Numerical Analysis of Fully Plugged Pipe Pile Groups in Sandy Soil

M Y Fattah[1] , N M Salim[2] and A M B Al-Gharrawi[3]
[1]Professor, Building and Construction Engineering Department, University of Technology, Baghdad, Iraq.
[2]Professor, Building and Construction Engineering Department, University of Technology, Baghdad, Iraq.
[3]Lecturer, Civil Engineering Department, University of Kufa, Iraq.

Abstract. Plugging is essential not only due to its direct contribution to pile end load carrying capacity but also due to its indirect contribution to mobilised shaft capacity. A pile with a plug displaces more soil than a pile that penetrates in boring mode, which enlarges the effective stresses around the pile. Numerical modelling of plugged pipe piles was carried out using PLAXIS-2015 software, with the Hardening Soil Model (HS small) used for soil modelling. The parametric study presented in this research was carried out with this computer program based on the finite element method. The case of a pipe pile group (2×2) with full plug was chosen as the basic problem, with spacing between piles of 3.0 m. It was concluded that there is slight increase in pile group capacity when increasing the spacing between piles by about 2.8%. It was found that the change of the angle of friction was the most important parameter; its increase from 31o to 40o caused an increase in the shear stress of about 150%.
Keywords. Pipe pile, plug, spacing, sandy soil, finite elements.

1. Introduction:

Small displacement piles may be either solid, as with steel H-piles, or hollow,as with tubular piles with open ends; they are always, however, of relatively small cross-sectional area. This kind of pile is usually constructed by means of percussion. However, a plug of soil may be formed during driving, especially with tubular piles, and periodic drilling may be required to decrease the driving resistance. A plug of soil can create greater resistance to driving than a closed end, due to damping on the internal face of the pile tube. The soil inside a pile with open end can form such a plug during the driving process, which prevents new soil accumulating at the toe; this is termed soil plugging. Soil plugging changes the driving properties of a pile with open end to those of a pile with closed end, often accompanied by an increase in driving resistance. If the plugging response of the pile is not correctly assessed, the result is either that excessive or costly additional power is used in hammering due to the high estimated resistance to driving or that the pile plugs [1]. The mechanisms required for plugging with soil in piles with open ends have been shown by [2]to require arching in cohesionless soil, which may lead to important internal skin resistance and affect capacity of the interior soil column [3]. Plugging with soil is therefore not fully assessed by means of drivability characteristics; it is also influenced by the method of driving, as illustrated by Henke and Grabe [4] and De Nicola and Randolph [5].The influence of different installation methods (piling, vibrating, and pressing) was described by Paik and Salgado [6], who concluded that compressed piles achieve a greater carrying capacity than identical piled piles in the same soil conditions. Using numerical modelling and solving for the situation that occurs when plugs develop in an open pipe pile, similar conclusions can be drawn, as in Henke and Grabe [4]. Their study was carried out on piles with diameters of 61 cm in densely packed sand, with installation by means of piling, pressing and vibrating. A total number of 60 model pile tests were carried out by Fattah et al. [7]to investigate the effect of plugs on pile bearing capacity and the effects of the removal of soil plugs. Several parameters were investigated, including pile diameter to length ratio and types of construction in sands of different densities, while plug removal to three levels (50%, 75%, and 100 %) was investigated in accordance with plug length. The changes in the length of soil plug and incremental filling ratio (IFR) with the depth of pile penetration during driving illustrated that piles with open ends are plugged partially due to the pile driving outset. The pile reached a fully plugged state for pressed piles in loose and medium sand and partially plugged (IFR = 10%) in dense sand. For driven piles, the IFR is about 30% in loose sand, 20% in medium sand, and 30% in dense sand. The pile load capacity increases with rises in the length of the plug length ratio (PLR).

The rate of increase in the value of the pile load capacity with PLR is greater in dense sand than in medium and loose sand. The experimental tests carried out by Fattah et al. [8] consisted of 36 tests on single piles. All tubular piles were tested using poorly graded sand from the southern city of Karbala in Iraq. The sand was prepared at three different densities using a raining technique. Different parameters were considered, such as method of installation, relative density, removal of soil plug with respect to length of plug, and pile length to diameter ratio. The soil plug was removed by using a new device manufactured to remove the soil column inside open pipe pile groups during driven and pressed service. It was concluded that the removal of soil plugs from piles causes a reduction in pile load carrying capacity due to the elimination of two components, internal friction and the confining effect on the end bearing zone. The maximum reduction occurred in the dense state of soil about 61.5%. The sand column length increased with the progression of installation pressure when the pressing method was used, but in driven piles, there was no systematic trend to the sand column length generated in the piles. Long piles exhibited a higher tendency to plugging and plugging was also more common in dilatant and dense soils. The present study aims to develop a numerical model to analyse pipe-pile group systems by using the finite element program PLAXIS-3D [9]and adopting a full-scale model to simulate the pipe pile group in situ.

2. Numerical Modelling of Pipe Piles

The finite element method represents one of the extensive proliferation techniques used in the simulation of engineering applications. In this study, PLAXIS-3D [9] Foundation was used. Based on the finite element method, a domain is discretized into several elements, and each element includes several nodes. The embedded pile was modelled to describe the interaction of a pile with the soil around it. The interaction at the pile surface and at its tip was modelled by means of embedment of interface elements. The pile was modelled as a beam consisting of a 10-node tetrahedral element at any position with any selected orientation, as illustrated in Figure 1. The presence of the beam element caused three additional nodes to be introduced within the 10-node tetrahedral element.

