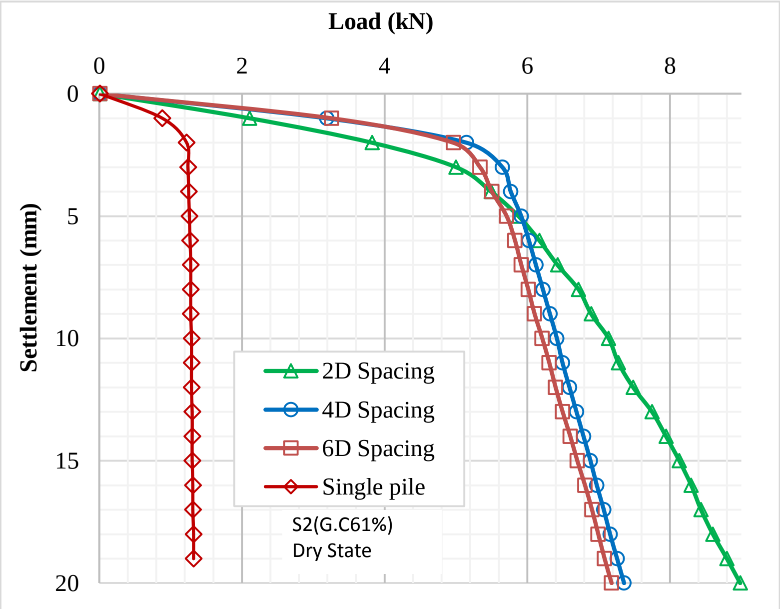
5.1. Effect of Pile Spacing on the Ultimate Load of Group Pile

A series of eighteen tests are conducted on two gypseous soil samples (S1 and S2) for different pile spacing (2D,4D and 6D) at two conditions (dry and soaked). Single pile and group pile are pushed into medium dense soil with penetration rate of (1mm/min). The tests in dry state are conducted after 4 hours from the end of the piles insertion to give enough time to soil relaxation, creep and distribution of stresses. Figure 9 shows the relation between load-settlement with pile spacing in S1 and S2. It can be seen from Figure 9 that the load of pile groups is larger than the single pile in S1 and S2. In addition, the settlement of group piles is larger than the single pile due to the increase in number of piles. In parallel, the increase in number of piles led to be increased the surface area of skin friction, which is led to increasing the load carrying capacity and reducing the settlement of group pile. Furthermore, it can be seen from Figure 9 c and d at soaked state illustrates that there are large draw down in load carrying capacity, and the trend behavior may be similar to local shear failure. This behavior is due to the breaking of cemented bonds of gypsum resulting from dissolution during soaking. Moreover, there is a loss in strength parameters of soil resulting from the loss action of gypsum cementing by soaking.

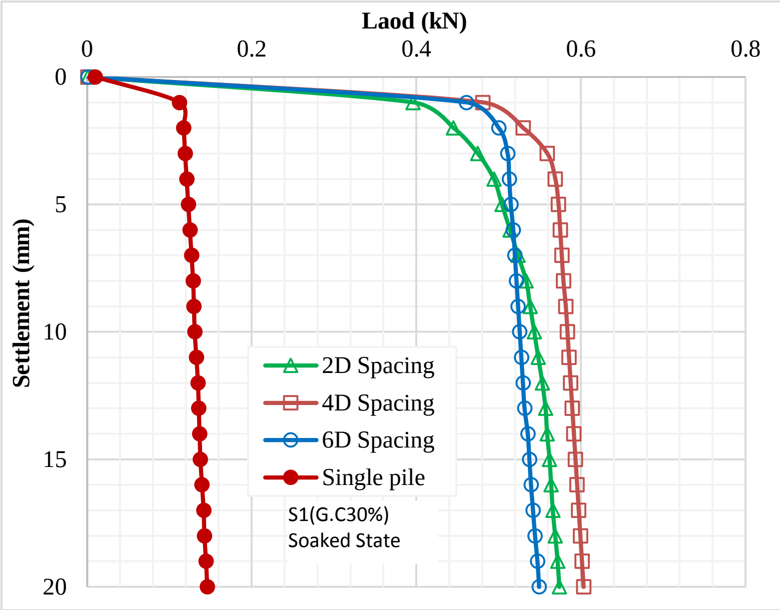
The ultimate load is taken as 15% of pile diameter based on ASTM D1143, which corresponding to 2.25mm settlement. In addition, it can be seen that the ultimate load of 4D is more than the 2D and 6D pile spacing as shown in Figure 10. Moreover, Figure 10 reveals that the ultimate load is increased with increasing pile spacing to a maximum of 4D in dry and soaked state. Furthermore, the ultimate load at dry state for 4D and 6D are (21.7% and 16.3%) in S1 and (28% and 22.7%) in S2 respectively which are more than the 2D pile spacing. On the other hand, at soaked state illustrates that the ultimate load for 4D and 6D are (18.8% and 11.3%) in S1 and (18.9% and 9.7%) in S2 respectively which more than the 2D pile spacing.



