A FINITE ELEMENT STUDY TO INVESTIGATE AN OPTIMAL DESIGN OF GROUP BORED PILES IN CLAYEY SOIL

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By

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A Thesis Submitted to the College of Graduate Studies, Universiti Tenaga Nasional, in Fulfillment of the Requirements for the Degree of Master of Civil Engineering

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DECLARATION

I hereby declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently submitted for any other degree at Universiti Tenaga Nasional or at any other institutions. This thesis may be made available within the university library and may be photocopies and loaned to other libraries for the purpose of consultation.

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ABSTRACT

The purpose of this study is to validate and develop viable parametric design of group bored piles in clayey soil. The various arrangement of bored piles considering various parameters of applied pressure, pile diameter, pile spacing and pile slope ratio was explored. The design of bored piles in the soil was done in order to avoid excessive consolidation settlement. The bored piles should be properly design before installation so as to prevent unnecessary cost and excessive consolidation settlement of the piles to occur. Numerical simulation offers an interesting solution to investigate the problem and optimize the design of the bored piles in a comprehensive way. For this study, finite element validation on single bored pile exposed to load test in clayey soil was done using PLAXIS software. Parametric assessment was conducted with a goal to develop a viable group design of bored piles in the setting of clayey soil. Several soil models were evaluated in the study namely Mohr-Coulomb (MC), Hardening-Soil (HS) and Softening-Soil (SS) models. Based on the PLAXIS simulation result on load test of the single bored pile in clayey soil, it was realized that the Mohr-Coulomb (MC) soil model in Very Fine mesh has the mesh size of 0.6 m. It best fits the measured data of the load-settlement behaviour of the pile because it has the highest coefficient of determination (R^2) value of 0.9840 for the simulated load in comparison to the measured load on the pile. As such, the soil model was applied for the parametric study on the group bored piles. The parametric study on the group bored piles showed that the optimal design of the group bored piles in clayey soil can be established when the bored piles are applied with 50 kPa applied pressure, 1.3 m pile diameter, 3D pile spacing and 1:2 pile slope ratio with reference to the criteria of 25 mm tolerable limit of consolidation settlement. It was further found from the parametric study that the optimal parametric design of the group bored piles best suits clayey soil with a cohesion and an angle of internal friction of 20 kPa and 20° respectively. The significant outcome of the study is that it is important to perform finite element assessment on the group bored piles by considering several pile and soil conditions in order to understand the interaction between the floating group bored piles and the clayey soil under the application of a pressure.

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Lastly, I would like to sincerely thank the Almighty God for His prestigious blessing to me including the guidance for the right track to successfully finish this research. I would also be responsible to gratitude Him for providing good hearted and helpful people around me to always deliver assistance and support for me to be successful in coming future.

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LIST OF ABBREVIATIONS

Abbreviation	Meaning
mm	Millimetre
kN	Kilo Newton
FEM	Final Element Method
G	Shear modulus
K	Bulk modulus
MC	Mohr-Coulomb
HS	Hardening-Soil
SS	Soft Soil
MRT	Mass Rapid Transit
PLAXIS	Software to perform analysis of deformation, stability and flow in geotechnical engineering.
R^2	Coefficient of determination
c	Cohesion
ø	Angle of internal friction
D	Diameter
kPa	Applied pressure
UNITEN	Universiti Tenaga Nasional

LIST OF PUBLICATIONS

Wong, L.S. & Somanathan, S. (2018). Analytical and numerical modelling of one-dimensional consolidation of stabilized peat. Civil Engineering Journal, 4(10), 2513-2526.

Somanathan, S. & Wong, L.S. (2018). A finite element study to analyze the numerical behaviour of single bored pile in clay soil under load tests. Jordan Journal of Civil Engineering (Under Review).

CHAPTER 1

INTRODUCTION

1.1 Background of research

Slender structural elements that transmit weight of a superstructure through weak compressible soils or water to stronger materials are known as piles. The weight of a structure and external loads are normally supported with piles either by compression or tension. Moreover, piles may also be subjected to an extra load from the surrounding soil due to negative skin friction. This may cause failure of a structure supported on lies and therefore it has to be considered in pile design. In Malaysia, bored piles are commonly use as foundation to support heavily loaded structures such as high rise building and bridges with its low noise, vibration and variety sizes to fit different loading condition and subsoil condition. Usually bored piles are constructed in tropical residual soils that are generally have complex soil characteristics.

Bored pile foundation is an important link to transfer structural load to the bearing ground located with different depth below ground surface. Feasible arrangement of bored pile with various parameters of length, diameter and space, different layers of soil such as clay, sand and slit, depth of ground water table and type and level load to be support the structure. The design of bored pile is necessary to avoid essential settlement. The cost of bored piles can be costly if the design is not properly done. Floating bored piles are the piles which does not touch the bedrock during installation. It is also one of the way to reduce settlement and the cost of installation can be optimized.

Method of construction for bored piles is through excavation of pile shaft, cleaning of pile shaft, preparation of reinforcement bar, installation of reinforcement bar and concreting the pile. The individual responses of piles are influenced when the piles are closely packed. In such cases, group piles are considered. Soil stress state, densities and size distribution caused by pile installation which can be different for group piles than for single piles.

In this research study, numerical investigation is being done to simulate the performance of bored pile using software and compare the results with the actual results in order to predict the behaviour of the consolidation of single and group bored piles. Progress in computer technology and geotechnical numerical modelling methods have made it possible to simulate more realistic soil properties and soil-structure interaction.

1.2 Problem statements of research work

Settlement induced by the bored piles is an important criteria in developing a feasible design of the piles. With respect to that, the technical and economic factors must be taken into consideration in studying the feasibility of the pile design. If the design of piles is inadequate, excessive settlement can be induced and cause damage to the supporting structures. If the piles are excessively designed, construction of the piles can be costly and therefore, not economical. As such, there is a need to perform a finite element study to evaluate the settlement of the bored piles to overcome these problems and optimize the design of the piles. Numerical study on the design of the bored piles can provide an insight into the effective interaction between the bored piles and the surrounding soil to resist loading applied on them.

1.3 Research objectives

The objectives of this research are:

i. To analyze and compare the settlement of single bored pile exposed to load test in soil with finite element model using PLAXIS Professional software.
ii. To determine the best soil model to be used in PLAXIS Professional software to predict single bored pile settlement.
iii. To conduct a parametric study on spacing, diameter, and length in order to develop an optimal design of group bored piles in clayey soils with respect to the settlement.

1.4 Scope of research work

The study is carried out on single and group bored piles with a realistic scenario for the optimization of the group bored piles. The realistic scenario assumes that the load and soil strength properties are known design parameters. The allowable upper limit of pile displacement is also known which is treated as a constraint. This left the pile diameter, spacing and slope as the parametric variables to be optimized. The type of group of bored piles under the simulation is arranged as 5 × 3 (5 piles over the length and 3 piles over the width). So altogether, there are 15 bored piles of the PLAXIS simulation under the study. Numerical analysis is done for the single and group bored piles to obtain results which is then compared with the actual test results for validation. In most projects, a specific number of load test is being conducted on piles. The reason is the unreliability of prediction methods. The vertical and lateral load bearing capacity of pile can be tested in the field. Besides, bored pile cap is used to transfer the loading from structure to the bored pile. The load test should be carried out at least a total load of two times to get a proper and safety in testing.

1.5 Thesis outline

In overall, the thesis is organized into five chapters with each chapter is briefly described below.

Chapter 1 is the introduction on the thesis which consists of background of research, problem statement of research work, objectives and scope of the research work. The purpose is to lead on how the expected outcomes will be obtained.

Chapter 2 is the literature review of the thesis, which concludes the research paper posted by other researchers on the title of the project. The mechanism is focused in detail such as the properties of soil and bored piles that affects in single pile group and group bored pile.

Chapter 3 is the methodology of the thesis, which manipulates with the numerical method of the research using PLAXIS Professional Software and other equation to obtain the results. Besides, this chapter also contains the meshes model to show the different parameters of the model with its boundary conditions required from the data.

Chapter 4 of the thesis is the results and discussion. The results of the simulation which has graph of different working parameters are written in this chapter. Later the results are compared with the actual data and the simulation data for validation. The discussion is written based on the factors that affect both the results.

Chapter 5 is the conclusion chapter of the thesis which concludes the overall findings and shows if the objectives are being achieved. Future researches can improve this project based on the recommendation provided for further studies.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to literature review

This chapter reviews the published research works regarding the experimental and finite element evaluation on single and group bored piles on soils. An overview of the numerical simulation regarding the behaviour of bored piles on soils were reviewed in order to assess the previous studies conducted to gage the accuracy in modelling of the load-settlement behaviour of piles. Next, a literature overview of the parametric studies for simulating the behaviour of group bored piles with various dimensions and arrangements were done in order to provide literature evidence on the numerical analysis of group bored piles behaviour. Through such literature studies, the current numerical research trend to predict the pile behaviour and design can be comprehended and this is necessary to establish the research gap of the study.

2.2 Types of soil

There are three categories for the soil properties namely physical, chemical and biological properties (Figure 2.1). The physical properties of soil are the soil texture which are proportions of sand, silt and clay, structure element, bulk density, moisture, infiltration and porosity. Besides, the chemical properties of soil are identified as the nutrient content, salinity, pH value, organic matter and mineral content. The biological properties of soil include activity of microbes such as fungi and bacteria, biomass, biodiversity and biological activity. It is discovered from the study of Carraro (2004).

Soil texture is termed as the relative proportion of sand, silt and clay in the soil. Figure 2.2 tabulates soil texture classification. The structural soil element is the form of soil that the particles take in as a clump. Moreover, the pads in soil is the structural units of soil and the bulk density is the weight per volume. With various layering of soils in soil strata, soil profiles are formed. It must be noted that a soil profile is referred to as the vertical soil section showing layers development analysed by Lindbo et al. (2012).

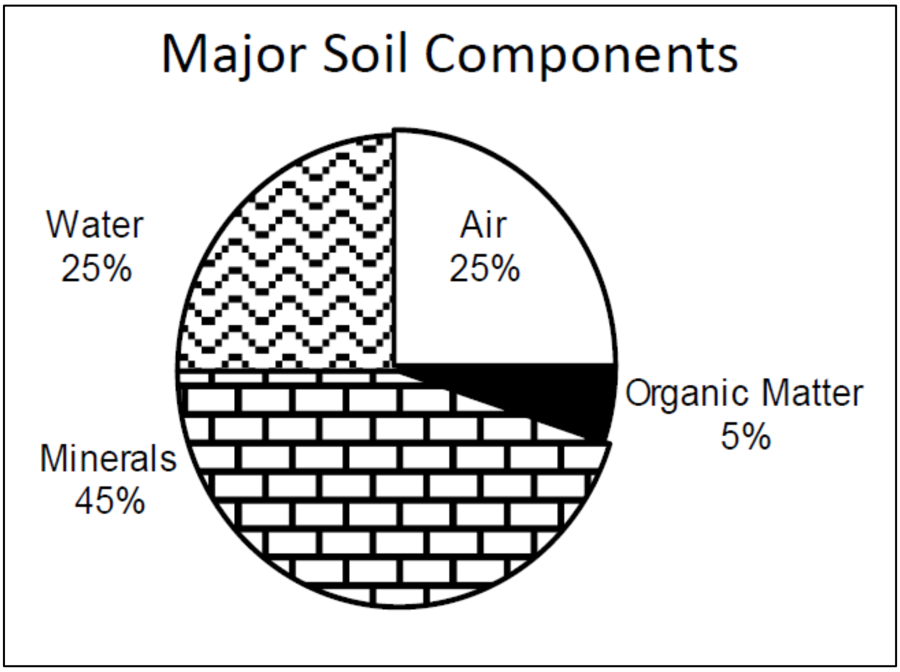


Figure 2.1. Major soil components (Carraro, 2014).

Soil Texture Classification:

Soil separate		equivalent diameter size (mm)
gravel		> 2 mm
Sand		0.05 - 2 mm
	very coarse	1 - 2 mm
	coarse	0.5 - 1 mm
	medium	0.25 - 0.5 mm
	fine	0.1 - 0.25 mm
	very fine	0.05 - 0.1 mm
Silt		0.002 - 0.05 mm
Clay		< 0.002 mm (< 2 micrometer)

Figure 2.2. Soil texture classification (Lindbo et al., 2014).

Sand is characterized as the largest particles in soil. It is porous and granular in nature and exhibits a certain degree of grittiness. It is predominantly composed of quartz. The particle size of silt is of intermediate between sand and clay and the soil is originated from the quartz and feldspar. The specific area of silt is moderate with the soil shows varying degrees of plasticity. It is powdery in physical state and in wet condition, it is slippery in nature. Clay on the other hand, is a fine-grained soil with particle size less than 2 μm. Depending on the clay type and content, the soil has a wide range of plasticity. Depending on the water content, clay can be hard when dry and plastic or liquid when it is mixed with water. The microstructure of clay particles can be observed with a scanning electron microscope researched by Fukushima and Tatsuoka (2003).