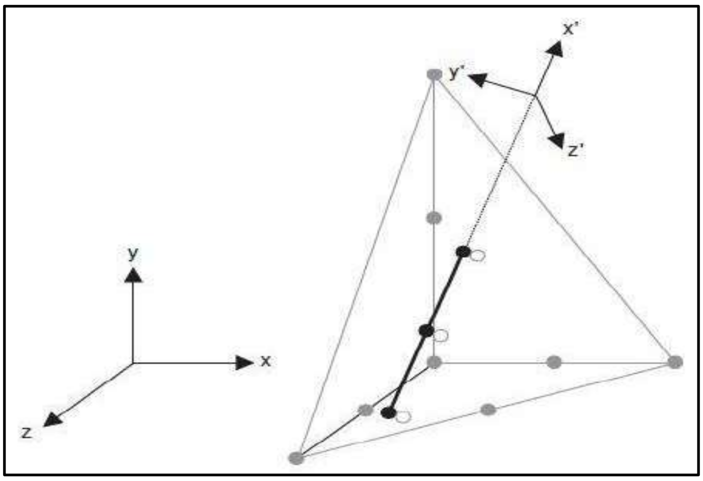


Figure 1: The embedded beam element denoted by the solid line. The blank grey circles denote the virtual nodes of the soil element, [9].

The interaction of the pile embedded at the cap (or raft) was modelled by an embedment of the interface element. This interaction is modelled by a cap (raft) force vector $f^{foot}f^{foot}$. As with the mobilization of shaft traction, the mobilization of the cap (raft) force is an incremental process.

The main soil elements of the three-dimensional finite element mesh are the 10-node tetrahedral elements. As well as the soil elements, special kinds of elements were utilised to describe structural behaviour. For the beams, 3-node bar elements were used, which are compatible with the 3-node edges of a soil element. In addition, 12 node interface elements were utilised to model soil-structure interaction behaviours.

IOP Conf. Series: Materials Science and Engineering **433** (2018) 012019 doi:10.1088/1757-899X/433/1/012019

The soil is assumed to behave as an elasto-plastic material; thus, before presenting plasticity models, it is necessary to describe some features of the theory of elasticity, as this is utilised to estimate the elastic strains that take place prior to yielding in an elasto-plastic material.

2.1 Hardening soil model with small-strain stiffness (HS_{small})

The hardening soil model including small-strain stiffness (HS_{small}) is a developed version of the hardening soil model that takes into account the increase in stiffness of soils under small strains. At low levels of strain, a number of soils show higher stiffness than at conventional levels of strain, and this stiffness changes nonlinearly with strain. This behaviour is modelled in the HS_{small} model byutilising an additional parameter of strain history and two additional parameters ofmaterial: G_0^{ref} G_0^{ref} and $\gamma_{0.7}\gamma_{0.7}$. $G_0^{ref} G_0^{ref}$ is the modulus of small strain shear and $\gamma_{0.7}\gamma_{0.7}$ is the strain level at which the shear modulus has decreased to approximately 70% of the modulus of small strain shear. The advanced characteristics of the HS_{small} model are most clear under conditions of working load. The model thus provides more reasonable displacements than the HS model. The model is, as the name suggests, a version of the hardening soil model, but the hardening soil model with small-strain stiffness (HS small-model) is a more developed version, with an emphasis on modelling the soil response more reasonably while un-loading and re-loading the soil. The first version of HS-model described the stress strain constitutive relation in this phase as linear elastic with a stiffness E_{ur} E_{ur}; in contrast, the HS small model demands several parameters which are usually well-known to most geotechnical engineers. The parameters can also be estimated from conventional tests on soil samples.

3. Full Scale Finite Element Analysis of Plugged Pipe Pile Groups

A full-scale case was studied in detail using the finite element model. The model relies on the study of a number of variables that may affect the bearing capacity of plugged piles within a group. The representation process for full scale model pipe piles in the program PLAXIS-3D [9]is not easy, because the program deals with the piles as solid material piles. In addition, a demonstration process for sand inside the tube does not exist in the original program. To solve this problem, and to effectively model the hollow piles, a type of volume pile was modelled. Initially, the representation of volumetric piles was given as flat surfaces, then the piles were given the embedded length of pile; after that, the piles could be given the characteristics of tubular piles. To study the effects of soil plugs formed by the driving of tubular pipe piles, a group of pipe piles consisting of four piles was modelled as shown in Figure 2. Three different cases of open ended pipe piles were created: fully plugged; a pile group with the sand inside the pile removed; and the pile group remaining closed ended**.** The sandy soil is assumed to follow the hardening soil model with small strain, while the steel tubes of the piles are assumed to act as elastic materials. The soil, pipe piles, and pile cap properties are listed in Tables 1 and 2, respectively.