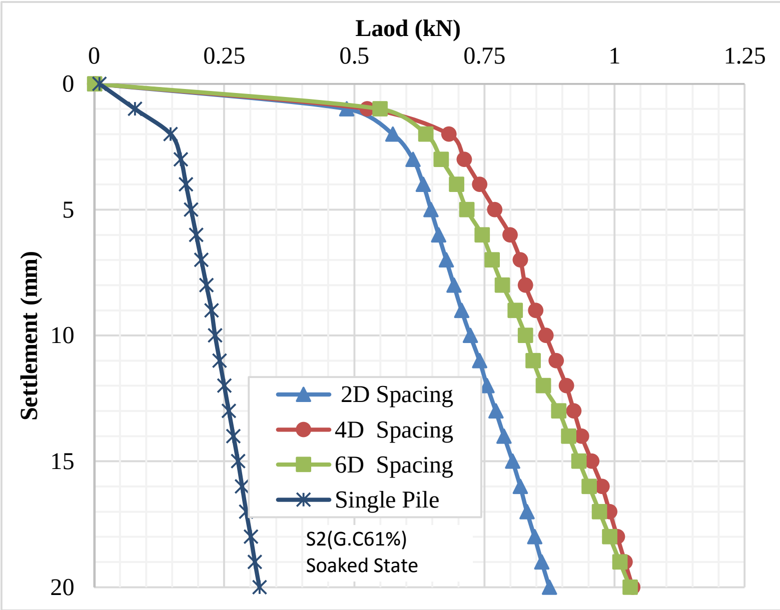
(a)



(b)

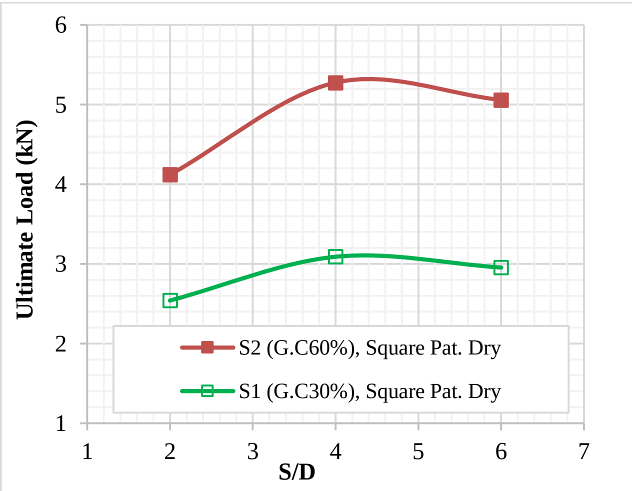


(c)

