Behavior of Group of Plugged and Unplugged Pipe Piles in Soil Containing Cavities

F A Abdullah¹*, Mohammed Y Fattah², and A A Al-Keifae³

¹ Lecturer, Civil Engineering Department, University of Kufa, Iraq. ² Professor, Civil Engineering Department, University of Technology, Baghdad, Iraq. ³ Professor, Civil Engineering Department, Al-Nahrain University, Baghdad, Iraq.

*Corresponding author. Email: firas.altufaili@uokufa.edu.iq

Abstract. The present study examines the effect of cavities on the pipe pile foundation settlement and capacity subjected to compressive axial loads and embedded in sandy soil. By inserting a prototype of cavity which is placed adjacent to the pile at different locations that lie at horizontal spacing between pile and cavity center to center defined by (X) and cavity depth from the soil surface by cavity depth (Y), the variation in cavity location was studied for all laboratory tests. The presence of cavity reduces the pile load capacity by different rates depending on its location. In group piles with of L/D =15 with cavity at Y/L = 1 and X/D = 1.5, 2.5, the reduction is between (6.1% to 26%).

Keywords: Pipe pile; soil plug; group; activity.

1. Introduction

The main purpose of using pile foundations which represent that segment of the substructure responsively to withstand and transfer the foundation loads of the superstructure to deeper strata situated at some depth below the surface of the ground, those structural components are long and slender components made of wood, concrete, or iron, used to transfer and deliver foundations loads through to the strong layers by penetrating the weaker upper layers had weak characteristics or passing be river layers or marine's infrastructure would be defined as piles, It may also be used on offshore structures or in other situations such as resistance to raising forces or resistance to horizontal loads under poor soil conditions [1].

A cavity that occurs with sufficient frequency under structures warrants special attention, since cavities can cause structural damage and loss of life. The precise inquiry to locate the voids and cavities near the soil surface is one of the valuable factors in which these cavities can be channels of attitude for water motility that first expanded and then collapsed when it reached a serious size and thus an unfavorable impact on the piles, building foundations and other facilities that appear.

Such cavities exit as follows in various structures depending on the origin of the formation [2]:

1) Artificial cavity due to the (oldest) construction of the vault.
2) Natural cavity, due to flowing water (dissolution of gypsum).

Large areas with existing gypsum are located in Al-Najaf soil and with continuous flow of groundwater in soils containing gypsum, the gypsum dissolves and produces several cavities of various shapes at different locations below ground surface. Different cavity sizes are found in various sizes ranging from 10 cm to 300 cm [2]. The construction on these soils caused sudden failure of buildings
happened in the soil mass due to the formation of the cavity after the load application (the presence of the building structure before or / and during the cavity forming). When a structure constructed above soils contains cavities, cracks may develop within the roofs and walls of the building because of differential settlement.

2. Soil Plugging in Tubular Piles

The piles of low displacement piles may either as solid body (I or H section piles) or tubular hollow that had a small cross section area, during the stage of pile insertion of those types through a soil layers may form a kind of soil with a special action preformed called "soil plugging"; because of soil entering inside the pile hall at shallow depths in the initial stages of driving or pressing the pile the plug formed cause defusing any new entered soil at the toe zone, referred to as soil plugging. Particularly with pipe piles (tube section piles), with a gradual drilling out may be necessary to minimize driving resistance, soil plug can create enormous resistance to drive process that may reach to a close end mode due to damping on the pipe pile's interior walls [3].

The tubular hollow piles behavior may more complicate, generally may be in the middle phase between displacement and non-displacement piles. Though driving process of pile with open end shape through soil layer, a soil plug represented by Paikowsky et al. [4] a column of soil that may initiated inside the tubular pile. Soil plug height may reach or equal to total pile driving length or less than it also, the soil column length (soil plug) may be less than that of the total length of the pile, either in full or in part plug state, through the pile driving cycle. These three types of driving modes can be found through installation process of a hollow pile completely unplugged, entirely in plug state or in partial plug mode.