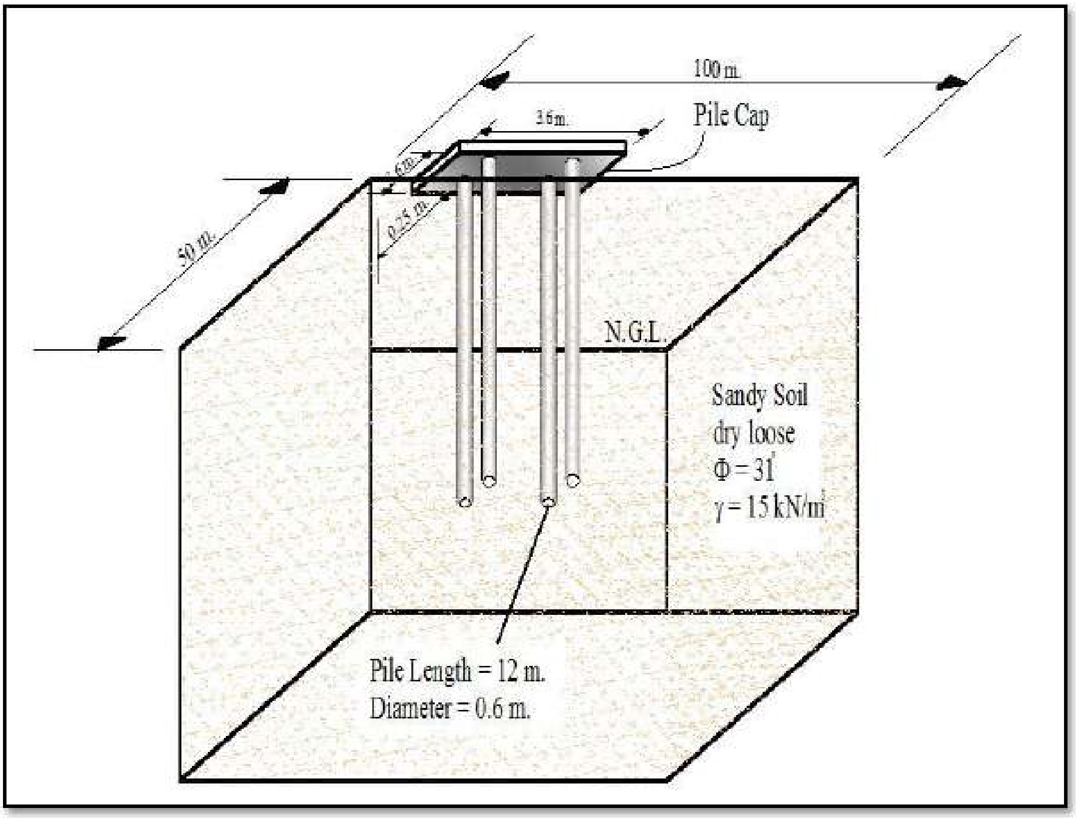


Figure 2: Representation of the problem of a (2x2) pile group with full scale modelling.

To predict the behaviour of a pipe pile group at large settlements, non-linear analysis is required. Therefore, the behaviour of the soil was also considered to be non-linear. The HS small model was utilised in order to simulate the non-linear stress-strain behaviour of the sand soil. Figure 3 shows the relationship between the applied loads on the pipe pile group versus settlement for different cases of tubular pipe piles. The soil was assumed to be homogenous sand soil. From this figure, it can be observed that the reduction percentage due to soil plug removal from inside the pile is about64.6%; when a comparison is made with closed ended pile, it can be noted that open-ended pipe piles behave as closed-ended if the soil plug formed inside the piles remains in a state of full plug. Figure 4 shows the distribution of normal stresses and shear stresses with depth for the original problem. It can be noted that the maximum value of shear stress is at depth of 10.5 m and gradually decreases after this depth. The shear stress consists of two components, outer shear and inner shear stress due to the presence of soil plug. In the fully plugged case, it can be noted that the shear stress increases with depth up to $\tau_{max.=}$425 kN/m^2 at a depth of 10.5 m; after that, the shear stress begins to decline. Furthermore, in the soil plug removal case, the shear stress increases in a linear relationship with depth up to $\tau_{max.}$=92 kN/m^2 at a depth of the tip of the pile. From these two cases, it can be concluded that the presence of a soil plug is very important because it leads to mobilisation of the internal friction component and reduces the value of the deformation in the group; if the soil plug is removed, the shear stress will be decreased to about 78.9%.

Table 1: Soil properties input in PLAXIS-3D program.

Parameters	Material model	Hardening soil small strain	Unit
Type of behaviour	Drained	Drained	---
Unit weight	γ_{dry}	15.5	kN/m^3
Drained triaxial test stiffness	E_{50}^{ref}	15	MN/m^2
Primary oedometer stiffness	E_{oed}^{ref}	15	MN/m^2
Unloading / reloading stiffness	E_{ur}^{ref}	45	MN/m^2
Power for stress dependent stiffness	m	0.625	---
Unloading / reloading Poisson’s ratio	$\acute{v}_{ur}$	0.2	---
Cohesion	$\acute{c}_{ref}$	0.1	kN/m^2
Friction angle	$\acute{\emptyset}$	31º	---
Dilatancy angle	ψ	1º	---
Coefficient for initial lateral stress	K_o	0.5	---
Reference shear modulus	G_o^{ref}	75000	kN/m^2
Reference stress for stiffnesses	p^{ref}	100	kN/m^2
Tension cut-off strength	σ_t	0	kN/m^2
Reduction interaction factor	R_{inter}	0.8	---
Shear strain level at shear modulus reduced to 70% (HSsmall only).	$\gamma_{0.7}$	0.176x10^{-3}	---

Table 2: Pipe piles and pile cap properties input in PLAXIS-3D program.