The classification shows the proportions of the different sized mineral particles in the soil or the relative amount of sand, silt and clay present in the soil expressed as percentage (Figure 2.3). There are 12 textural class categories of soil. Primary minerals is present in original rock form of which soil is formed. These occurred predominantly in sand and silt fractions and are weathering resistant.

Secondary minerals are formed by decomposition of primary minerals and their subsequent weathering and decomposition into new ones. Humus and organic matter are resulted from the decomposition of plants discovered by Briaud (2013). On the other hand, as the soil particle size decreases, the surface area increases (Figure 2.4). It must be noted that surface area has a great influence on water holding capacity, chemical reaction, soil cohesion and ability to support microorganism. Loam is defined as a mixture of sand, silt and clay.

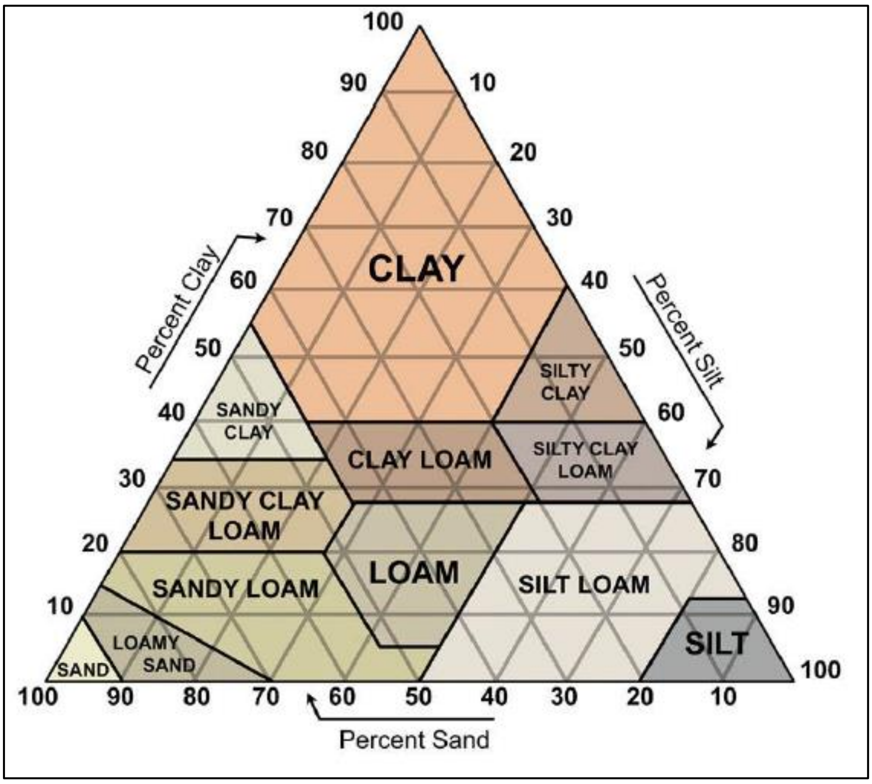


Figure 2.3. Soil texture diagram (Briaud, 2013).

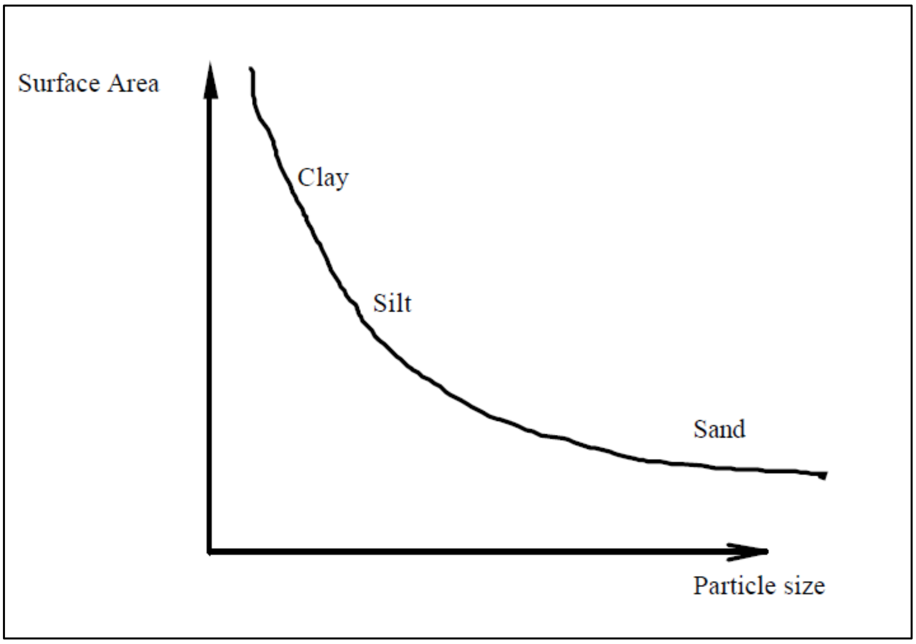


Figure 2.4. Surface area versus particle size of soil (Briaud, 2013).

2.3 Bored pile

Worldwide, bored piles are most often used as a foundation to carry heavily loaded structures such as high rise buildings and bridges to suit different loading conditions and subsoil conditions. Summary of bored pile design under axial load compression together with a brief description on the aspects of bored piles are presented in the work of Wehnert and Vermeer (2004). In general, the soil mechanics methods for analyzing bored pile design can be classified into two conditions, which are the designs in fine grained and coarse grained soils. In fine grained soils, the ultimate shaft resistance (f_{su}) of bored pile can be estimated by using the following equation:

$$f_{su} = \alpha \times s_u \quad \text{(Equation 2.1)}$$

where,

$\propto$ = adhesion factor

s_u = undrained shear strength of soil (kPa)

The $\propto$ values of residual soils in Malaysia are in the range of 0.3 to 0.9 for stiff clay while for soft clay, it is estimated to range from 0.8 to 1.0 and the value is usually adopted together with the corrected undrained shear strength from the vane shear stress. If the bored piles are used in the construction of soft clay near river or coastal area, then the method of using the adhesion factor is useful. The value of $\propto$ to be used for soil shall be verified by preliminary load test. In coarse grained soils, the ultimate shaft resistance (f_{su}) of bored piles can be expressed as below:

$$f_{su} = \beta \times \sigma'_v \qquad \text{(Equation 2.2)}$$

where,

β = shaft resistance factor for course grained soil

σ'_v = vertical effective stress

From the back analysis of pile load test, the β value can be obtained. In loose and dense sand, the typical β values are in the range of 0.15 to 0.3 and 0.25 to 0.6 respectively. Although the theoretical f_{su} values for bored piles in coarse grained soil can be related to plastic theories, it is not encouraged to use in the calculation of the bored piles geotechnical capacity due to difficulty and uncertainty in base cleaning.

2.3.1 Numerical simulation of single bored pile in soil

Several research works were performed to analyze the behaviour of single bored pile which was subjected to load tests in sandy soil at various sites. ABAQUS software was used to simulate the phenomenon of the single bored pile and the results obtained from literature studies showed a good agreement between the load-settlement relationships at a low value of load (Figure 2.5). As the load gets higher, the numerical analysis tends to reveal different level of accuracies in predicting the load-settlement relationship of the bored pile.

This indicates that there is a need to vary the soil models used in the study in order to verify a precise numerical prediction of the load- settlement relationship of the bored pile in soil. The study was done by Tosini et al. (2010).

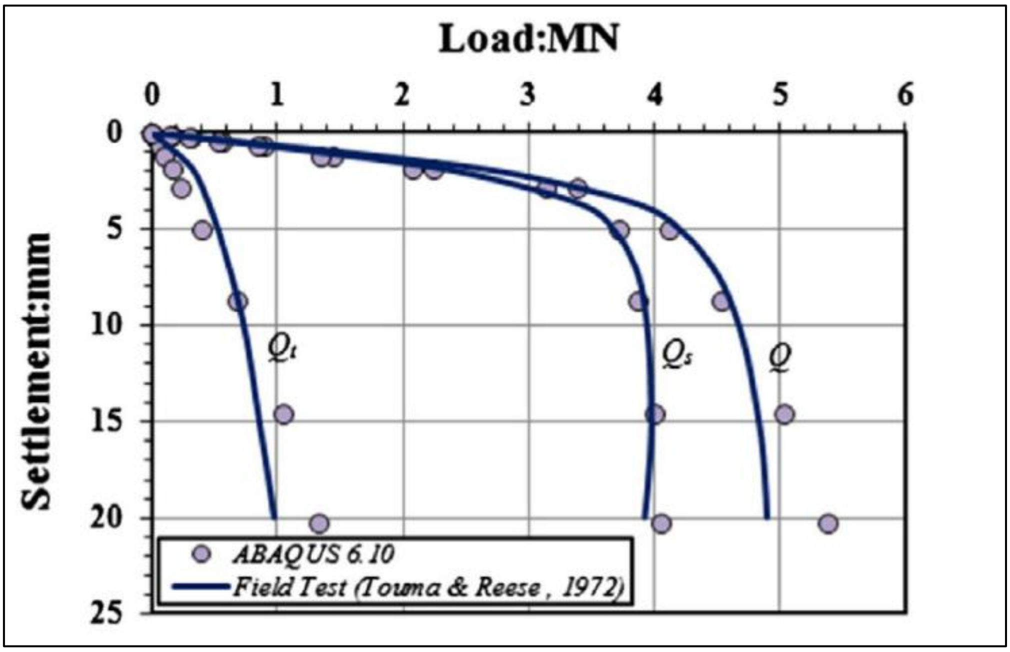


Figure 2.5. Comparison between field test data and numerical simulation of Load-Settlement curves of single bored pile in soil (Tosini et al., 2010).

The constitutive model used in the research to predict non-linear behaviour of bored pile in sand is reflected in Drucker-Prager model (DP) which is available in ABAQUS software. The input parameters influenced the shape of yield and flow surfaces of the deformed soil. Figure 2.6 shows single element used for simulation of single bored pile in ABAQUS software simulation. The Drucker-Prager (DP) model can be represented in the equation as below.

$$\tan\beta = \frac{6\sin\phi}{3-\sin\phi}$$

$$d = \frac{18c\cos\phi}{3-\sin\phi}$$

(Equation 2.3)

$$F = t - p\tan\beta - d$$

where,

p = pressure stress

β = slope of the linear yield surface commonly referred to the friction angle

t = von Mises equivalent stress

d = cohesion of the material

K = ratio of the yield stress

The single bored pile is simulated using ABAQUS software through meshing process and boundary condition is indicated for the base model analysis as shown in Figure 2.7. Besides, the pile and soil were modelled using 8-noded elements, radius of soil was set at 15 m and the soil depth is 30 m. The pile model is 18 m long which was embedded in sand. The soil is divided into two layers which are upper and lower layers. The upper soil layer represents clay with thickness 9.5 m modelled as Mohr-Coulomb and the soil lower layer represents the sand layer modelled by Drucker-Prager as illustrated earlier. Fine mesh was used near the pile soil interface and the mesh became coarser further from the pile discovered by Kamal (2016).

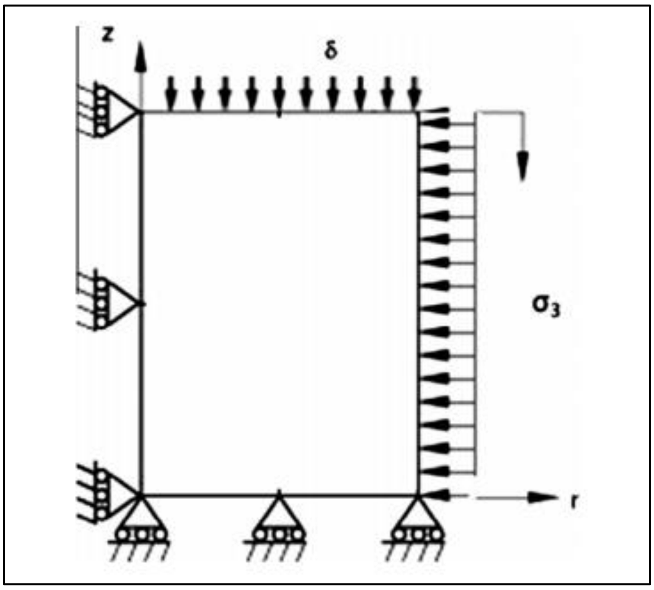


Figure 2.6. Single element used for simulation of single bored pile in ABAQUS software simulation (Kamal, 2016).