During pile insertion with open end shape sand soil may enter through pile tube with a rate maybe larger the penetration. With the progress in pile insertion process the soil column core that formed inside the tube may provide enough resistance (frictional resistance) through all of wall interface of pile till reach to a mount that may prevent no further soil intrusion, causing a phenomena called plug state. Plugging mode importance, not just having great effect on to the pile tip resistance of the applied loads, but it causes indirect effect on the pile shaft capacity also. A plugged pile displaces more soil than a pile that penetrates into a coring mode, raising the effective stresses that surround the pile. Plugging also affects the dynamic nature of the pile, which complicates the dynamic study of the plug's characteristics, which can have a major impact on the pile capacity as a percentage (PLR) (Paikowsky et al. [4]; Paikowsky, and Whitman [5]).

Cavities that happen beneath structure having enough frequency need distinctive concern as cavity can lead to structure harm and short of life. Specific investigation to identify the cavity and vacuums close to the surfacing for the soil is an important factor in which this cavity could cause water to move and collapse as they reach critical size of buildings, piles and other facilities.

A number of scholars performed lab testing with centrifuging model testing for studying tunneling effects on the piles settling and bearing capacity. It was hypothesized that, for geotechnical designers, impact of tunnel upon near piles foundations within poor soils might be of substantial significance. So far, techniques that manage the examination of this issue could fundamentally be arranged into double kinds. The main technique is a finished category of three-dimension investigation that considers the pile and the soils around it, in general, all through the removal of the tunnel, and normally 3D limited component examination has been received (Chen et al. [6]).

Morton and King [7] Lab research examined the impact of tunnel upon pile foundation ' bearing capability and settlement. They found that piles can be greatly affected by tunneling, and therefore concluded that the effects of tunneling on existing adjacent or superincumbent pile foundations in weak soils can be a major and governing concern in underground work design and execution.

Aziz [2] examined the performance of lateral loading piles embedded in cohesive ground with cavity in Iraq's Al-Najaf city. An experimental and numerical study of cavity / neighboring pile interaction in sand soils. Experimentation researches had been conducted to investigate the impact on the late of the various factors (such as cavity positions, batter angle of pile pulling height and vertical dead loads).

2
The conduct of along the side stacked pile developed in sand soil that contains pits was explored by Al-Mosawe et al. [8]. Five gatherings were made; the principal bunch was completed on heap built-in soil that does exclude pits. Gatherings two and three were performed on heap developed in soils containing single depression situated in front and in contact with heap face for the gathering two and in the back and in contact with pile’s face for bunch three. Tests in bunch four had been done on piles in the sand having two depressions situated in front and in contact with the pile’s face. Tests in the fifth gathering were completed on piles in soils having three pits situated in front and at various good ways from the pile’s face.

Fattah et al. [9, 10] studied the effect of presence of cavity on groups pile lies on sand embedment by examining settlement value and single and group pile capacity of piles with different cavity location using experimental and analytical modeling. Pile models were tested in a sand box under a load applied using a hydraulic operated jack, the load is monitored with a load cell. Three strain gages were provided to piles to measure the strains and then calculate the load transmitted to each pile in the group using a strain data logger. Three groups of piles (single pile, pile group (1 × 2), and pile group of (2 × 2)) were inspected in the laboratory as a free-standing pile group. A prototype of a cavity was simulated and positioned adjacent to the piles at different distances from the piles centerline and different depths below the soil surface. The influence of varying the location of cavity (X), depth of cavity (Y), and cavity diameter (d) on the load and settlement of the pile and pile groups has been investigated for all tests. It was concluded that the measured pile load increases with increase of (X/D, D is the diameter of pile) caused by decrease of the zone influenced by the existence of cavity. When the cavity is positioned at a close distance to the pile, it will decrease the soil density and hence reduce the skin friction along the pile and result in reduction in the pile failure load. The ultimate pile load is not influenced by the existence of a cavity at a distance of 5.5 pile diameters at all depths.

The main objective of the current work is to ensure significant performance of soil and pipe groups under axial loading with or without soil plug formation in piles embedded in cavity soils and to generate useful parameters and required geotechnical data. The main aims of the current study may be identified by examining the impact of cavity positions in X and Z directions on vertical dead loads and their effect on stabilization of the piles in addition to examining the effect of soil plug on capability determination of single and group tubular piles or when removal of soil plug compared to close-end piles in soil layer form with or without cavity.