Parameters	Material model	Material properties		Units
		Concretepile cap	Steel hollow piles	
		Linear elastic		---
Type of behaviour	Drained type	Non-porous		---
Unit weight	γ	24.0	78.5	kN/m^3
Young´s modulus	E_{ref}	23,500x10^3	200x10^6	kN/m^2
Poisson´s ratio	$\acute{\upsilon}$	0.2	0.3	---
Thickness	t	1.5	0.016	m

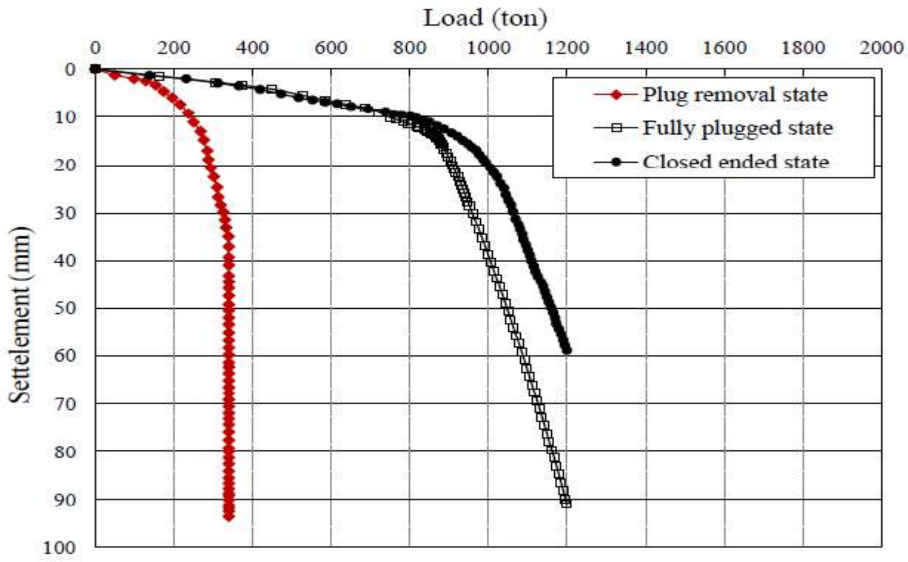
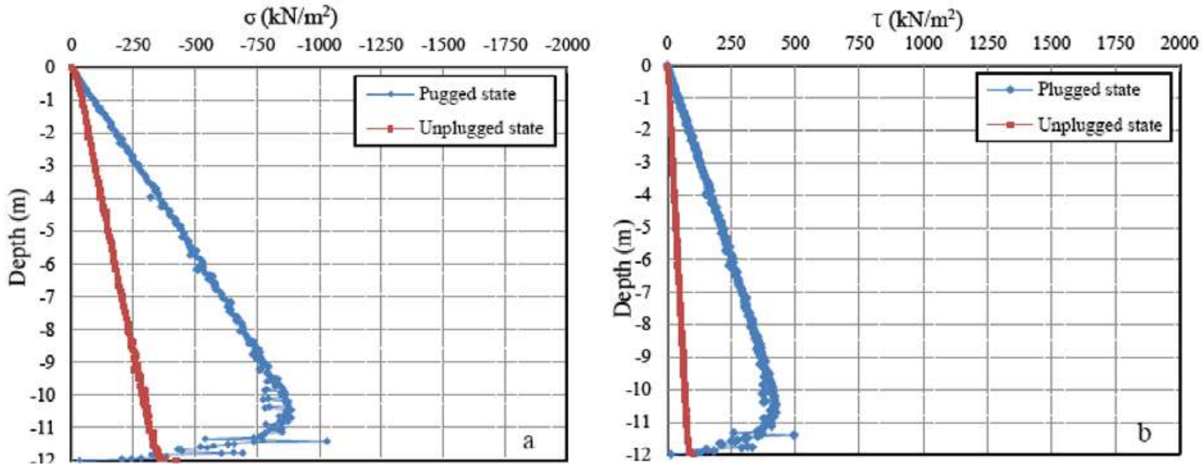


Figure 3: Load versus settlement for different cases of tubular(2x2) pile.