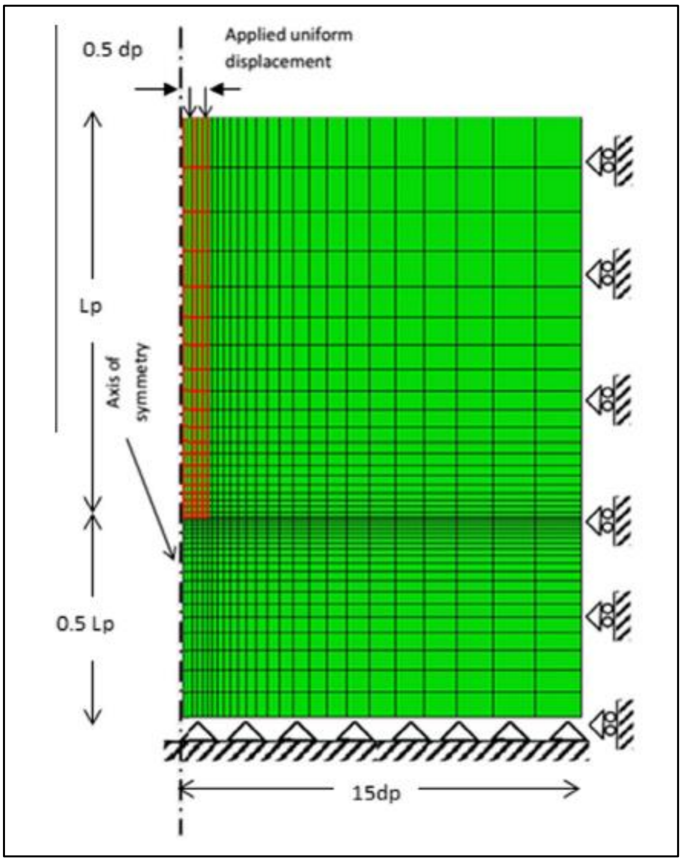


Figure 2.7. Finite element mesh and boundary conditions in full pile simulation (Kamal, 2016).

2.3.2 Numerical simulation of group bored piles in soil

Several literatures studies are focused on numerical interpretation of load test on bored piles in granular soils. Researchers further discovered on the numerical analysis that the bored pile group with foundation mat that tends to show a slower rate of settlement as compared to that without foundation mat. Figure 2.8 shows evidence of the calculated load–settlement curves for 12 pile group with and without foundation mats. The pile group arrangement is logical as the foundation served to uniformly transmitted load to the group piles, thus reducing the differential and total settlements of the granular soils (Higgins, 2011).

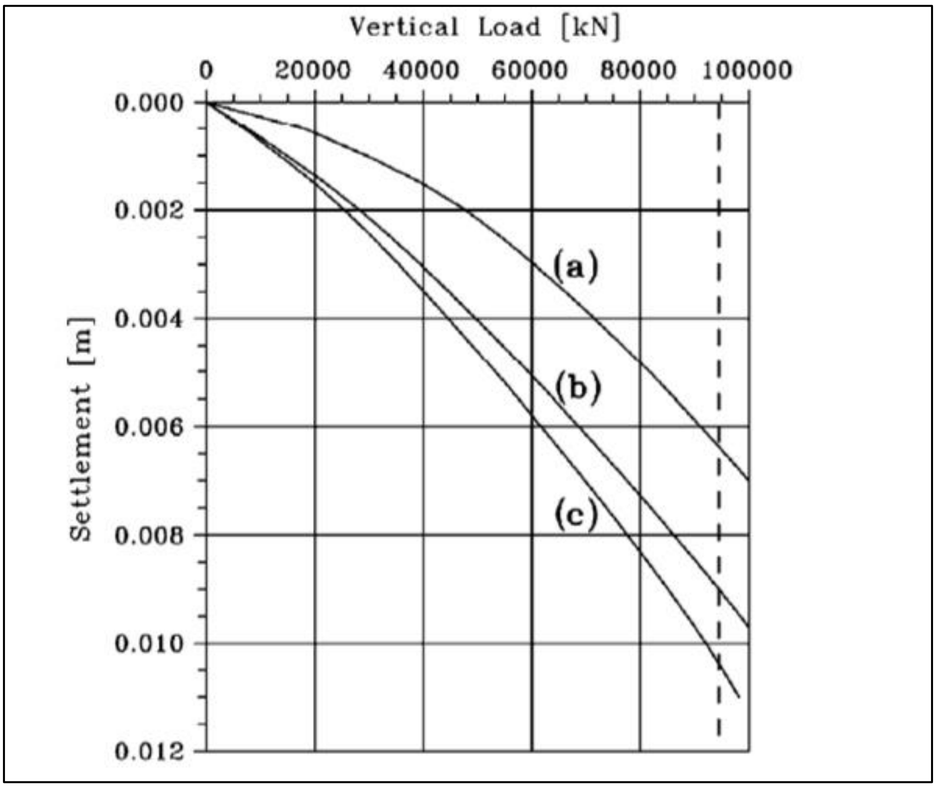


Figure 2.8. Calculated load–settlement curves for the 12 pile group: (a) simple superposition of 12 independent piles; (b) pile group and interaction between soil and foundation mat; and (c) pile group without soil–mat interaction (the dashed line represents the overall working load of the foundation) (Higgins, 2011).

In general, piles are constructed in a group and tied together with a thick pile cap. Moreover, pile groups possess various behaviour which differ from that of a single pile due to the soil interaction. The pile-soil interaction arises as a results of overlapping of stress or strain fields and can affect both the capacity and the settlement of the piles. Piles that are in the centre of the group have smaller stress filed to resist an applied load. With the same condition, the centre piles have more settlement. Sarmad (2013) studied that for a rigid cap, the local settlement cannot occur, and therefore, the loading would transfer from the central piles and redistribute to the outer piles.

Furthermore, the group efficiency factor (*h*) is widely used to quantify the group interaction effects defined as the ultimate group capacity to the sum of the ultimate capacity of each pile in a group (Equation 2.4):

$$\eta = \frac{Q_g}{\sum_{i=1}^{i=n} Q_i}$$

(Equation 2.4)

where,

Q_g = ultimate group capacity

Q_i = ultimate capacity of pile

n = number of piles in group

Certain factors can influence the ultimate capacity of pile group foundation which are method of pile installation such as replacement or displacement of piles, ground bearing cap, nature of foundation materials and relative stiffness of the structure, piles and the ground condition.

Shakeel and Ng (2018) studied the settlement and load transfer mechanism of a pile group adjacent to a deep excavation in soft clay. Through numerical computation of load settlement relationship of the piles, the ultimate bearing capacity of the pile groups were estimated as shown in Figure 2.9. Axial uniform distributed load is applied on the pile cap and gradually increased to 4500 kN and 15,000 kN corresponding to 20 m and 40 m long pile groups. With reference to the failure line established by Ng et al. (2001), the ultimate-load carrying capacity of the pile group were discovered to be 2400 kN and 14500 kN respectively. The result also provides an indication that the longer the pile, the higher is the ultimate-load carrying capacity.

In another research development, Mali and Singh (2018) studied the behaviour of large piled-raft foundation on clay soil. Three dimensional PLAXIS finite element modelling was performed on a large piled raft in the study with the study primarily focused on the evaluation of pile spacing, pile length, pile diameter and raft-soil stiffness ratio on the settlement, load-sharing, bending moments, and shear force behaviour of large piled-raft foundation. The finite element results were compared and validated with those of the work of Sinha and Hanna (2016). A raft of 24 m × 24 m size with 2.0 m thickness and 16 piles of 1.0 m diameter with different lengths (5 m, 10 m and 15 m) were used in the study of Mali and Singh (2018). It must be noted that the piles are spaced at 6 times greater than the pile diameter and a uniformly distributed load of 0.5 MPa is exerted on the pile foundation. Table 2.1 shows the material properties of the raft, piles and the soil used in the study with reference to the research work of Sinha and Hanna (2016). Figure 2.10 shows comparison of load settlement behaviour of the piles of the study of Mali and Singh (2018) with the results of Sinha and Hanna (2016). It is observed from the figure that there is a reasonable good fitting of the results as compared to those of Sinha and Hanna (2016) for different pile length.

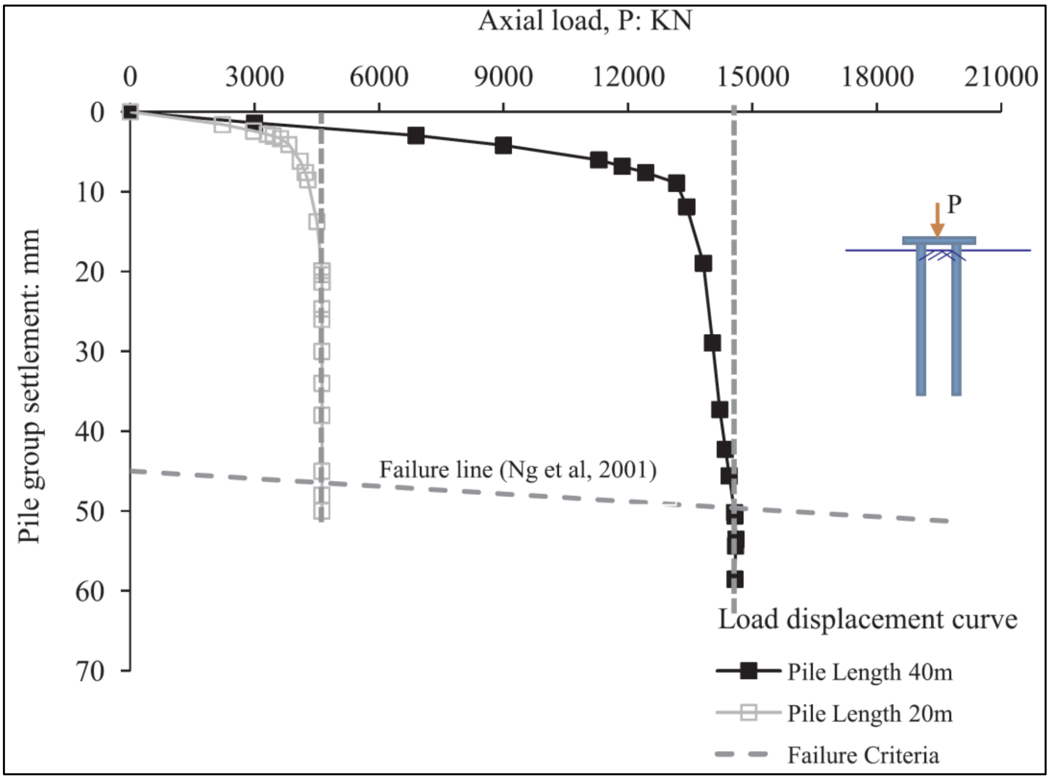


Figure 2.9. Computed load settlement curves for pile group in soft clay (Shakeel and Ng, 2018).

Table 2.1. Material properties used in the validation for the simulation work of Mali and Singh (2018) with reference to the research work of Sinha and Hanna (2016).

Material	Properties	Unit	Value
Soil	Young's modulus, E_s	MPa	54
	Poisson's ratio, ν_s	–	0.15
	Unit weight, γ	kPa	19
	Angle of internal friction, φ	°	20
Raft	Young's modulus, E_r	GPa	34
Pile	Young's modulus, E_p	GPa	25
	Poisson's ratio, ν_p	–	0.2

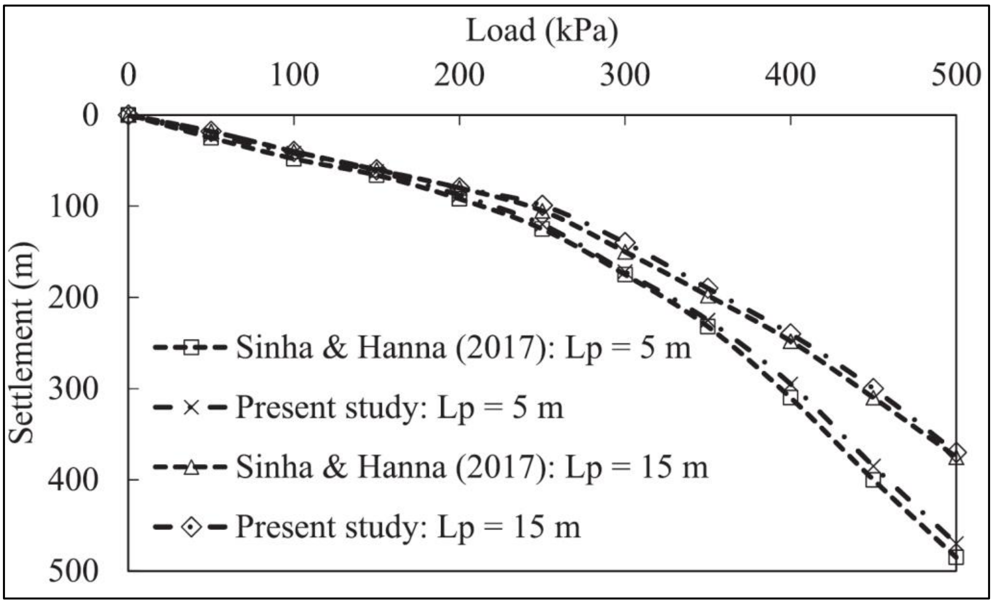


Figure 2.10. Comparison of load settlement behaviour of the study of Mali and Singh (2018) with the results of Sinha and Hanna (2016).

2.3.3 Numerical simulation of pile raft foundation combined with group bored piles

The impact of raft foundation when combined with group piles at reducing soil settlement can also be observed from the study of Park and Lee (2016). It was found that there was a significant decrease in the rate of settlement in both analytical and numerical results when the pile raft foundation was combined with group piles as compared to those with unpiled raft (Figure 2.11). In spite the positive findings, little attention was paid on numerical study of bored piles in silty soil largely due to the complexity of the soil-pile interaction. This creates a research gap of which a better finite element prediction must be done in order to accurately simulate the behaviour of bored piles in silty soil.