3. Experimental Work
3.1. Soil characteristics
Due to the soil morphology of Al-Najaf city, the tested soil used in the current study was chosen from some sites on Al-Najaf city. Soil samples were taken from a region correspond to Al-Najaf sea region near Al-Kafeel college. The site characteristics of soil were determined to be used in the laboratory model tests. These characteristics include soil properties, pile material properties, and the properties of the interface between the pile and soil. The soil properties are summarized in table 1. The soil is classified, according to the Unified Soil Classification System, as SP type.

3.2. Model Setup
All model tests were conducted using laboratory model that consists of a frame, soil tank, and loading machine. A new device was needed to be produced for simulating the pile loading testing in the area. The device is made of the next segments:
1. Cubical containers made of steel, loading frame with mechanical jack. 2. Axial load system. 3. Loadings cell and digital weighting indicator. 4. Raining frame. 5. Impact hammer device. 6. Pile driving system –pressing system installation. 7. Data taker with PC device. 8. AC Drive (speed regulator) and gear box. 9. UPS (Universal Power System). 10. Soil plugs removal and measurement devices.
Table 1. Sand chemic and physical features.

| Features                        | Value | Specification       |
|---------------------------------|-------|---------------------|
| **Chemical features**           |       |                     |
| Organic matter                  | 5.5 % |                     |
| Sulfate content SO₃             | 7.27 %| B.S 1377-Part 3 [11]|
| Gypsum content                  | 15.6 %| B.S 1377-Part 3 [11]|
| **Grain size analysis** (Physical soil classification according to USCS) |       |                     |
| D₆₀, mm                         | 0.36  |                     |
| D₃₀, mm                         | 0.22  |                     |
| D₁₀, mm                         | 0.16  |                     |
| Gravel (%)                      | 0     |                     |
| Sand (%)                        | 96    | ASTM D422 [12]      |
| Silt and Caly (%)               | 4     |                     |
| Uniformity coefficient, Cu      | 2.25  |                     |
| Curvature coefficient, Cc        | 0.84  |                     |
| Specific gravity (Gs)           | 2.62  | ASTM D 854 [12]     |
| **Dry unit weights**            |       |                     |
| Maximum dry unit weight (kN/m³) | 16.9  | ASTM D4253 [12]     |
| Minimum dry unit weight (kN/m³) | 13.6  | ASTM D 4254 [12]    |
| Dry unit weight (γd) (kN/m³) at RD 70% | 16.01 |                     |
| **Void ratios**                 |       |                     |
| Maximum void ratio (eₘₐₓ)       | 0.895 |                     |
| Minimum void ratio (eₘᵦₙ)       | 0.526 |                     |
| Angle of internal friction (ϕᵦ) at RD 70% | 34°   | ASTM D 3080 [12]    |

3.3. Steel containers
Two steel containers with dimensions 700 mm in length, 700 mm in width, and 625 mm in height, figure 1.

![Figure 1. Steel container.](image)

3.4. Axial loading system
The axial load system was adjusted with the end goal of this examination. The loading is subjected to a mechanic jack linked through an apparatus box engine and AC drive (velocity controller), it thus
manages the velocity of the gear box engine as indicated within figure 2. The maxi loading which could be subjected is two tons. The loading rate is kept steady at 1 mm/min as suggested according to ASTM D1143-07. The model is conceivable for moving within horizontal and vertical ways to a pile group, whereas the first model got fit for move any way, this is opposite with the piles' cross area, thus one can ensure that the heap demonstrations in the heap framework and no proof of any eccentricities exists, figure 3.

Figure 2. Steel loading frame and axial loading system.

a) Driven pile instrument  
b) Pressed pile instrument

Figure 3. Pile group system installation.

3.5. Identifying of model piles utilized in the test program
So as to make the documentation utilized for piles simple, distinguishing the symbol was provided to every model as showed in table 2. Every pile gets recognized by the proportion of pile's length to measurement, sort of installing and pile end kind.
Table 2. Pile identifying by various lengths of soil plug.