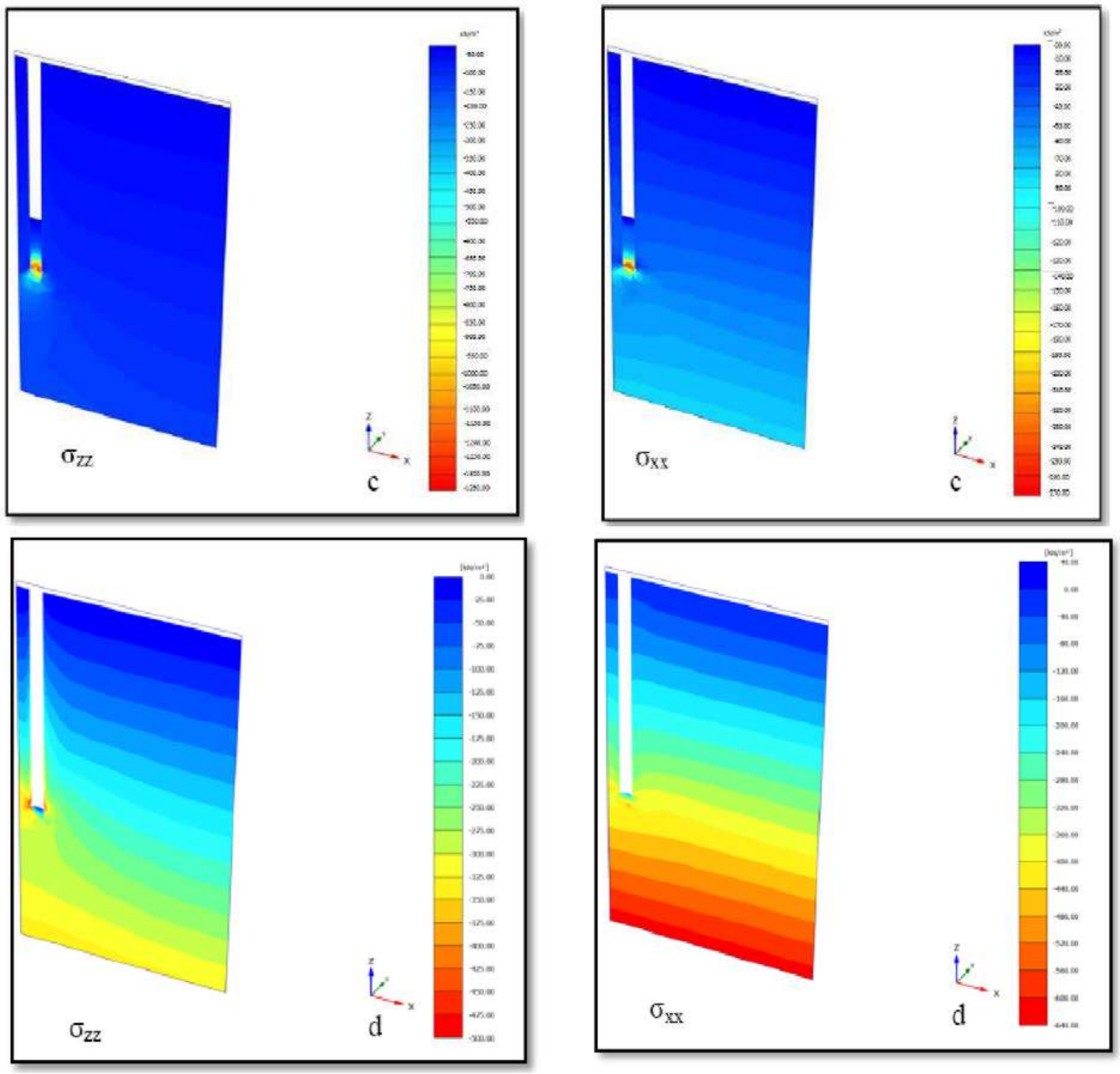


Figure 4: Stress distribution versus depth for pile within group (2x2) with spacing between pile(3d).(a) Normal stress,(b) Shear strength,(c) cross section planes σ_{zz} and σ_{xx} for fully plugged case (d) cross section planes σ_{zz} and σ_{xx} for plug removal case.

3.1 Parametric Study

The behaviour of a pipe pile group is influenced by several parameters that must be considered in the design of pile pipe group, as it is important to take these parameters into consideration to achieve the objective of economic construction with satisfactory performance. Based on the results presented in the previous section, this work notes the influences of different parameters on the optimum design for a pile group foundation. The case of a pile group (2×2) with full plug was chosen as the basic problem**.** The PLAXIS-3D [9] computer program was used as a finite element tool and the soil was represented using the hardening soil model with small-strain. In the finite element solution, a square section of pile groups was chosen, and both the soil and pipe pile group systems were meshed with the 15-node triangular elements as shown in Figure 5.

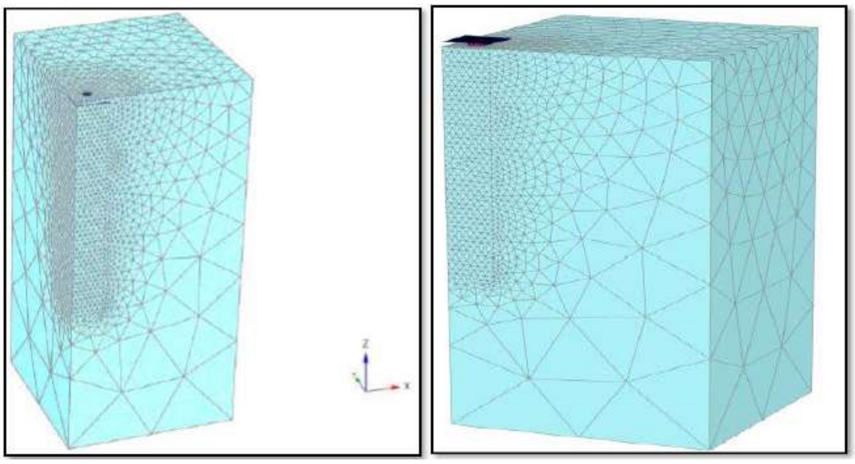


Figure 5: Generated mesh with local refinement case (2×2).

Figure 6 shows a quarter of the problem and the distribution of nodes and interface elements in the problem of a pipe pile group in the fully plugged case. In all cases, the configurations of piles are arranged symmetrically. In the finite element solution, only a quarter of the problem was used to represent the whole problem to minimise the necessary computer time, as shown in Figure 7.