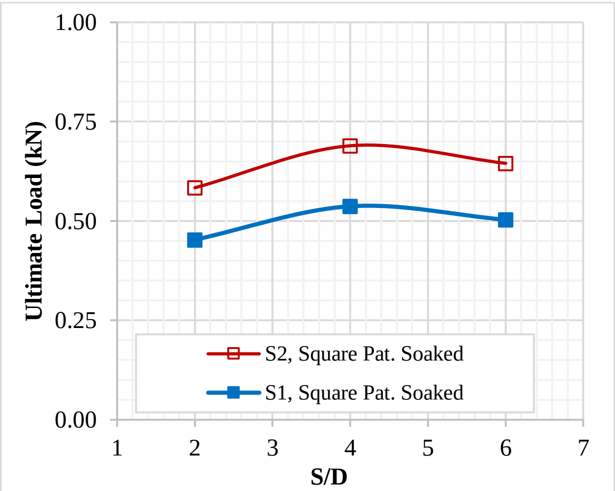


(d)

Figure 9. Influence of pile spacing on load-settlement behavior of group pile, a) For S1 at dry state, b) For S2 dry state, c) For S1 at soaked state, d) For S2 at soaked state



(a)



(b)

Figure 10. The relation between ultimate load versus (Spacing/Diameter) ratio for S1 and S2, a) At dry State, b) At sokaed state

Actually, it is believed that the reason of the high ultimate load of 4D pile spacing is due to densification the soil during driving process that led to increase the skin friction between soil and pile along the pile shaft and the stresses that comes from adjacent pile. In addition, the smaller value of the ultimate load of 2D pile spacing is due to the narrower spacing, which led to increase the interaction of soil-pile at greater value causes over densification of soil around pile or dilatancy of soil. That mean the lateral shaft friction is more than the load carrying capacity. There is no possibility to densification the soil in limit spacing of 2D that led to decrease the ultimate load. In addition, the narrower spacing (2D) act as large block or failed as block but not individual, whereas the wider spacing of (4D and 6D) failed as individual pile group.

5.2. Effect of Pile Spacing on the Group Efficiency

Figure 11 reveals the efficiencies of group pile at two conditions (dry and soaked) in two samples of gypseous soil (S1 and S2). The efficiency is often used to evaluate the group effect according to following formula:

$$\eta = \frac{Q_g}{n\, Q_s} \tag{1}$$

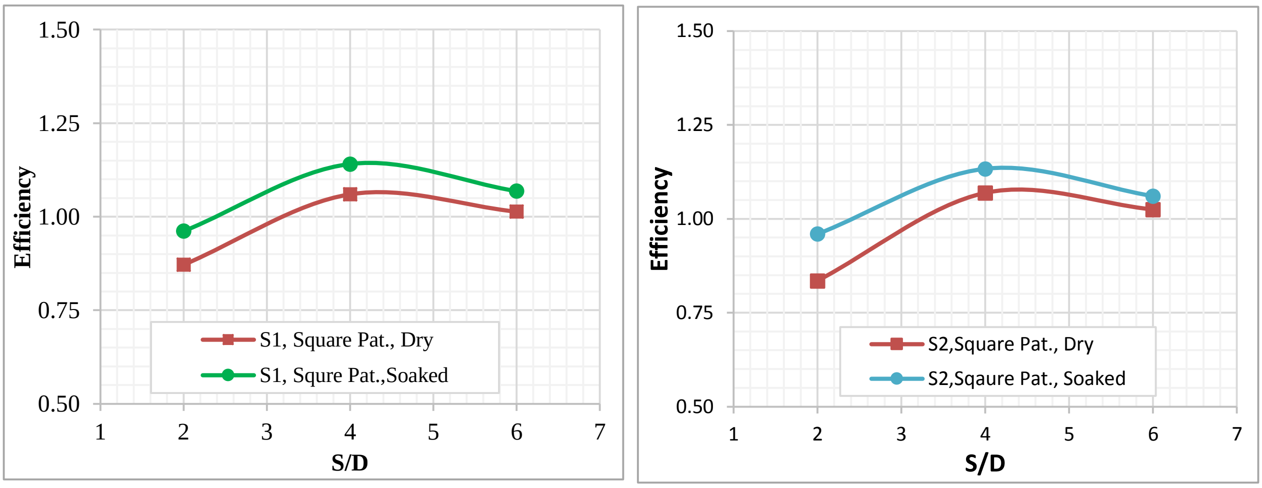
Where: η: efficiency of pile group

Q_g: Axial capacity of pile group

n: number of piles;

Q_s: Axial capacity of single pile.