| No. | Method of penetration | Pile case | L/D | Pile ID          |
|-----|-----------------------|-----------|-----|------------------|
| 1   | Driven                | Single-open ended-full plugged-without cavity | 12  | 1(N)DOF(12)      |
| 2   | Driven                | Single-open ended-full plugged-with cavity    | 12  | 1(C)DOF(12)      |
| 3   | Driven                | Two pile-open-full plugged-without cavity     | 12  | 2(N)DOF(12)      |
| 4   | Driven                | Two pile-open-full plugged-with cavity        | 12  | 2(C)DOF(12)      |
| 5   | Driven                | Four pile-open-full plugged-without cavity    | 12  | 4(N)DOF(12)      |
| 6   | Driven                | Four pile-open-full plugged-with cavity       | 12  | 4(C)DOF(12)      |
| 7   | Driven                | Single-open ended-75% unplugged-with cavity   | 12  | 1(C)DOF75%(12)   |
| 8   | Pressed               | Single-open ended-full plugged-without cavity | 12  | 1(N)POF(12)      |
| 9   | Pressed               | Two pile-open-full plugged-without cavity     | 12  | 2(N)POF(12)      |
| 10  | Pressed               | Two pile-open-full plugged-with cavity        | 12  | 2(C)POF(12)      |
| 11  | Driven                | Single-close ended-full plugged-without cavity| 12  | 1(N)DCF(12)      |
| 12  | Driven                | Single-close ended-full plugged-with cavity   | 12  | 1(C)DCF(12)      |
| 13  | Driven                | Two pile-close-full plugged-without cavity    | 12  | 2(N)DCF(12)      |
| 14  | Driven                | Two pile-close-full plugged-with cavity       | 12  | 2(C)DCF(12)      |
| 15  | Driven                | Single-open ended-full plugged-without cavity | 15  | 1(N)DOF(15)      |
| 16  | Driven                | Single-open ended-full plugged-with cavity    | 15  | 1(C)DOF(15)      |
| 17  | Driven                | Two pile-open-full plugged-without cavity     | 15  | 2(N)DOF(15)      |
| 18  | Driven                | Two pile-open-full plugged-with cavity        | 15  | 2(C)DOF(15)      |
| 19  | Driven                | Four pile-open-full plugged-without cavity    | 15  | 4(N)DOF(15)      |
| 20  | Driven                | Four pile-open-full plugged-with cavity       | 15  | 4(C)DOF(15)      |
| 21  | Driven                | Single-open ended-75% unplugged-with cavity   | 15  | 1(C)DOF75%(15)   |
| 22  | Pressed               | Single-open ended-full plugged-without cavity | 15  | 1(N)POF(15)      |
| 23  | Pressed               | Single-open ended-full plugged-with cavity    | 15  | 1(C)POF(15)      |
| 24  | Pressed               | Two pile-open-full plugged-without cavity     | 15  | 2(N)POF(15)      |
| 25  | Pressed               | Two pile-open-full plugged-with cavity        | 15  | 2(C)POF(15)      |
| 26  | Pressed               | Four pile-open-full plugged-without cavity    | 15  | 4(N)POF(15)      |
| 27  | Pressed               | Four pile-open-full plugged-with cavity       | 15  | 4(C)POF(15)      |
| 28  | Driven                | Single-close ended-full plugged-without cavity| 15  | 1(N)DCF(15)      |
| 29  | Driven                | Single-close ended-full plugged-with cavity   | 15  | 1(C)DCF(15)      |
| 30  | Driven                | Two pile-close-full plugged-without cavity    | 15  | 2(N)DCF(15)      |
| 31  | Driven                | Two pile-close-full plugged-with cavity       | 15  | 2(C)DCF(15)      |

D: Driven ; O: Open ; F: Full plugged ; P: Pressed ; U: Unplugged ; (C): with cavity
(N): No cavity ; C: close

4. Testing program

Ninety seven model piles were evaluated as pressed or powered piles. Key model classification by pile length L / pile diameter D ratio (L / D= 12 and L / D = 15). The study uses three classes of piles: the first group consists of (36) single piles of items, the second includes (36) model pile group with an arrangement of (1 x 2) while the third one consists of 16 pile group models (2 x 2). Both models get identical geometry concerning pile’s length (L), pile diameter (D) and pile length on the ground level (60-70 mm).
• Cavity site (X): the horizon spacing amid the cavity as well as the single or group of piles center to center, \(X / D = 0\) cm, 1.5, 2.5.
• Cavity deepness (Y): the vertical distance from the soil surface to the cavity centerline, \(Y / L = 0.5\), (10 \(D / L = 0.833\)), 1.0, and 1.2.