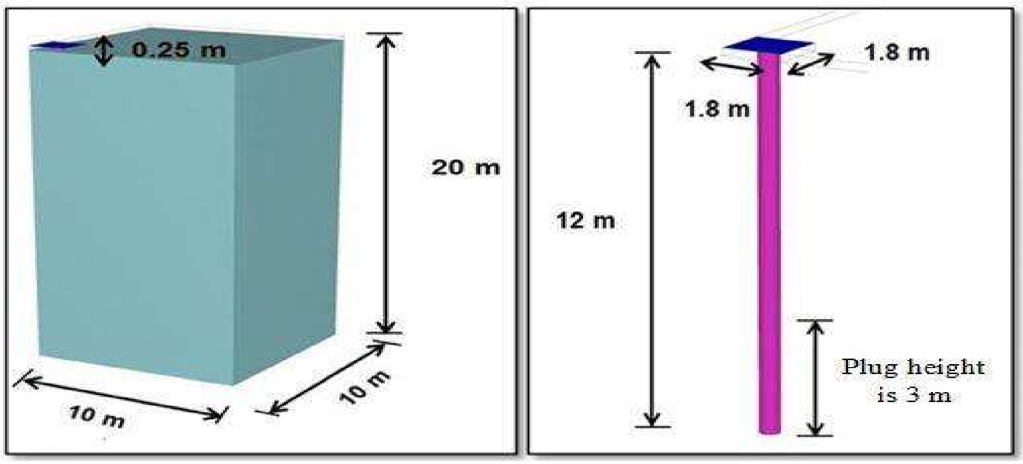


Figure 6: Nodes and surfaces with contact properties interaction for (2×2) pile group.

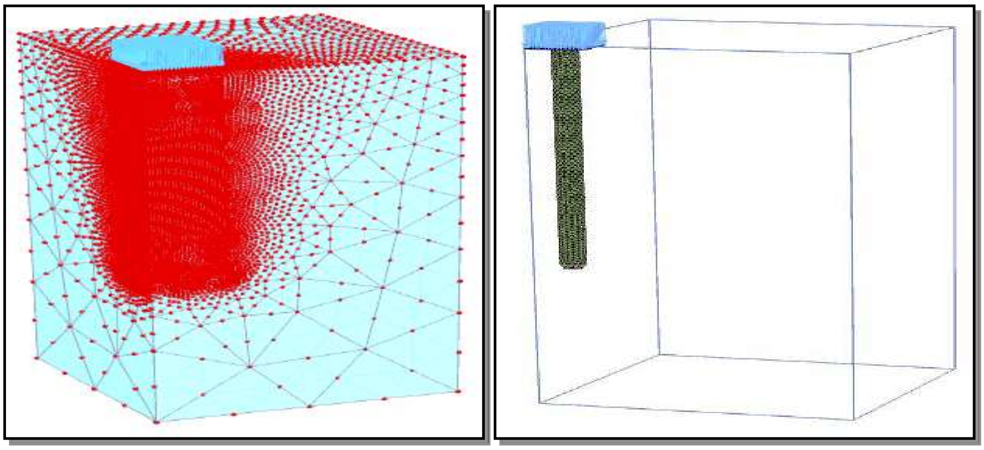


Figure 7 : Nodes and surfaces with contact properties interaction for (2×2) pile group.

3.1.1 Influence of pile spacing

The effect of the pile spacing (3d, 5d, and 7d) on the pipe pile groups for the fully plugged state was studied where the pile groups were subjected to a vertical load of1,200 tons. The hollow piles were 0.6 m in diameter and 12 m in length (L_p). An investigation was performed to observe the influence of pile spacing on the pile groups' behaviours. Three models with various pile spacings were developed and simulated for this purpose. The geometric properties of the pipe pile groups were as illustrated in Table 3. The dimensions of the pile cap can be represented in each case by (BxL), where B represents the width of the pile cap and L is the pile cap length.

Table 3: Geometric properties of pile group models at various spacing.

Pile spacing	Pile diameter (m)	Pipe pile groups dimensions (B x L) (m)	No. of piles
3d	0.6	3.6 x 3.6	4
5d	0.6	6.0 x 6.0	4
7d	0.6	8.4x 8.4	4

The numerical analysis output of PLAXIS-3D [9] for pile spacing ranging from 3d to 7d was presented as load settlement curves, as shown in Figures 8 and 9. The output shows

- Increase inthe spacing of piles from 3d to 5d and thence to 7d leads to a slight decrease in the total settlement of the pipe pile groups foundation, by 0.3% and 2.8%, respectively.
- The percentage increase in the pipe piles capacity when the values of spacing between piles are changed from 3d to 5d then 7d, is 5% and 9.1% respectively.

The increase in the distances between the piles does not cause an increase in the tolerability of the system, but a slight increase occurs in the amount of settlement, as shown by the above figures. The interpretation of this phenomenon is that the increase in stress distribution (bulb of stress) causes the largest area in the soil to be affected by these stresses, and thus this increase is predicted. The effect of spacing on the normal and shear stresses for the fully plugged case and the variation of shear stress with depth along piles at the interface element between the soil and pile zone was investigated. The shear stress behaviour of external and internal stresses generally differed. Table 4 shows the maximum values of shear stress with different spacing of piles and the ratio of internal shear stress to external stresses due to soil plug formation. Increasing the spacing between piles leads to mobilisation of larger shear stresses due to decreases in soil confinement between piles.