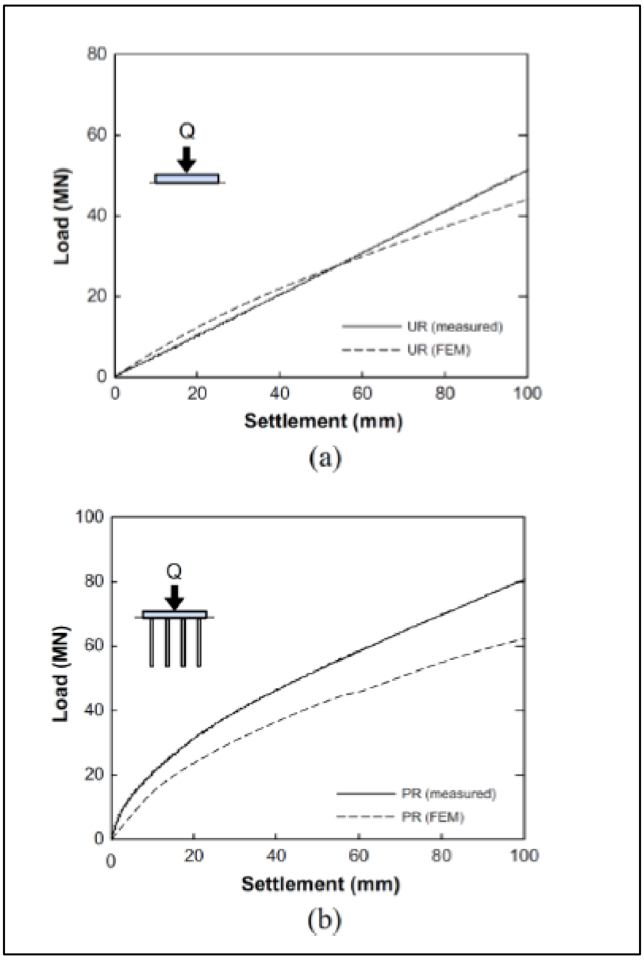


Figure 2.11. Measured and calculated load settlement curve of (a) unpiled raft and (b) piled raft (Park and Lee, 2016)

Piles play an important role in total settlement and differential settlement reduction in foundation, thus it can lead to economical design without compromising the safety of the structure. The piles are allowed to yield under the design load in certain design cases. Furthermore, piled raft foundation can hold additional loads with controllable settlement although the load capacity of the pile is exceeded. Thus, accurately determining the settlement of the foundation is critical and for the designers to evaluate the role of the raft and the function of piles in combination, as well as the interactions between the foundation components studied by Park and Lee (2016).

A design method that effectively simplifies the calculation procedure considering the nonlinear behaviour of the raft for application to engineering work is presented in this paragraph. The method must consider the foundation as a plate and employs finite element analysis to solve the stress distribution of the raft. The plate is supported by springs and subjected to vertical loads. The interactions between the piles, raft and soil are considered by means of the interactions between these springs. This can give a reasonable results for the settlement and bending moment of the raft. The results are compared with the results obtained by the proposed method and by the commercial program using PLAXIS software.

2.4 Review of finite element analysis using soil model

Numerical modelling methods is done for this research to produce the results which closely agreed to the field ones. Finite element method (FEM) is used to give more optimized estimations. FEM is an advancement over load transfer method. It allows intrinsic properties of soil to be applied in the models. To model more complicated problems, the division of soil structure into elements makes it easier such as complex soil layering, geometry and consolidation. FEM can produce large data and computational power is needed. Thus PLAXIS Professional software is used to obtain the results.

2.4.1 Finite element analysis using PLAXIS *s*oftware

FEM involves a series of interconnected finite elements and those elements can be in 1D, 2D or 3D. The equations are developed in the form of shape and interpolating functions. In this analysis, PLAXIS software is used to solve geotechnical engineering problems such as deformation, stability and groundwater flow. This is because it has a wide use in geotechnical engineering and its implementation of advanced soil models. In order to perform full numerical analysis of a pile foundation, constitutive models for the pile, soil and pile-soil interface are required discovered by Emilios (2003).

In linear elastic model, the materials are characterized by elastic properties such as shear modulus (*G*) and bulk modulus (*K*). Structural parts are modelled by using linear elastic model such as steel and concrete elements. Pile-soil interaction is modelled using interface elements. These interface allows displacement are expressed in terms of slipping and gapping.

2.4.2 Soft soil model

Soft soil model is based on cam clay and is nearly normal consolidated clay, clay silt and peat soil which are highly compressible. In soft soil model (Figure 2.12), volumetric strains are logarithmically related to the mean effective stresses, so that under compression and unloading, it is expressed as:

$$\varepsilon_v - \varepsilon_v^0 = -\lambda^* . ln\left(\frac{p\prime}{p^0}\right)$$

$$\varepsilon_v - \varepsilon_v^0 = -\kappa^* . ln\left(\frac{p\prime}{p^0}\right)$$

(Equation 2.5)

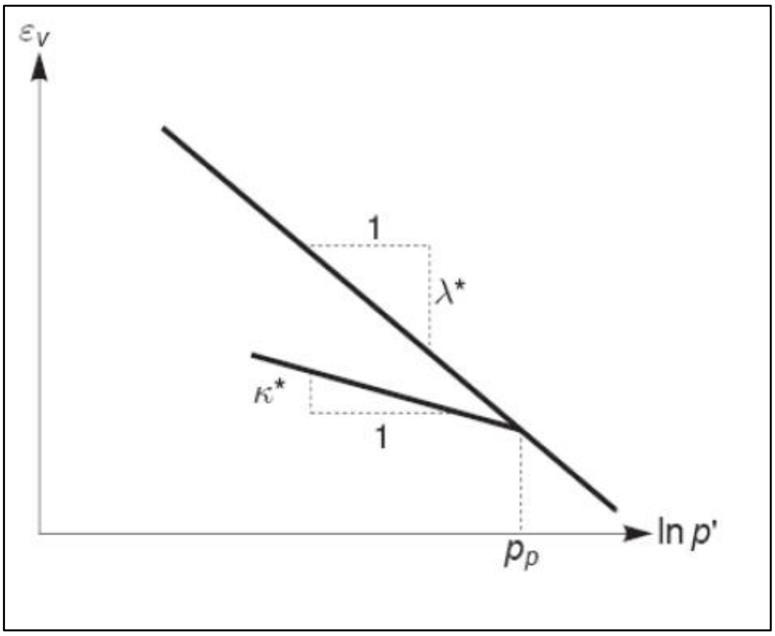


Figure 2.12. Volumetric stress-strain relationship in soft soil model (Naveen and Sitharam, 2011).

The yield function in soft soil model in an ellipse where parameter M determines the height while P_p determines its width. It undergoes irreversible volumetric strain deformation as the yield surface expends by movement along the primary compression line. Naveen and Sitharam (2011) studied that inside the yield curve, the soil undergoes revisable deformation described by swelling lines.

2.5 Three dimensional primary consolidation settlement of pile

The underlying assumption of 2D consolidation is that when a pressure is applied on a clayey soil, the pore water pressure would dissipate from the soil until the total stress of the soil is equivalent to its effective stress. At the site, however, such assumption is not true when a pressure is applied over a limit area on the ground surface. With regard to that, estimation of the soil consolidation settlement must cover the three-dimensional effect by taking into consideration, both the vertical and horizontal stresses. Based on the Skempton–Bjerrum modification (1957) for a consolidation settlement calculation, the three dimensional consolidation settlement for the group pile foundation, is given by Equation 2.6.

$$S_{c(p)} = K_{cir} S_{c(p)-oed} \qquad \text{(Equation 2.6)}$$

where,

K_{cir} = settlement ratio of the group pile foundation.

$S_{c(p)-oed}$ = two dimensional consolidation settlement of the group pile foundation.

The value of K_{cir} can be estimated from Figure 2.13 based on the pore water pressure parameter, A of the soil.

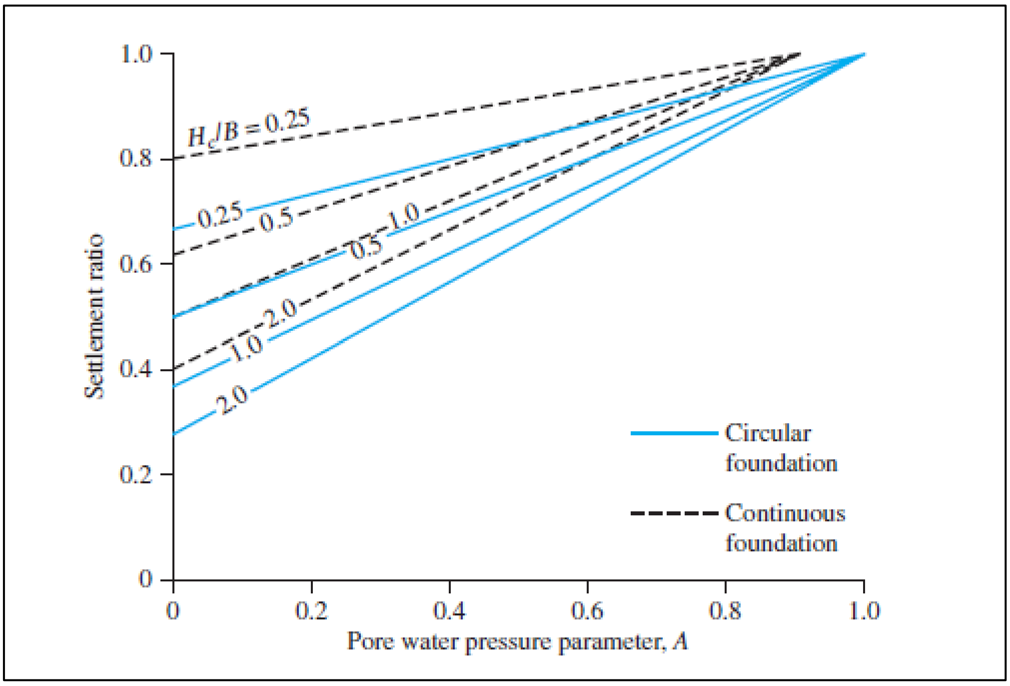


Figure 2.13. Settlement ratios for circular (K_{cir}) and continuous (K_{str}) foundations (Skempton–Bjerrum modification, 1957).

Note: H_c = Depth of the clayey soil from the pile tip, and B = Width of the group pile foundation.

2.6 Finite element formulation (coupled or uncoupled)

The fundamental equations of consolidation theory of Terzaghi (1925) were expanded by Biot (1941; 1965) with consideration on the deformation and seepage flow in three-dimensional analysis. Such theory is identified as coupled consolidation theory, which evaluates soil excess pore water pressure and deformations simultaneously by considering the compressibility of soil particles and pore water. Due to the complication in solving the coupled consolidation equations, Booker & Small (1975) evaluated the excess pore water pressure and deformations in a separate manner by applying uncoupled finite element equations. In order to solve the uncoupled finite element equations, certain assumptions must be made for the coupled theory. However, these assumptions may influence the precision of the results. Recently, Tall et al. (2015) performed a numerical analysis on saturated soil pore water pressure and verified the findings with the analytical solution. For this research, a saturated soil layer between two drainage layers subjected to a strip uniform load is considered (Baqersad et al., 2016). The analytical solution of Terzaghi's one-dimensional consolidation was applied for validating the numerical solution of the research work. Prediction of pore water pressure in a compressible and saturated soil layer under uniform pressure can be done based on the outcome of the research work. Fox et al. (2015) further demonstrated the numerical solution of two benchmark problems that can be used to check other numerical and analytical solutions. The current research direction is focused on the study of finite element method to solve the consolidation problems using both coupled and uncoupled equations (Baqersad et al., 2016).

2.7 Soil constitutive models

In soil constitutive modelling, the solutions are normally based on the Hooke's characterization of linear elasticity which depicts the soil behavior under an applied pressure and Coulomb's law of perfect plasticity for soil under the failure state. The combination of a formula between Hooke and Coulomb's law of soil generates a plasticity framework known as Mohr-Coulomb model. However, it is understood that cohesive soils do not exhibit linear elastic or perfectly plastic for the entire range of the applied pressure. As the matter of fact, the complication in the characteristics of cohesive soils is evident when their compression behaviour varies with different conditions. This led to the evolution of various constitutive models from several research works to simulate the various aspects of the soil behaviour in finite element studies. It must be stressed that no soil constitutive model can be used to completely utilized simulate the complex behaviour of real soils under all conditions.

The first-order constitutive model is also known as the Mohr-Coulomb model. It assumes that the stress-strain behaviour of soil is linear within the range of elasticity, with two defining parameters from Hooke's law namely, Young's modulus, E and Poisson's ratio, v. The failure criteria of the model are defined by two parameters, namely the angle of internal friction, ϕ and cohesion, c as well as another parameter known as the angle of dilatancy, ψ. The parameter, ψ is based on non-associated flow rule which can be used to simulate the irreversible change in volume due to shearing. Reseachers found that by means of true triaxial tests that stress combinations causing failure in real soil samples agree quite well with the hexagonal shape of the failure contour (Goldscheider, 1984). This model can be utilized to assess the stability of dams, slopes, embankments and shallow foundations.