The group efficiency is increased with increasing the spacing between piles with a maximum value more than unity at 4D pile spacing, beyond this spacing, the efficiency is decreased with increasing pile spacing and reached approach to unity as shown in Figure 11. The group efficiency of spacing 2D, 4D and 6D at dry state are (0.87, 1.06 and 1.018) in S1 and (0.84, 1.07 and 1.03) in S2 respectively, whereas, the group efficiency of spacing 2D, 4D and 6D at soaked state are (0.958, 1.14 and 1.07) in S1 and (0.97, 1.15 and 1.06) in S2 respectively.



(a) (b)

Figure 11. The relation between efficiency versus (Spacing/Diameter) for S1 and S2, a) At dry State, b) At soaked state

When 2D pile spacing, the group behaves as block failure due to the maximum interaction of soil-pile. Moreover, the overlapped stresses are mostly concentrated from the adjacent piles making soil dilatancy and group effect are at maximum value and extend to greater depth more than that for single pile. In addition, it can be noticed that the group effect is increased with decreasing pile spacing. In other word, it is recorded that there is no possibility to densify the soil in limit distance that led to decrease the load carrying of pile group. Therefore, the group efficiency may be less than unity.

In parallel, when 4D pile spacing, the group pile will failed as individual. The overlapping stresses transmitted from the adjacent piles to the soil, which causes the soil will be densified in adequate distance and dilatancy is decreased compared with spacing 2D. At this range, the group effect will be decreased and load carrying capacity will be increased as regards to spacing 2D. The group effect and additional loads from adjacent pile will be decreased with increasing pile spacing. Beyond this range (more than 6D) the pile group is behave as a single pile and the group efficiency is approach to one.

In the other word, the loads are transmitted from the piles to via soil surrounding via their tip and skin of pile. When the group piles are loaded, the additional stresses transmitted to via tip and skin of piles if there is enough spacing. In addition, the soil will be densified and the coefficient of lateral earth pressure (k) and bearing capacity factor (Nq) will be increased. As a result, from that the load carrying capacity of piles are increased due to increasing the ultimate capacity of individual pile in pile group.

There are other reasons that contributed to make group efficiency is more than unity, which are:

- There are two main parameters that effect on group efficiency, those are additional stresses comes from adjacent piles and pile spacing.
- Additional stresses and group effect are increased with decreasing pile spacing to a maximum value at 2D piles spacing. Moreover, the Load carrying capacity of piles are decreased with increasing the group effect, therefore, the group efficiency appears less than one.
- Additional stresses and group effect are decreased with increasing pile spacing. In addition, the Load carrying capacity of piles are increased with decreasing group effect, during this time the additional loads still existing and hold on group efficiency larger than one at optimum value at 4D pile spacing. After that, the group efficiency will be decreased gradually to 6D.
- Beyond this range, there is no possibility to still group efficiency more than one. On the other hand, the group effect and additional loads from adjacent pile will be decreased with increasing pile spacing and group efficiency is approach to one. In this range (more than 6D); each pile of pile group will behaved as a single pile or fialed as individual piles.

Finally, the group efficiency at soaked state illustrates a slight excellency more than as dry state, the reason of that is the reduction in load carrying capacity for single pile which more than the corresponding in group piles in both S1 and S2. This fact have led to increase the group efficiency of group piles. However, these results seem to be compatible with many contributions in the literature [20, 21, 25, 26, 28].