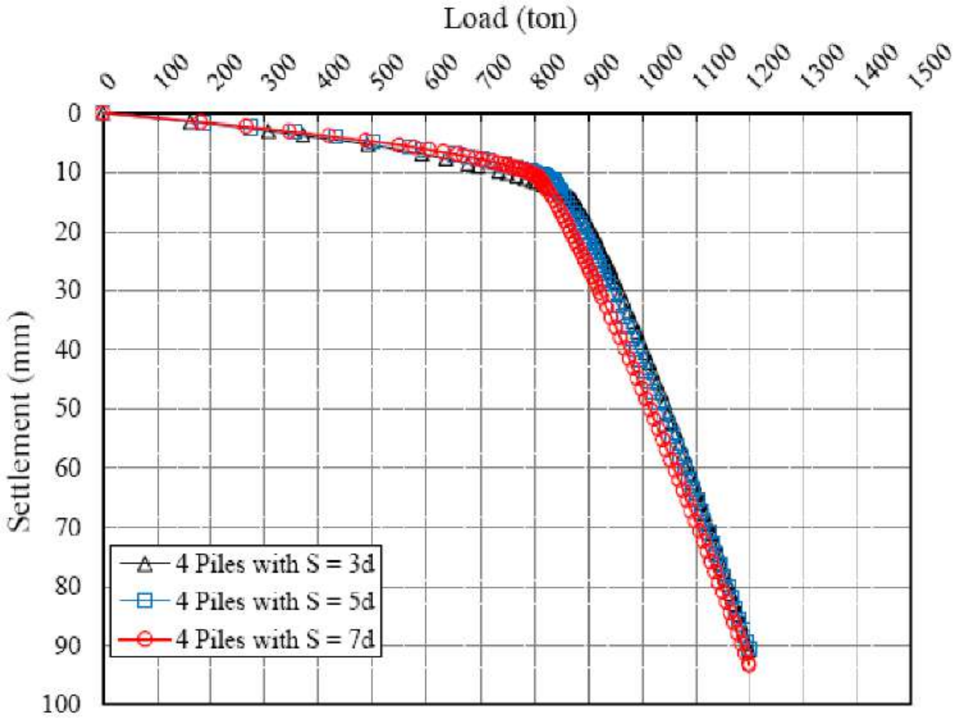


Figure 8: Influence of pile spacing on the load settlement behaviour of (2x2) pile group.

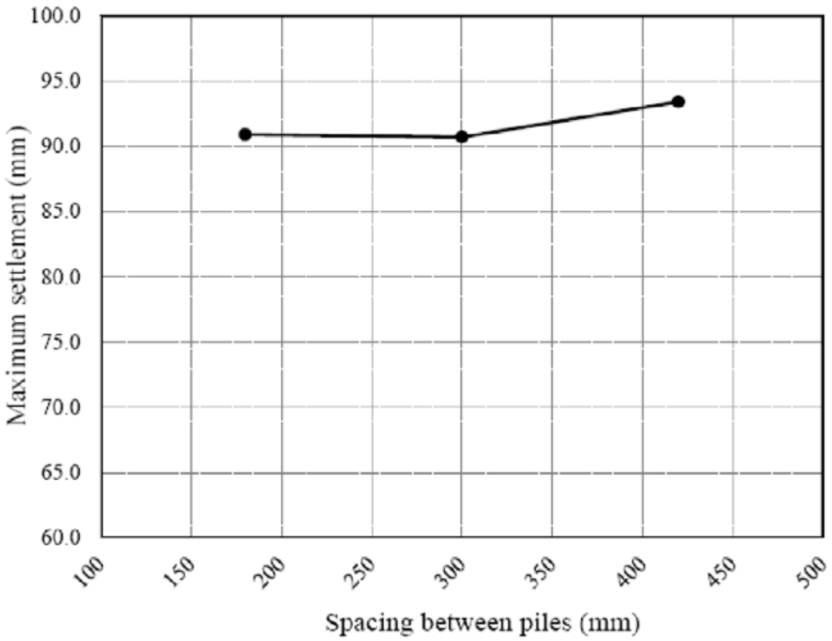


Figure 9: Maximum settlement for various pile spacings in a(2x2) pile group.

Table 4: Maximum shear stresses in external and internal pile walls for (2x2) group with different spacing between piles.

Pile spacing	Pile diameter (m)	Maximum external shear stress (kN/m^2)	Ratio of internal to external shear stress (%)
3d	0.6	425	51.76
5d	0.6	443	54.31
7d	0.6	500	65.11

3.1.2 Influence of the soil angle of internal friction

The effect of the friction angle, φ, on the settlements was investigated. A pipe pile group of (2×2) piles with a spacing of 3d was used for the analysis of the pile group. In each case, the maximum applied load on the top of the pile cap was 1,200 tons. The numerical analysis output of PLAXIS 3D [9] for pile groups embedded in soil with angles of friction of 31˚,36˚' and 40˚ispresented in the form of load settlement behaviour, as shown in Figure 10. Figure 11 presents the effective reduction in settlement with increases in the soil friction angle. The reduction in settlement values when the angle of internal friction is changed from 31˚ to 40˚is 73.8%, suggesting that the angle of internal friction is a very important parameter because it has a greater effect on reducing the value of settlement. The settlement decrease and pile bearing increase can be attributed to the internal friction increase due to the plugging phenomena and the concomitant increase in soil column weight at this area. It is well known that the angle of internal friction is related to soil density, and thus this behaviour complies with Fattah et al. [7]. When the soil density increases, the air voids in the soil will decrease, causing reducing in the pile settlement value.