The second order constitutive model is identified as the Hardening Soil model. The soil model was studied by Brinkgreve (2005). It requires a friction hardening to assess the plastic shear strain in deviatoric pressure, and a cap hardening to assess the plastic volumetric strain in primary consolidation of soil. The two main types of hardening in such soil model are shear hardening and compression hardening. Irreversible soil strains as a result of the primary deviatoric pressure are modelled by shear hardening. On the other hand, compression hardening is applied to simulate irreversible plastic soil strains due to primary consolidation under oedometric vertical pressure and isotropic pressure. The failure of the soil model is governed by Mohr-Coulomb failure criterion. With the presence of the two types of hardening in the soil model, the model can be precisely applied to solve problems that cover reduction of mean effective stress and simultaneously time mobilization of shear strength. The Hardening Soil model is characterized by the stress dependent stiffness based on the power law (m), plastic straining due to primary deviatoric pressure ($E^{ref}{}_{50}$), plastic straining due to primary consolidation ($E^{ref}{}_{oed}$), elastic unloading/reloading input parameters ($E^{ref}{}_{ur}$, ν_{ur}) and failure criterion according to the Mohr-Coulomb model (c, ϕ and ψ).

Soft Soil model also known as Cam Clay model applied strain hardening theory of plasticity to develop a stress-strain model for normally consolidated or lightly over-consolidated clay in triaxial test (Schofield and Wroth, 1968). Burland (1965) further revised the model to be extended to a general three-dimensional stress state. This is known as Modified Cam Clay model. The model was established based on Critical State theory on the basis of the assumption that there is a logarithmic connection between the mean effective stress, p' and the void ratio, e of soil. The model is suitable to be applied for simulating the soil deformation than failure particularly for normally consolidated soft soils. It is also practical to be applied for soil under loading conditions that are subjected to embankment or foundation. Four parameters are involved in the soil model, namely the isotropic logarithmic compression index, λ, the swelling index, κ, Poisson's ratio for unloading and reloading, ν_{ur}, friction constant, M, pre-consolidation stress, p_{c} and the initial void ratio, e. Under such soil model, prediction of soil shear strength can be done using the effective friction constant. When applying the primarily undrained deviatoric pressure on the soft soil, the model best predicts the soil undrained shear strength as compared to that of the Mohr-Coulomb model.

2.8 Effect of relevant parameters on the pile performance in soil

Numerous parametric studies were conducted and published with regard to the pile performance in soil. Tang et al. (2018) explored the three-dimensional numerical model with reference to the field measurements on the lateral earth pressure distribution on sheet pile walls, with the goal to develop guidelines and recommendations on the sheet pile walls design. Under the study, a parametric evaluation was done with respect to the pile length, sheet's location, pile's stiffness, and soil properties on the pile performance. As an outcome of the study, it was discovered that an optimal pile length of 14 m could be used for the design of the sheet pile walls in a China high-speed railway. The finding is justified by the moment of inertia of the sheet pile walls at limiting pile displacement and earth stress. The research findings give helpful indications for safe and economical design of the sheet pile walls.

Hamderi (2018) claimed that in the past, only a few input parameters which gave limited estimation of the actual settlement for group piles in soil. Although it is more precise to produce large three-dimensional numerical models with a more precise settlement estimation, they are not common in practice due to their high cost implication and complexity. To solve the issue, Hamderi (2018) came out with a pile settlement formula based on about 120 finite element model configurations. The group pile settlement formula considers the size of a rectangular raft, namely, the diameter, length and spacing of the piles, vertical uniform pressure, soil moduli up to five layers, ultimate pile-soil resistance, pile-tip resistance and elastic modulus of the piles. It has to be noted that the average deflection rate of the raft is approximated. Five case studies were used to verify the validity of the proposed formula. Hamderi (2018) justified that the formula can assist researchers to optimize group pile configurations effectively by utilizing the quality of three dimensional finite element prediction to practice.

To gain new insights into single pile responses to adjacent excavations in soft ground, three dimensional numerical parametric studies are carried out by Soomro et al. (2019). In their studies, Soomro et al. (2019) adopted an advanced hypoplastic (clay) constitutive model which takes account of small-strain stiffness. Soomro et al. (2019) evaluated the implications of excavation depths (H_e) relative to pile (L_p) by performing simulation on the excavation near the pile shaft (i.e., H_e/L_p = 0.67), next to (H_e/L_p = 1.00) and below the pile toe (H_e/L_p = 1.33). Other than that, the investigation from the study was also focused on the effect of pile head boundary conditions and different working loads with Factor of Safety (FOS) = 3.0 and 1.5. Calibration and validation were done between the model parametric results with the ones measured in centrifuge as published in the literature. It was realized that the pile responses to excavation are dependent on the degree of excavation and the depth of the wall embedment. It is notable that with the varying wall depths for the three cases, the induced settlement, lateral displacement and bending moment in the pile at the same stage of the excavation were also varied. After evaluating the three cases, it was noticed that the excavation in case of H_e/L_p = 1.33 resulted in the largest pile settlement (i.e., 7.6% pile diameter) (Soomro et al., 2019). The largest pile deflection happened to the case of H_e/L_p = 0.67. The bending moment and changes in axial load distribution caused by the pile on completion of the excavation were not apparent. However, Soomro et al. (2019) claimed that significant bending moment (60% of pile BM capacity of 800 kN m) induced in the pile with fixed head condition. It was also traced that the different working loads (with FOS = 3.0 and 1.5) control the pile settlement but induce a little effect on induced bending moment.

2.9 Loading increment and time step

Karim & Oka (2010) studied about an automatic time increment selection scheme for numerical analysis of long-term response of geomaterials. With a great convenience and high reliability, the scheme which is governed by a simple empirical expression can be adaptively suit the time increments on the basis of the strain rate-dependent temporal history of the material response. Only a few parameters were needed for the empirical expression of which the choice of the selection of these parameters have small influence on accuracy but have a large impact on computational efficiency. Performance of the automatic time increment selection scheme is investigated through finite element analyses of the long-term consolidation response of clay under different geotechnical profiles and loading conditions (Karim & Oka, 2010). Consideration was particularly given to both elastic and elasto-viscoplastic constitutive relations focusing on the de-structuration effects of geomaterials. The numerical findings revealed that the automatic time increment selection scheme could perform at a reasonably excellent way. In fact, the temporal stability at the optimal computational efficiency can be assured with the reasonable precision in the finite element solution. In addition to the Euler implicit method, the automatic time increment selection scheme also performs well even when the explicit fourth-order Runge-Kutta method is employed for the integration of time derivatives (Karim & Oka, 2010).

Figure 2.14 shows a typical two-dimensional problem of an embankment resting on the soil. The solution to the problem was based on the assumption that the soil properties and boundary conditions are similar to those with the elastic one-dimensional analysis. The numerical mesh configuration is shown in Figure 2.15. The applied loading profile is shown in Figure 2.16(a), which is similar to the construction load of the test embankment D over the Champlain clay at St. Alban (Oka et al. 1991). Figures 2.16(b) and 2.17(a) illustrate the time increments calculated via the automatic selection scheme. To ensure that the time increment profile reflects the loading history, the time increments Δt are always reassigned to $\Delta t = \Delta_{cf}$ when the construction loading is increased (Karim & Oka, 2010). There are frequent increases in the time increments between 5 to 18 days as depicted in Figure 2.16(b). It should be recognized that the profile of the time increment also follows the strain history of the material as indicated in Figure 2.17(a) and (b). As such, for the two-dimensional analysis, the computation for a duration of 100 days could be done in just five minutes and three seconds. During and after the construction, the temporal distribution of the two-dimensional elastic soil responses is shown in Figure 2.18 (a) and (b). As anticipated, the pore water pressure increased as the applied pressure increased at the initial stage. Later, dissipation of the pore water pressure happened once the loading increment was gradually reduced after 18 days of soil compression.

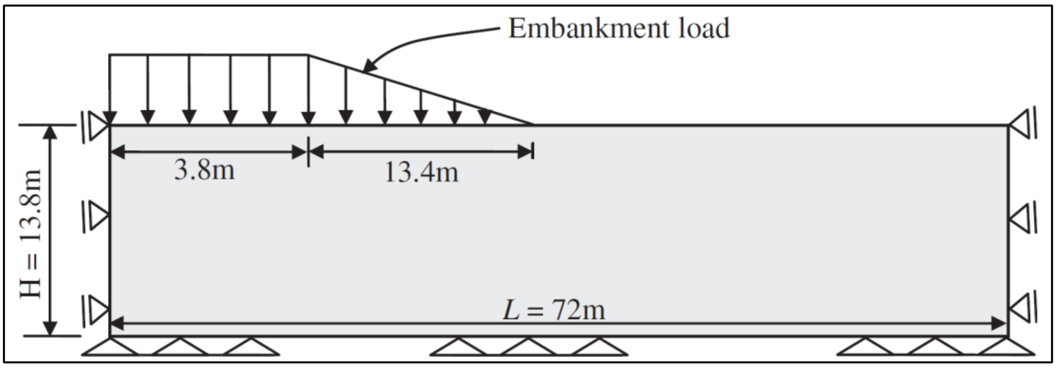


Figure 2.14. Typical two-dimensional consolidation problem (Karim & Oka, 2010).

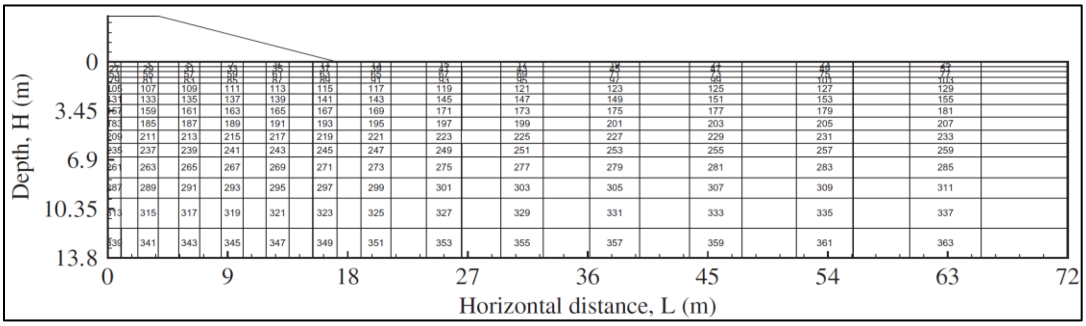


Figure 2.15. Discretization scheme for two-dimensional analysis (Karim & Oka, 2010).

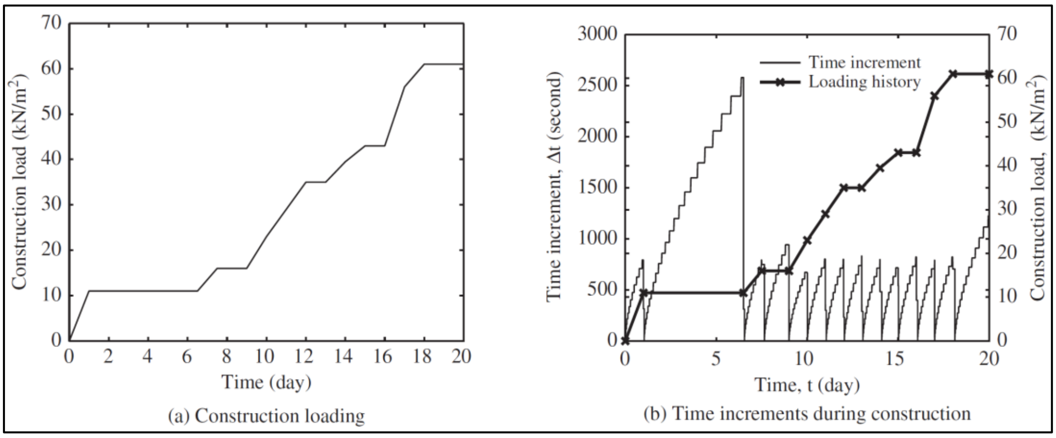


Figure 2.16. Loading profile and time increments during embankment construction (two-dimensional elastic) (Karim & Oka, 2010).

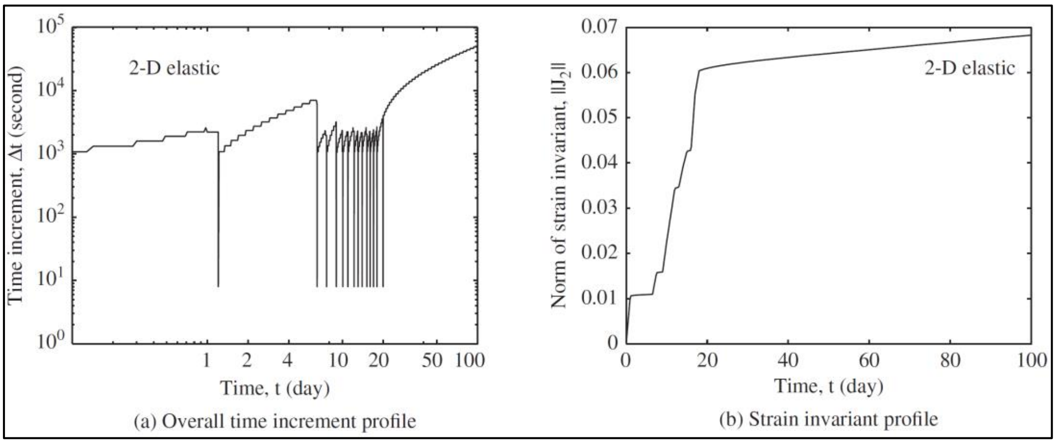


Figure 2.17. Time increments and observed strain history for two-dimensional elastic consolidation (Karim & Oka, 2010).