5.3. The Reduction of Ultimate Load Carrying Capacity for Single and Group Pile at Different Pile Spacing

Table 5 shows summary of reduction of ultimate load carrying capacity due to inundation for 24 hours. The percent of reduction is obtained according to the following formula:

$$Rd\ \% = \frac{P\ dry - P\ soaked}{P\ dry} \times 100 \quad (2)$$

Where: R_d %: Reduction percent in ultimate load, P_{dry}: The ultimate load at dry state; P_{soaked}: The ultimate load at soaked state.

It can be seen from Table 5 that the reduction of single pile is more than that of group pile in S1 and S2 due to the decrease in densification and there is no additional stresses or group effect compared with group pile. Therefore, single pile will fails as alone. Moreover, the reduction of single pile capacity have led to a consequent increase in pile group efficiency in both S1 and S2. More precisely, the reduction of single pile is slightly 1.1% and 0.8% for S1 and S2 respectively more than that the average reduction of group pile. Moreover, the reduction in load carrying capacity is increased slightly with increasing pile spacing. In addition, the reduction is decreased with decreasing pile spacing due to the overlapping stresses and the group effect at maximum value. Furthermore, the reduction of S2 is more than S1 due to the presence of gypsum content and C.P (collapse potential) are (61% and 7.9%) in S2 and (30% and 5%) in S1 respectively. The crashed of gypsum particle during driving process act as layer covering the skin of pile and mainly concentrated at tip. At this stage, the soaking process will decrease the skin friction and load carrying capacity of single and group piles, as shown in Figure 12.

Table 5. The reduction of ultimate bearing capacity for the single and pile-group

S1 (G.C 30%)			
Slenderness Ratio	**Pile spacing**	**Reduction (%)**	
		Group pile	**Single pile**
L/D=20	2D	82.2	83.8
	4D	82.6	
	6D	83	
S2 (G.C 61%)			
Slenderness Ratio	**Pile spacing**	**Reduction (%)**	
		Group pile	**Single pile**
L/D=20	2D	85.8	87.7
	4D	86.9	
	6D	87.2	

Moreover, the highly crushed of gypsum particle is developed along the pile shaft (due to gypsum hardness which is less than sand by four times based on Mohs scale) which is increased with increasing the embedded depth of pile and axial load. In addition to that, the thickness of crushed layer is about (1.5 to 2 mm) as shown in Figures 12. Furthermore, beyond this range a layer has been appeared with moderately crushing showing about 3mm thickness. Moreover, Figure 13 shows the profile of embedded group piles and the gypsum layer around the piles. The crashing gypsum particle as shown in white color is increased with depth and concentrated mainly in piles tip due to penetration process as mention earlier.

Furthermore, the gypsum at soaked state will be dissolved and loss their cemented bond between sand particles, which allow water to occupy the voids and decreases the friction between soil particle and skin friction between soil-pile that led to high reduction in capacity of piles. Moreover, the high reduction in ultimate load in addition to gypsum content is due to silt content which is about (35% and 20%) in S1and S2 respectively as shown in Figure 4. However, the presence of gypsum of (30%) and silt content of (35%) in sample S1 leads to high collapse about 82%with respect to dry state. In the other hand, the gypsum content which is 61% in S2, as well as silt content which is 20% leads to collapse higher than that for S1. It can be concluded that the effect of silt content in S1 is more than in S2, whereas the effect of gypsum content in S2 is more than in S1.