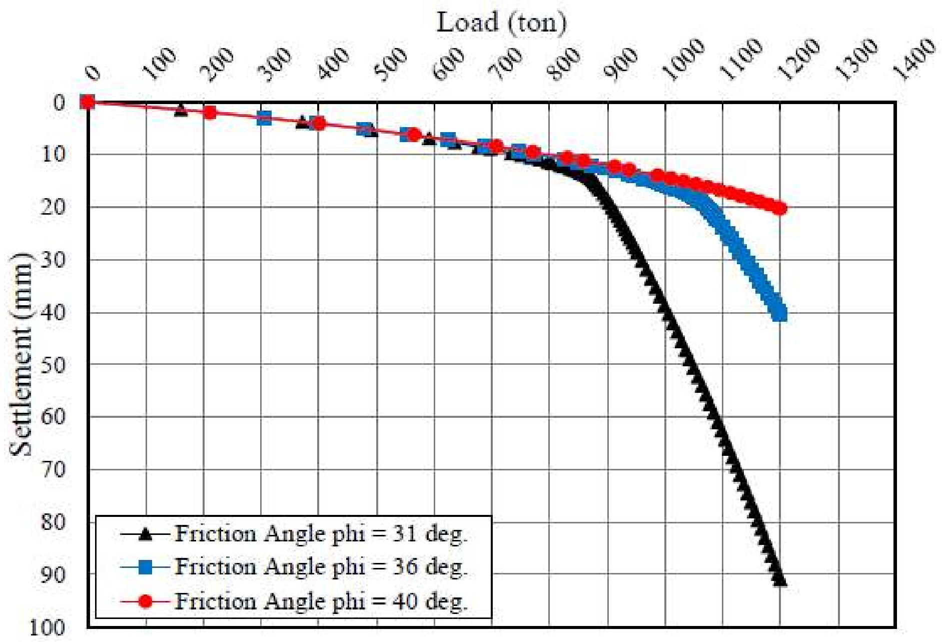


Figure 10: Influence of the angle of internal friction on the load settlement behaviour of a (2x2) pile group.

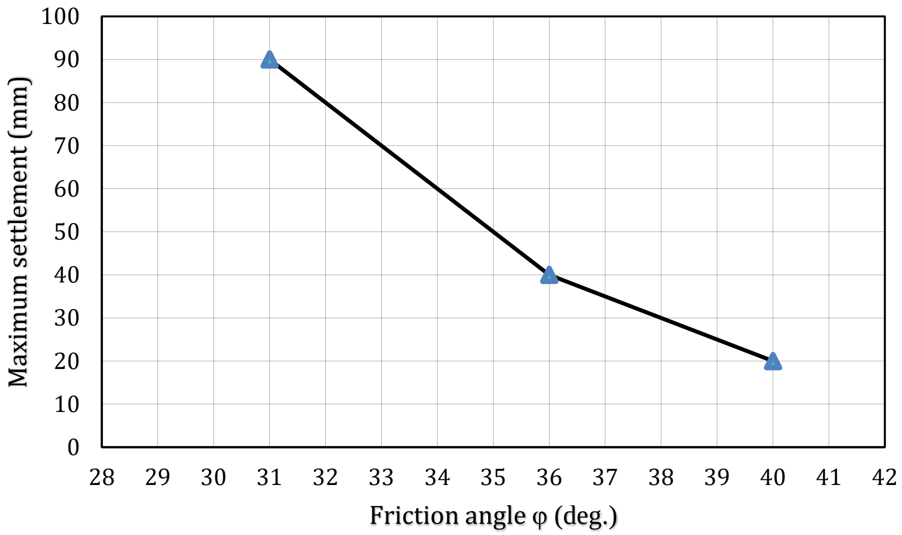


Figure 11: Maximum settlement for various angles of internal friction in a (2x2) pile group.

Table 6 shows the maximum shear stress for outer surface ofpileand the ratio of shearing and internal friction due to soil plugs. From this table, the increase of the maximum shear stress when the angle of internal friction changes from the original case is about 135%.

Table (5): Maximum shear stress with different values of friction angle.

Pile spacing	Angle of internal friction (°)	Maximum externalshear stress (kN/m^2)	Ratio of internal to external shear stress (%)
3d	31	425	54.76
3d	36	727	66.03
3d	40	1000	70.11

4. Conclusions:

After numerical analysis using PLAXIS-3D and HS-small model in which a full-scale group of piles was modelled, the following conclusions can bedrawn:

1. The soil stiffness and the strength model parameters have limited effects when the remaining parameters are within the acceptable range.
2. The change of spacing between piles from 3d to 7d has a very small effect on the group settlement and shear stress.
3. Achange of the angle of internal friction of the soil from 31° to 40° will reduce the group settlement to about 74%.
4. Anincrease in the distances between the piles does not cause an increase in the tolerability of the system, but a slight increase does occur in the amount of settlement.

5. References:

[1] Karlowskis V 2014 *Soil Plugging of Open-Ended Piles During Impact Driving in Cohesion-less Soil* (Stockholm, Sweden: Department of Civil and Architectural Engineering)

[2] Paikowsky S G, Whitman R V. and Baligh M M 1989 A new look at the phenomenon of offshore pile plugging *Mar. Geotechnol.* **8** 213–30

[3] Randolph M F, Leong E C and Houlsby G T 1991 One-dimensional analysis of soil plugs in pipe piles *Géotechnique* **41** 587–98
[4] Henke S and Grabe J 2008 Numerical investigation of soil plugging inside open-ended piles with respect to the installation method *Acta Geotech.* **3** 215–23
[5] De Nicola a. and Randolph M F 1997 The plugging behaviour of driven and jacked piles in sand *Géotechnique* **47** 841–56
[6] Paik K and Salgado R 2004 Effect of Pile Installation Method on Pipe Pile Behavior in Sands *Geotech. Test. J.* **27** 78–88
[7] Fattah M Y, Al-Soudani W H and Omar M 2016 Estimation of bearing capacity of open-ended model piles in sand *Arab. J. Geosci.* **9**
[8] Fattah M Y, Salim N M and Al-Gharrawi A M B 2016 Effect of plug removal on load transfer in plugged open ended pile behavior *Int. J. Civ. Eng. Technol.* **7** 124–136
[9] PLAXIS Foundation 2015 Tutorial Manual **1**