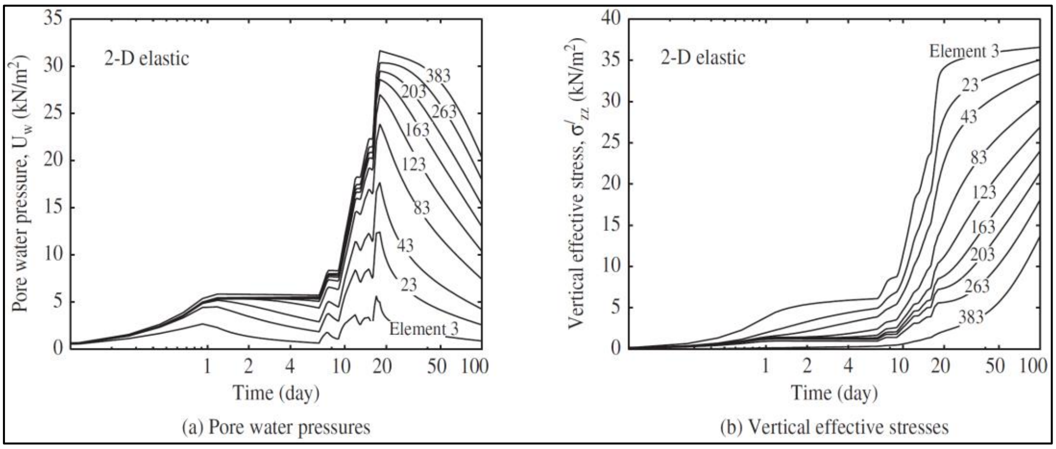


Figure 2.18. Two-dimensional elastic consolidation response (Karim & Oka, 2010).

2.10 Research gaps

Based on the literature review, it is realized that studying the behaviour of a single pile from test data allows understanding on the development of the ultimate load of the piles, and also makes it possible to consider a nonlinear response of the foundation system. Although similar numerical works on single pile in clayey soil were done and published, none of these works addressed the fineness of mesh for the finite elements under their studies in providing the most accurate load-compression behaviour of piles in soil in comparison to that of the field data. In addition, none of these studies further optimize the group performance of the piles by taking into consideration the frictional resistance and group efficiency of the piles under various applied pressures, soil cohesion and angle of internal friction. As such, it is intriguing to carry out the finite element simulation of the single bored pile in clayey soil and then conduct parametric evaluation on the efficiency of group bored piles with respect to consolidation settlement.

The combination of group piles allows convenient consideration of the various parameters involved to induce optimal impact on the soil consolidation settlement. It allows for the use of any structural commercial program to solve the piled raft foundation problem. It can be stated that the piled raft foundation problem can be solved effectively through a combination of structural responses and geotechnical characteristics without a complex model of the soil and foundation. The finite element method is done by using PLAXIS software to simulate and the numerical results can be generated. The experimental data from the field and simulated numerical data can be validated in order to ascertain the closeness of the results.

The literature findings point to the fact that the research gap regarding parametric study on floating group bored piles in clayey soil exists. As such, the current numerical study was conducted on the effects of pile applied pressure, pile length, pile spacing, and pile slope ratio of floating group bored piles in clayey soil. It is also notable that the parametric study must also consider the most suitable soil model with varying cohesion and angle of internal friction so as to provide a better understanding on the soil-pile group interaction in term of consolidation settlement.

CHAPTER 3

METHODOLOGY

3.1 Introduction to methodology

This chapter discusses the overview and methodology done on the research work regarding the simulation of load test on single bored pile and parametric study on group bored piles in clayey soil. Figure 3.1 summarizes the methodology of the research work. The simulation of load test on single bored pile in clayey soil was done using PLAXIS software and compared with that of literature study. Based on the field results using constant load test on the soil from Wehnert & Vermeer (2004), simulation on the single bored pile in the soil was done for the comparison purpose. Parametric evaluation on load settlement behaviour of group bored piles was done in order to assess the optimal performance of group bored piles at the particular loadings and soil conditions on the basis of numerical simulation using the software.

Computer analysis was done using numerical simulation of load test on single bored pile to predict the load-settlement behaviour. A few soil models were applied for the simulation purpose inclusive of Mohr-Coulomb (MC), Hardening-Soil (HS) and Softening-Soil (SS) models. In this research work, the soil models were applied to the soil layer of varying degree of mesh fineness in order to assess the closeness of the simulated results of the load-settlement of single bored pile with those of the real-time monitored ones. During the simulation of geotechnical problems by finite element method, there could be some numerical and modelling errors involved. To minimize the errors, it is advisable that the geotechnical engineers should possess the capability to model the problems, understand the soil models and relevant parameters in order to judge the computational results with respect to the accuracy of the output data which was discovered by Wehnert & Vermeer (2004).

The parametric evaluation of group of bored piles is based on the most accurate soil model with the degree of mesh fineness of the single bored pile test in the clayey soil. The soil parameters adopted in the simulation were based on literature studies. With the specification of the material and soil parameters with the most accurate degree of mesh fineness, optimization in the design of the group bored piles could be modelled. It is notable that the scope of this research is outlined and limited to the simulation of load test of bored piles in clayey soil for the settlement behaviour of single and group bored piles. Thus, conclusion from the recent research work and some recommendations for future study are made at the end of the results.

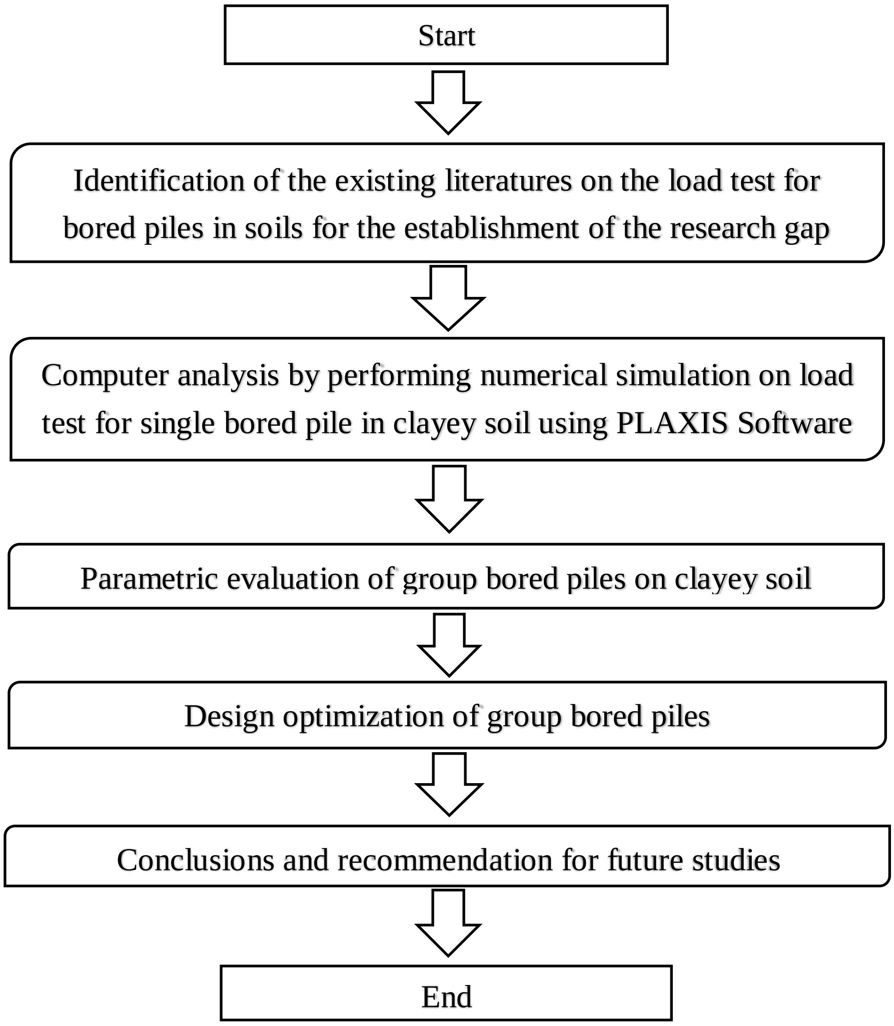


Figure 3.1. Summary of research methodology for the simulation work.

3.2 General procedure of the simulation using PLAXIS software

Figure 3.2 illustrates the specific flow chart of methodology of PLAXIS simulation on the bored piles.

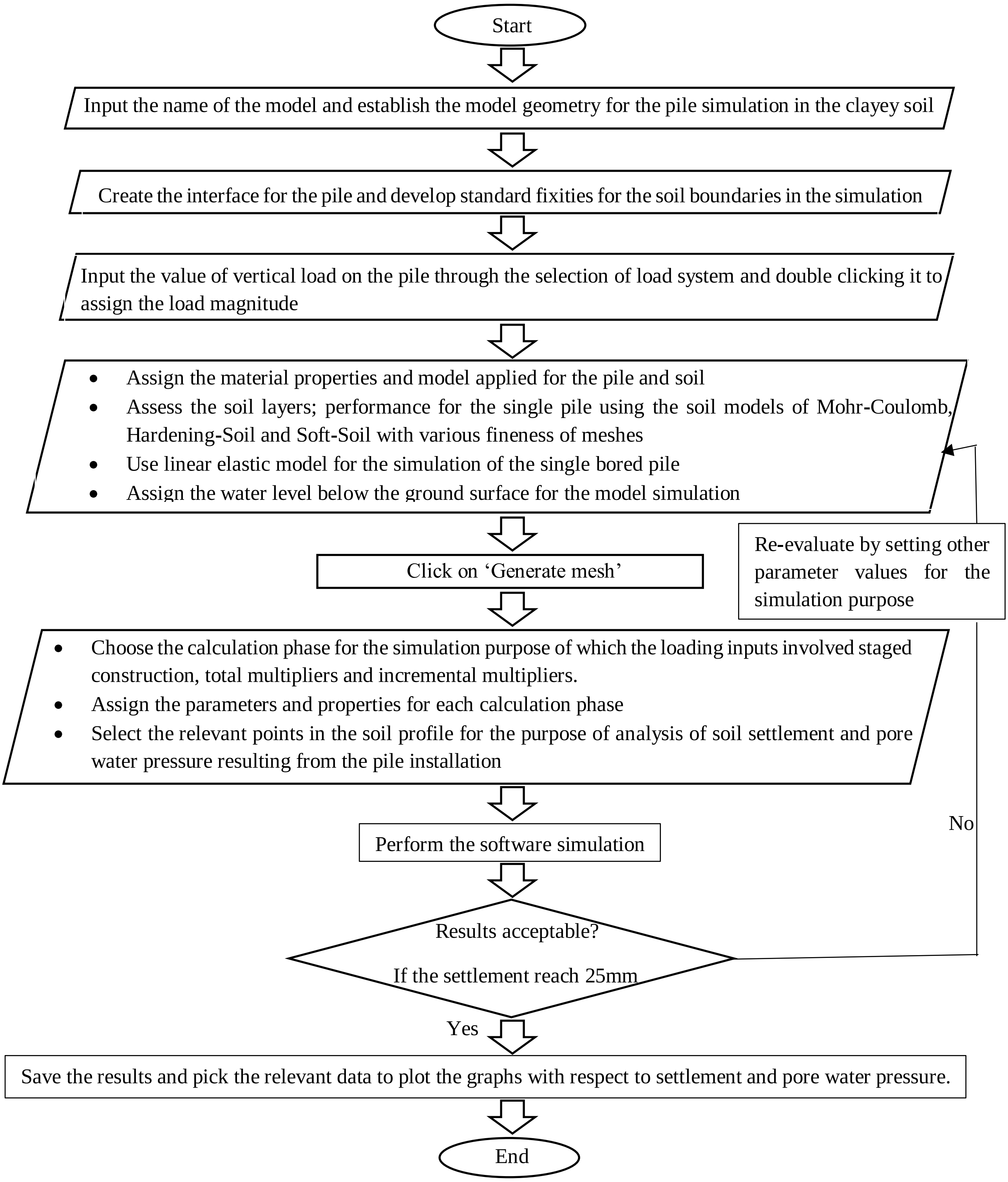


Figure 3.2. Flowchart of methodology of PLAXIS simulation on the bored piles.

The simulation work is done by first drawing and setting the necessary data to generate the meshes and calculations (Figure 3.3). The input data of soil layer, structure, loads and boundary condition is done based on the previous literature study. The geometry model was first drawn by geometry lines such as the soil layers and pile dimension on the gridline which provides coordinates. The pile is surrounded with interface which are the joint elements between soils and structure. It is notable that the values of friction angle and cohesion for the soil are not the same.