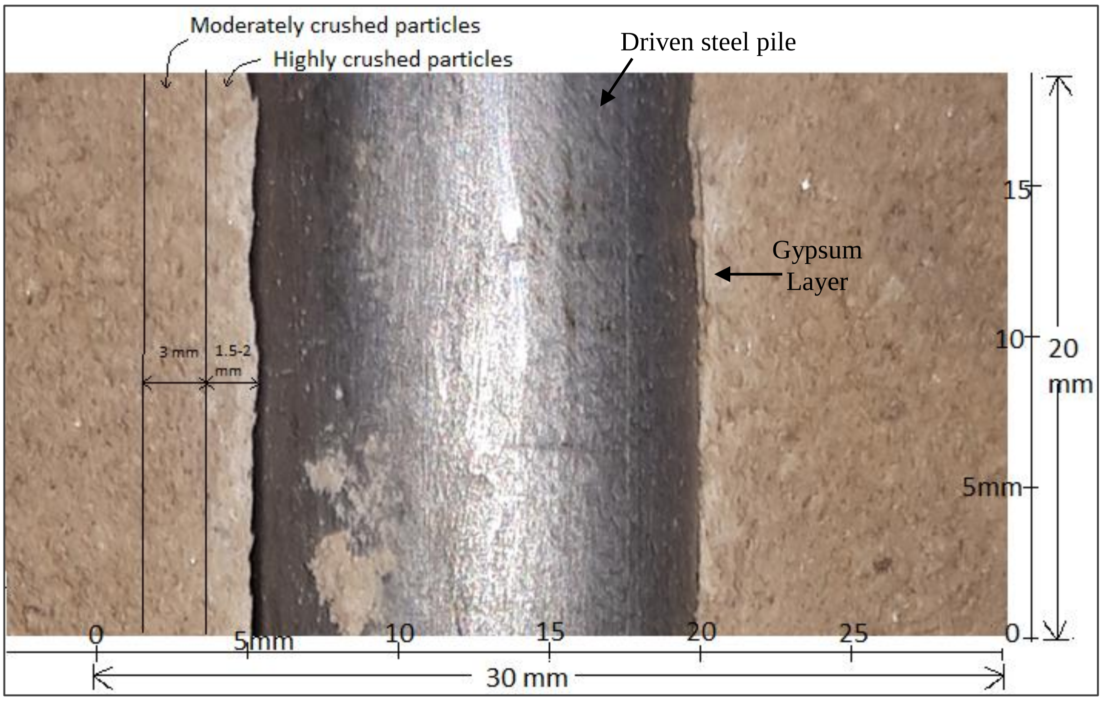


Figure 12. Close up image of soil-pile interface of a model driven pile in gypseous soil

In addition, in soaked state the loss of cohesion is higher than the loss of angle of internal friction of soil. The values of cohesion are about (9 and 14 kPa at dry change to 4 and 5 kPa at soaked) in S1and S2 respectively. In the other hand, the values of angle of internal friction are about (34° and 38° at dry change to 31° and 34° at soaked) in S1and S2 respectively. Moreover, the reduction in angle of interface friction about (24° and 28° at dry change to 22° and 24° at soaked) in S1and S2 respectively. These outcomes are observed also in some recent scientific research programs [5-10].

(a) (b)