Two values of cavity diameter (d) are used in the study, \(d / D = 1, 1.5\).

5. Results and Discussion

5.1. Effect of cavity location on group piles

Figure 4 shows the effect of changing the cavity location on the load settlement of group of two open ended driven piles in fully plugged state that cause a reduction in pile load capacity of about 16.4% to 22% for \(X/D=1.5\) and 2.5 while in figure 5, the reduction is between 28.6% and 18.2. Figure 6 shows that the reduction is between 52.8% and 45.7) while in figure 7, this amount is between 28.6% and 21.4%.

![Figure 4](image1.png)

**Figure 4.** Load-settlement relation of group of two open ended driven piles with a cavity at \(Y/L=1.2\) and \(X/D = 0.0, 1.5\) and 2.5.

![Figure 5](image2.png)

**Figure 5.** Load-settlement relation of group of two open ended driven piles with a cavity at \(Y/L=1\) and \(X/D = 1.5, 2.5\).
Figure 6. Load-settlement relation of group of two open driven fully plugged piles with a cavity at Y/L=0.833 and X/D= 1.5, 2.5.

Figure 7. Load-settlement relation of group of two open ended driven fully plugged piles with a cavity at Y/L=0.5 and X/D= 1.5 and 2.5.

5.2. Effectiveness of the process of insertion group piles into the soil

Figure 8 shows the effect of cavity location in different elevation (Y/L=0.5, 0.833 and 1) with constant X/D=1.5 for pressed and driven open ended group pipe piles that reduction amount between 14.3% for pressed state, 21.46% for open fully plugged group two pipe pile and reach between (18.2% – 28.6%), cavity at Y/L=1 and X/D=2.5 and 1.5.

Figure 9 shows the load-settlement relation of a group of closed ended driven and pressed piles with L/D=15 and cavity at Y/L=1 and X/D = 1.5, 2.5 that caused a reduction in pile capacity between 6.1% to 26%. Figure 10 shows the load-settlement relation of a group of pressed piles having L/D=15 with cavity at Y/L=1.2 and X/D = 1.5 and 2.5 that caused a reduction in pile capacity between 16.7% and 26.5%. After examining the failure definition proposals and by inspection of the behavior of the load-settlement relations for the piles in the present work, it was found that two tangents proposal can be adopted in specifying the ultimate pile group capacity. Table 3 summarizes the load carrying capacity of piles of different conditions. It can be concluded from table 3 that the presence of cavity reduces the ultimate capacity of piles (failure load of pipe pile).
Figure 8. Load-settlement relation of group of two open ended driven piles and pressed fully plugged with a cavity at $Y/L=0.5$, 0.833, 1, and $X/D=1.5$.

Figure 9. Load-settlement relation of a group of closed ended driven and pressed piles having $L/D=15$ with a cavity at $Y/L=1$ and $X/D=1.5$, 2.5.

Figure 10. Load-settlement relation of a group of pressed piles with $L/D=15$ and a cavity at $Y/L=1.2$ and $X/D=1.5$ and 2.5.
Table 3. Piles loading limit of single and group driven or pressed pipe pile.