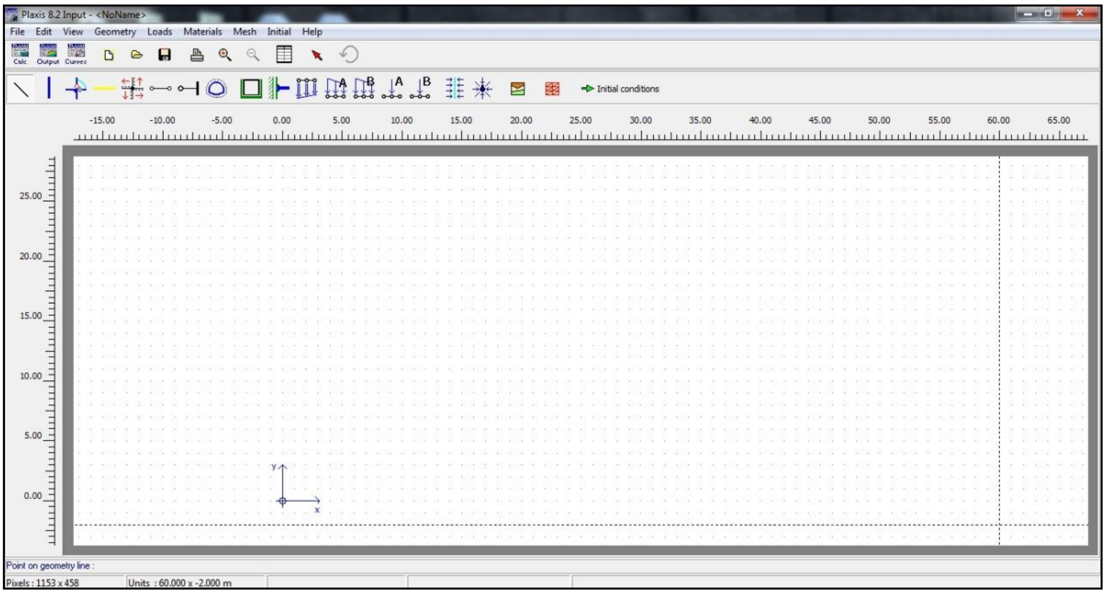


Figure 3.3. Space layout for the drawing of bored piles and soil layer using PLAXIS software.

Parameters of the materials for the soil layers and pile are defined first before generating the mesh. The simulation was based on the literature review data test in order to obtain the analysis under the similar soil condition and pile specifications. The pile was model using a linear elastic model. In PLAXIS, soil layers can be set up according to drained or undrained soil condition, depending on the state of the permeable boundaries of the soil layers. The depth of the water table is 8 m from the ground surface. With standard fixities as boundary conditions, the soil is set in undrained condition as no excess pore water is dissipated from the soil before the application of the initial pressure. As such, the ground water table is set at a constant level for the numerical modelling of the bored piles.

3.3 Input parameters for simulation on single bored pile test in clayey soil

The soil parameters for the varying soil models were taken from the research work of Wehnert & Vermeer (2004) (Table 3.1). Such parameters are important for the simulation of the load test on single bored pile in clayey soil. Table 3.2 shows the summary of the parameters used for single bored pile simulation in clayey soil from the study of Wehnert & Vermeer (2004).

Table 3.1. Summary of the parameters for clayey soil models (Wehnert & Vermeer, 2004).

Parameter	**Unit**	**MC**	**HS**	**SS**
γ_{unsat}	kN/m^3	15	15	15
γ_{sat}	kN/m^3	20	20	20
k_x	m/day	1×10^{-8}	1×10^{-8}	1×10^{-8}
k_y	m/day	1×10^{-8}	1×10^{-8}	1×10^{-8}
E_{ref}	kN/m^2	2.451×10^4	2.451×10^4	2.451×10^4
E_{oed}	kN/m^2	3.300×10^4	3.300×10^4	3.300×10^4
v	-	0.300	-	-
$E_{ur\ Ref}$	kN/m^2	-	9.000×10^4	-
c_{ref}	kN/m^2	20	20	20
φ	o	20	20	20
ψ	o	0	0	0
v_{ur}	-	-	0.200	-
Power (m)	-	-	0.500	-
$K_o\ N_c$	-	-	0.800	0.800
λ^*	-	-	-	0.003
K^*	-	-	-	0.001
R_{inter}	-	1.0	1.0	1.0

Table 3.2. Summary of the parameters used for single bored pile simulation in clayey soil (Wehnert & Vermeer, 2004).

Parameter	**Unit**	**Single bored pile**
Material model	-	Linear elastic
Material type	-	Non-porous
Diameter of pile	m	1.3
Length of pile	m	9.5
γ_{pile}	kN/m^3	25
E_{pile}	kN/m^2	30000 kPa

Note: E_{pile} is the modulus of elasticity for the reinforced concrete pile.

3.4 Input parameters for the bored pile simulation purpose

Once the PLAXIS software is turned on, the new chart is clicked. Next, the General Settings are depicted after the clicking. Then the title of the file is typed as 'Single Pile Load Test'. Under the model, plain strain and elements with 15 nodes are selected. Earth gravity parameter is set at 9.81 m s^{-1}. For the relevant dimensions, the suitable units for each parameters are chosen. A load is applied on the bored pile in the simulation. The pressure distribution icon is clicked and applied on the bored pile. Based on the literature review from Wehnert & Vermeer (2014), the pressure applied on the bored pile is 3014 kN m^{-2} at the position of the *y*-axis (Figure 3.4). Such pressure application is based on the constant load test conducted by Wehnert & Vermeer (2014) on a single bored pile in clayey soil. Similar amount of pressure needed to be applied on the single bored pile in the soil for the PLAXIS simulation in order to compare its numerical load-settlement behaviour with that of Wehnert & Vermeer (2014).

In this simulation, two types of meshes are generated which are very fine mesh and fine mesh. Figure 3.5 shows the simulation of single bored pile in clayey soil with very fine mesh. During the generation of mesh, clusters are split into triangular elements. In the mesh analysis, the 15-node elements were selected because they are good enough to provide precise calculation of stresses and failure loads. The step is followed by a simulation for pore water pressure distribution and a simulation for effective stress distribution. Figure 3.6 shows the simulation of pore water pressure distribution of the single bored pile in clayey soil. The phreatic level below the ground surface must be set first before the 'Generate pore water pressures' button in the PLAXIS toolbar can be clicked. Figure 3.7 illustrates the simulation of effective stress distribution of the single bored pile in clayey soil. For the stress simulation, the 'Generate initial stresses' button must be clicked with the total multiplier for soil weight assigned as 1.0 in the K_0 procedure dialogue box.

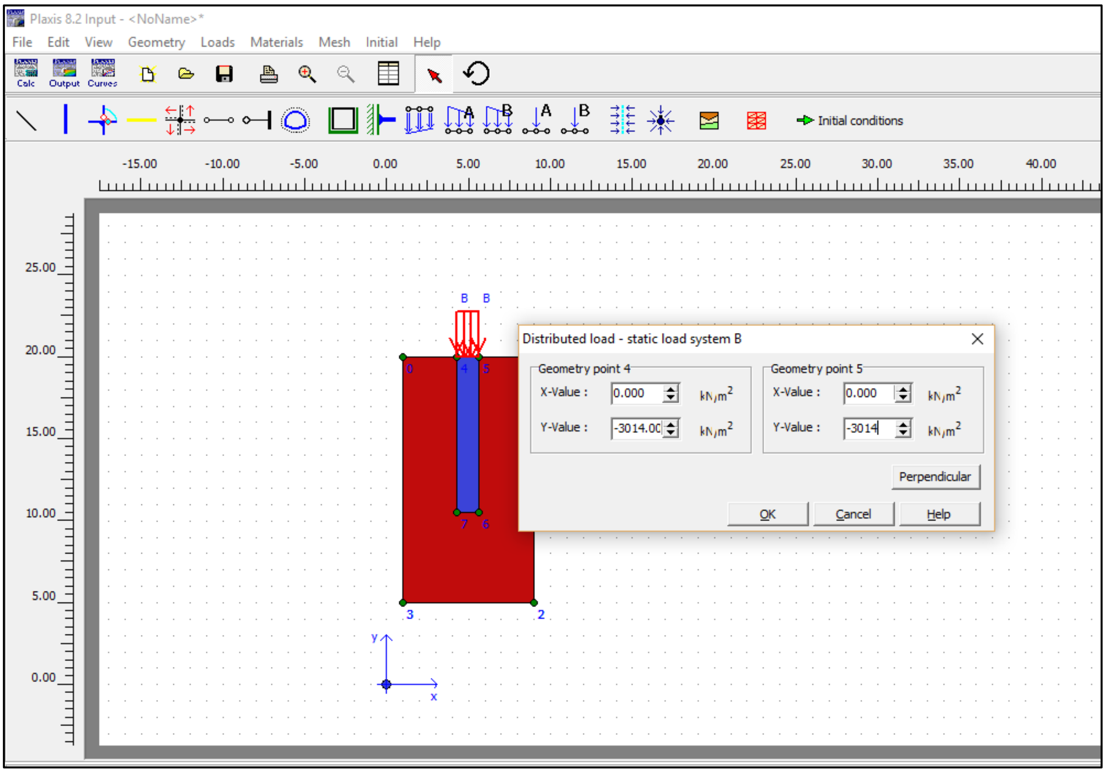


Figure 3.4. The single bored pile simulation in clayey soil under constant load test.

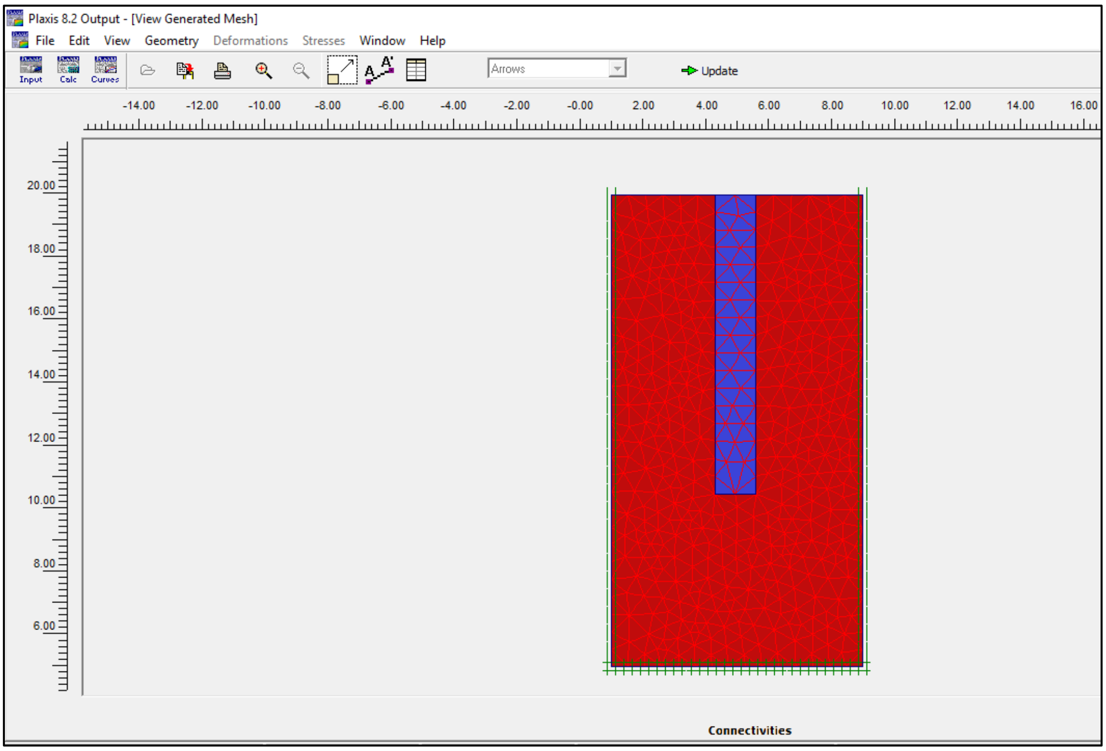


Figure 3.5. Simulation of the single bored pile in clayey soil with very fine mesh.