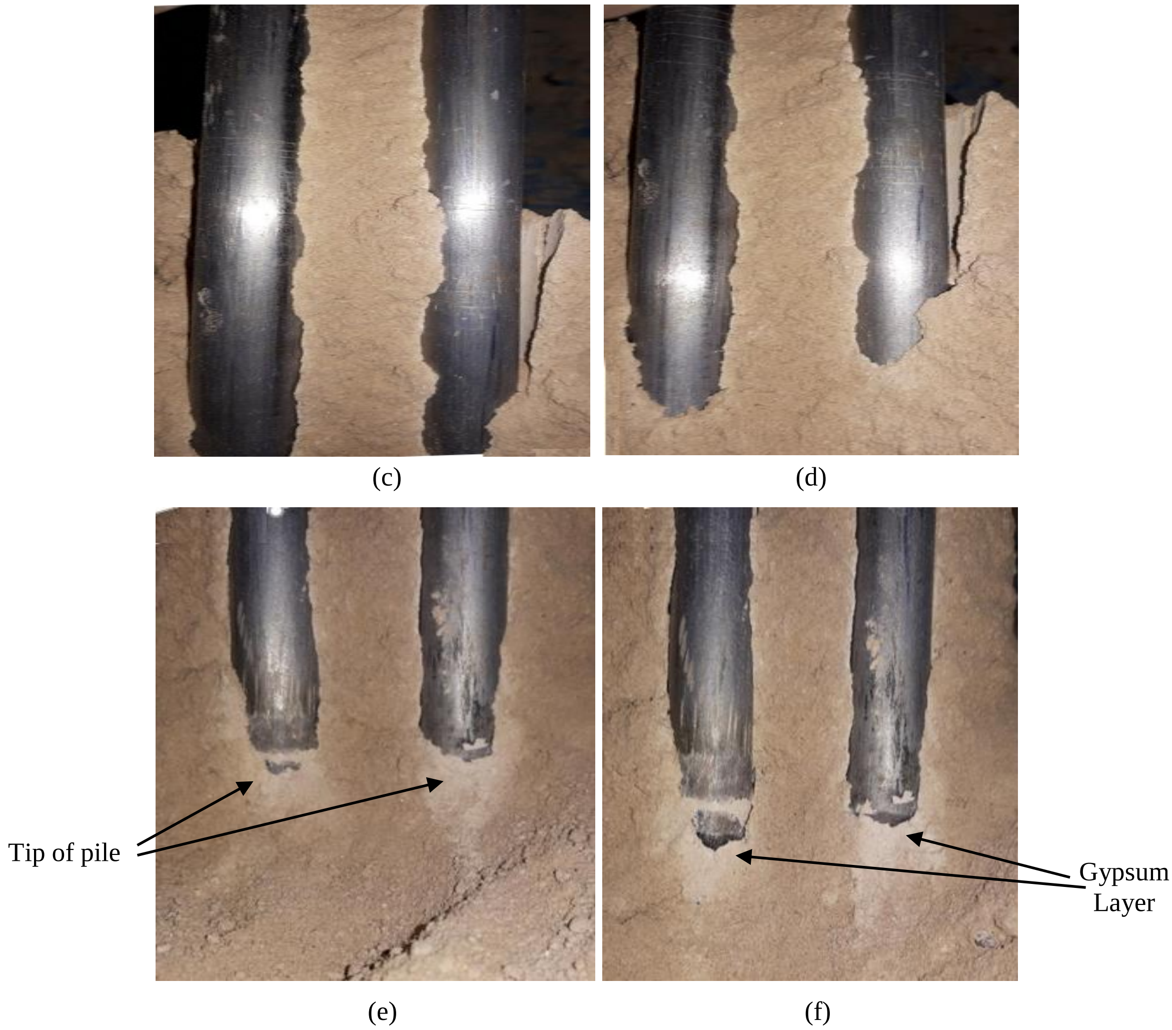


Figure 13. Clarity of gypsum particles between the soil and group pile surface along embedded depth, a) at 10 cm, b) at 15 cm, c) at 20 cm, d) at 25 cm, e) at 28 cm, f) at 30 cm

6. Conclusions

- Group efficiency for 2D is less than one, whereas for 4D and 6D the group efficiency are more than one for both dry and soaked in S1 and S2. In addition, it found that 4D spacing is more efficiency than 6D and 2D.
- The group efficiency is increased by 21% at dry and 19% at soaked when pile spacing increased from 2D to 4D and decreased by 4% at dry and 6% at soaked when pile spacing increased from 4D to 6D in S1. In addition, the group efficiency in S2 is increased by 27.8% at dry and 18.5% at soaked when pile spacing increased from 2D to 4D and decreased by 3.7% at dry and 7.8% at soaked when pile spacing increased from 4D to 6D.
- The reduction in load carrying capacity is increased slightly with increasing pile spacing. However, this reduction is also increased with increasing gypsum content and silt content.
- The reduction in capacity of single pile is more than group pile, in which the reduction of single and group pile are (83.8% and 82.7%) in S1 and (87.7% and 86.9%) in S2 respectively.
- The increment of ultimate load of spacing 2D, 4D and 6D in S2 are (62%, 70% and 71%) at dry and (22.4%, 22.1% and 22%) at soaked respectively more than that for S1.
- In practice, the driven pile not recommended in gypseous soil.

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7. Conflicts of Interest

The authors declare no conflict of interest.

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