| Pipe pile type | Embedded length (mm) | No. of pile | L/D | Y/L | X/D | Ultimate pile capacity (N) |
|----------------|----------------------|-------------|-----|-----|-----|--------------------------|
| 1(N)DOF(12)    | 360                  | 1           | 12  | ==  | ==  | 1130                     |
| 1(C)DOF(12)    | 360                  | 1           | 12  | 1.2 | 0   | 471                      |
| 1(C)DOF(12)    | 360                  | 1           | 12  | 1.2 | 1.5 | 965                      |
| 1(C)DOF(12)    | 360                  | 1           | 12  | 1.2 | 2.5 | 1020                     |
| 1(C)DOF(12)    | 360                  | 1           | 12  | 1   | 1.5 | 907                      |
| 1(C)DOF(12)    | 360                  | 1           | 12  | 1   | 2.5 | 981                      |
| 1(C)DOF(12)    | 360                  | 1           | 12  | 0.833 | 1.5 | 685                      |
| 1(C)DOF(12)    | 360                  | 1           | 12  | 0.833 | 2.5 | 980                      |
| 1(C)DOF(12)    | 360                  | 1           | 12  | 0.5 | 1.5 | 956                      |
| 1(C)DOF(12)    | 360                  | 1           | 12  | 0.5 | 2.5 | 1010                     |
| 2(N)DOF(12)    | 360                  | 2           | 12  | ==  | ==  | 3434                     |
| 2(C)DOF(12)    | 360                  | 2           | 12  | 1.2 | 0   | 2650                     |
| 2(C)DOF(12)    | 360                  | 2           | 12  | 1.2 | 1.5 | 2697                     |
| 2(C)DOF(12)    | 360                  | 2           | 12  | 1.2 | 2.5 | 2870                     |
| 2(C)DOF(12)    | 360                  | 2           | 12  | 1   | 1.5 | 2453                     |
| 2(C)DOF(12)    | 360                  | 2           | 12  | 1   | 2.5 | 2810                     |
| 2(C)DOF(12)    | 360                  | 2           | 12  | 0.833 | 1.5 | 1620                     |
| 2(C)DOF(12)    | 360                  | 2           | 12  | 0.833 | 2.5 | 1864                     |
| 2(C)DOF(12)    | 360                  | 2           | 12  | 0.5 | 1.5 | 2452                     |
| 2(C)DOF(12)    | 360                  | 2           | 12  | 0.5 | 2.5 | 2698                     |
| 1(N)DCF(12)    | 360                  | 1           | 12  | ==  | ==  | 1226                     |
| 1(C)DCF(12)    | 360                  | 1           | 12  | 1.2 | 0   | 450                      |
| 1(C)DCF(12)    | 360                  | 1           | 12  | 1.2 | 1.5 | 590                      |
| 1(C)DCF(12)    | 360                  | 1           | 12  | 1.2 | 2.5 | 705                      |
| 1(C)DCF(12)    | 360                  | 1           | 12  | 1   | 1.5 | 981                      |
| 1(C)DCF(15)    | 450                  | 1           | 15  | 1.2 | 2.5 | 1165                     |
| 1(C)DCF(15)    | 450                  | 1           | 15  | 1   | 1.5 | 1107                     |
| 1(C)DCF(15)    | 450                  | 1           | 15  | 1   | 2.5 | 1224                     |
| 1(C)DCF(15)    | 450                  | 1           | 15  | 0.833 | 1.5 | 1175                     |
| 1(C)DCF(15)    | 450                  | 1           | 15  | 0.833 | 2.5 | 1250                     |
| 1(N)DCF(15)    | 450                  | 1           | 15  | ==  | ==  | 1593                     |
| 1(C)DCF(15)    | 450                  | 1           | 15  | 1.2 | 1.5 | 1375                     |
| 1(C)DCF(15)    | 450                  | 1           | 15  | 1.2 | 2.5 | 1505                     |
| 1(C)DCF(15)    | 450                  | 1           | 15  | 1   | 1.5 | 1350                     |
| 1(C)DCF(15)    | 450                  | 1           | 15  | 1   | 2.5 | 1428                     |
| 1(C)DCF(15)    | 450                  | 1           | 15  | 0.833 | 1.5 | 1450                     |
| 1(C)DCF(15)    | 450                  | 1           | 15  | 0.833 | 2.5 | 1490                     |
| 1(C)DCF(15)    | 450                  | 1           | 15  | 0.5 | 1.5 | 1472                     |
| 1(C)DCF(15)    | 450                  | 1           | 15  | 0.5 | 2.5 | 1520                     |
| 2(N)POF(15)    | 450                  | 2           | 15  | ==  | ==  | 4806                     |
| 2(C)POF(15)    | 450                  | 2           | 15  | 1.2 | 1.5 | 3531                     |
| Pipe pile type | Embedded length (mm) | No. of pile | L/D | Y/L | X/D | Ultimate pile capacity (N) |
|---------------|----------------------|-------------|-----|-----|-----|---------------------------|
| 2(C)POF(15)   | 450                  | 2           | 15  | 1.2 | 2.5 | 4002                      |
| 2(C)POF(15)   | 450                  | 2           | 15  | 1   | 1.5 | 4120                      |
| 2(C)POF(15)   | 450                  | 2           | 15  | 1   | 2.5 | 4512                      |
| 2(N)DCF(15)   | 450                  | 2           | 15  | ==  | ==  | 3237                      |
| 2(C)DCF(15)   | 450                  | 2           | 15  | 1.2 | 1.5 | 2158                      |
| 2(C)DCF(15)   | 450                  | 2           | 15  | 1.2 | 2.5 | 2453                      |
| 2(C)DCF(15)   | 450                  | 2           | 15  | 1   | 1.5 | 2450                      |
| 2(N)DOF(15)   | 450                  | 2           | 15  | ==  | 1   | 2845                      |
| 2(C)DOF(15)   | 450                  | 2           | 15  | 1.2 | 1.5 | 2452                      |
| 2(C)DOF(15)   | 450                  | 2           | 15  | 1.2 | 2.5 | 2551                      |
| 2(C)DOF(15)   | 450                  | 2           | 15  | 1   | 1.5 | 2256                      |
| 2(C)DOF(15)   | 450                  | 2           | 15  | 1   | 2.5 | 2354                      |

6. Conclusions

1. Soil plug removal (100% soil column removed) from group or single pile will cause severe reduction in pile capacity specially when there is a cavity near the pile. The reduction may reach to 90% loss in ultimate pile capacity in single pressed pile and about 84% in single driven open ended pipe pile and about 91.5% loss in group (1×2) open driven piles and about 78% in group (1×4) open driven piles.

2. Cavity orientation affects the load settlement relation of group of two open ended driven piles in fully plugged state that cause a reduction in pile load capacity from (16.42%) to (22%) for X/D=1.5 and 2.5 that including the changing in cavity location.

3. The effect of cavity location at different elevations (Y/L=0.5, 0.833 and 1) with constant X/D=1.5 for pressed and driven open ended group pipe piles revealed a reduction in the pile load carrying capacity between 14.27% for pressed state, 21.46% for open fully plugged group two pipe pile and reach between (18.17% – 28.56%), cavity at Y/L=1 and X/D=2.5 and 1.5.

4. In group of closed ended driven and pressed piles with L/D=15 with cavity at Y/L=1 and X/D = 1.5 and 2.5, there was a reduction in pile capacity between 6.1% to 26%.

7. References

[1] Bowles LE, others. *Foundation analysis and design*. McGraw-hill; 1996.
[2] Aziz L J, Mahmoud M R and Shlash K T 2012. Lateral resistance of a single pile embedded in sand with cavities. *Engineering and Technology Journal*, 30(15), 2641-2663.
[3] Fattah M Y and Al-Soudani W H 2016. Bearing capacity of closed and open ended pipe piles installed in loose sand with emphasis on soil plug.
[4] Paikowsky S G, Whitman R V and Baligh M M 1989. A new look at the phenomenon of offshore pile plugging. *Marine Georesources & Geotechnology*, 8(3), 213-230.
[5] Paikowsky S G and Whitman R V 1990. The effects of plugging on pile performance and design. *Canadian Geotechnical Journal*, 27(4), 429-440.
[6] Cheng C Y, Dasari G R, Chow Y K and Leung C F 2007. Finite element analysis of tunnel–soil–pile interaction using displacement controlled model. *Tunneling and Underground Space Technology*, 22(4), 450-466.

[7] Morton J D and King K H 1979. Effects of tunneling on the bearing capacity and settlement of piled foundations.

[8] Al-Mosawe M J, Al-Shakarchi Y J and Al-Taie S M 2007 The performance of laterally loaded piles embedded in sandy soils with cavities. *Journal of Engineering, University of Baghdad*, ISSN: 17264073 25203339 Vol. 13, No.1, pp.1168-1185.

[9] Fattah M Y, Al-Helo K H I and Abed H H 2014 Effect of cavity in sandy soil on load distribution of pile group. *Engineering and Technology Journal*, 32(7 Part (A) Engineering), 1733-1751.

[10] Fattah M Y, Al Helo K H I and Abed H H 2018 Load distribution in pile group embedded in sandy soil containing cavity. *KSCE Journal of Civil Engineering*, 22(2), 509-519.

[11] BS 1377 – 1990 Methods of Testing Soils for Civil Engineering Purposes.

[12] ASTM Book of Standards 2020 Volume 04.09 Soil and Rock (II) ASTM International.