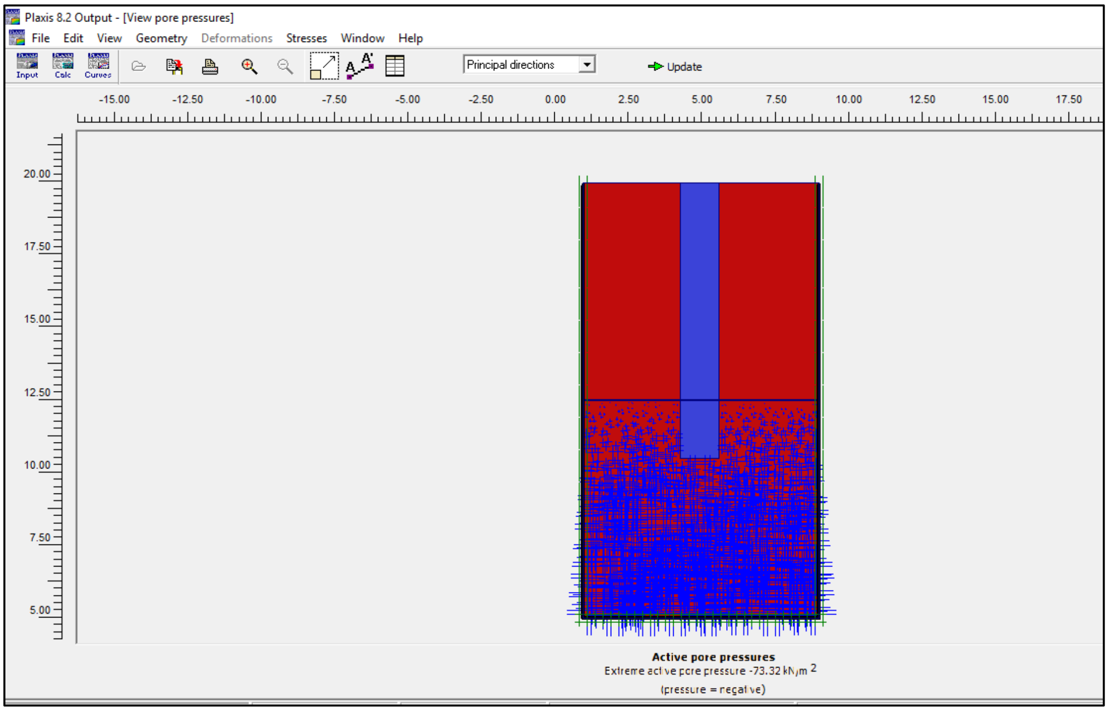


Figure 3.6. Simulation of pore water pressure distribution of the single bored pile in clayey soil.

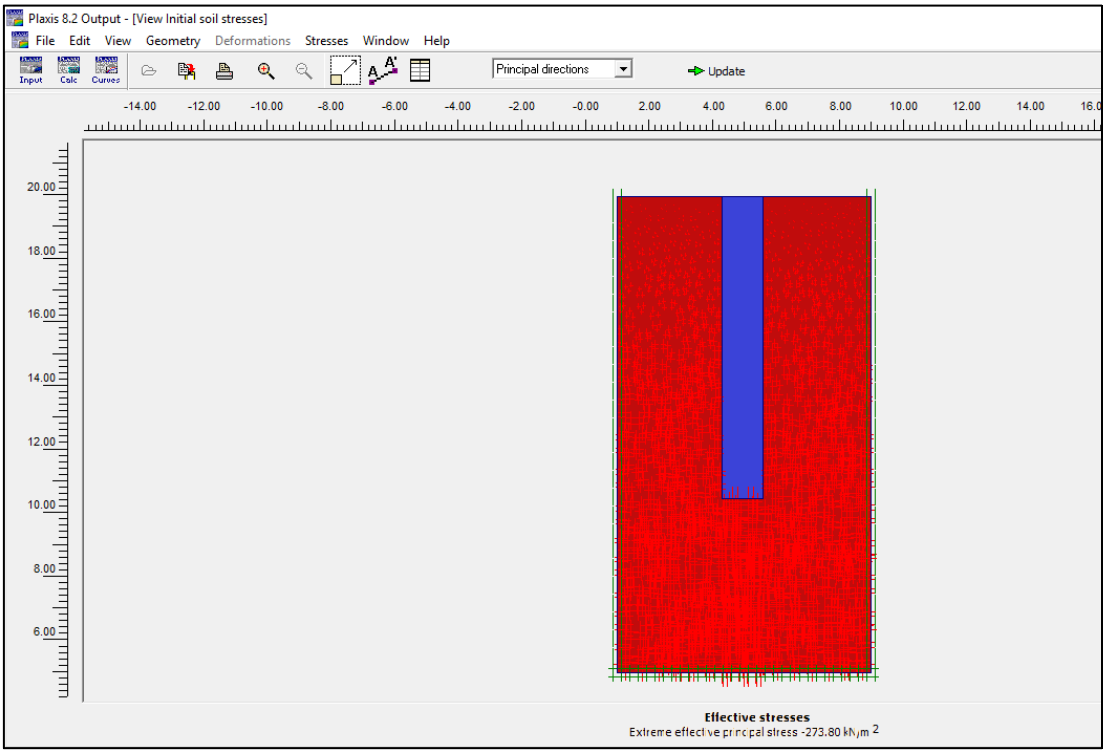


Figure 3.7. Simulation of effective stress distribution of the single bored pile in clayey soil.

3.5 Problem boundary

All the finite element models under the study were assigned with standard fixities for the boundary limits. Standard fixities fix the bottom of the model in all directions and the vertical sides in the horizontal directions. By the default, the bottom boundary of each model was fixed with zero dissipation of pore water in *x*, *y* and *z* directions (u_x = u_y = u_z = 0) and the vertical sides of the horizontal boundaries were fixed with zero dissipation in the *x* direction (u_x = 0) and free flow of pore water in the *y* and *z* directions (u_y = u_z = free). In addition, the surface boundary condition was fixed at free flow of pore water.

3.6 Calculations and output of the resulting simulation

A total of 3 phases of loading input were examined in the calculation and output of the resulting simulation. The 3 phases are specified as Phase 1 for plastic stage, Phase 2 for dynamic analysis and Phase 3 for Phi/c reduction (Figure 3.8). For the dynamic analysis phase, the end time of the simulation is automatically set at 0.01 sec. Dynamic analysis is done by applying Dynamic Multipliers. These Multipliers operate as scaling factors on the inputted values of the loads to produce the actual load magnitudes. Under the analysis, the load is initially kept active, but the corresponding load multiplier is set to zero in the Input program. In the Calculation program, it is specified how load multiplier changes with time rather the input value of the load. The time dependent variation of the load multiplier acts on all loads corresponding in the corresponding load system. Under constant load test, the end time of the simulation for the Plastic and Phi/c reduction phases is also automatically set at 0.00 sec. because the soil failure occurred rapidly as a result of the constant load application to yield the load-settlement curve. Figure 3.9 illustrates a typical calculation in PLAXIS based on the 3 phases of loading input. The loading inputs are staged construction, total multipliers and incremental multipliers.

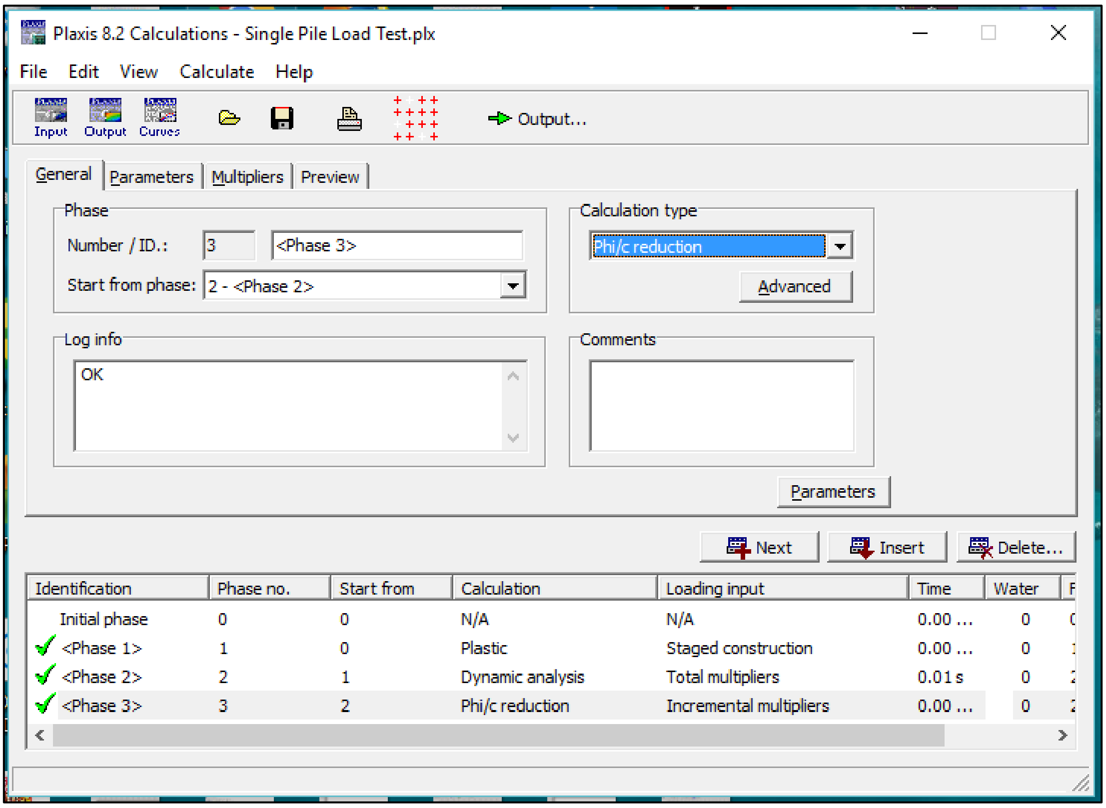


Figure 3.8. The 3 phases of loading input in the software setting for the simulation.

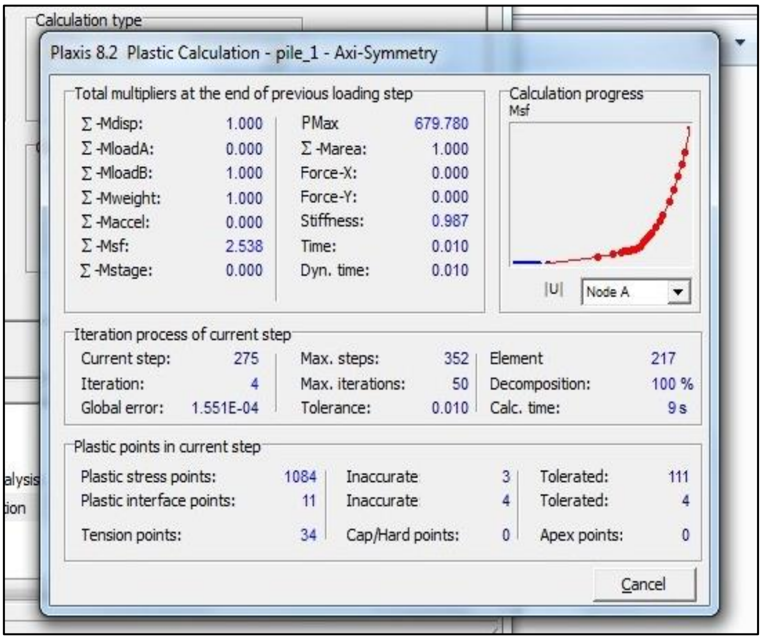


Figure 3.9. Calculation in PLAXIS based on the 3 phases of loading input.

For graphical plotting, the curves and the new chart are clicked. The file should be saved before any graphical plotting starts. On the graphical plot, the *X*-axis is set as 'Displacement' and the *Y*-axis is set as 'Multiplier'. In order to get the curve for other point, the relevant point option should be selected. In this way, the load-settlement behaviour of the bored pile at the selected point in the clayey soil can be analyzed.

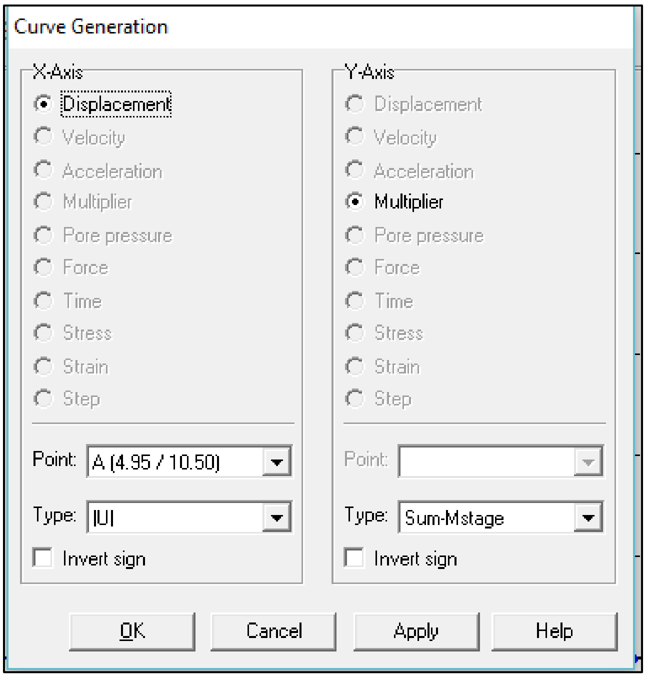


Figure 3.10. Curve generation in the software with the *X* and *Y* axis options.

3.7 Parametric study on group bored piles in clayey soil

After evaluating the closeness of the predicted results from the simulation as compared those of the field measured ones for single bored pile in clayey soil, parametric study on group bored piles in the soil was carried out in order to optimize the diameter, spacing, length and slope of the piles under the application of various pressure, soil cohesions and angles of internal friction. The values of the material parameters are based on the most accurate soil model and the degree of mesh fineness for the single bored pile. Through such analysis, the influencing factors that affect the load-settlement behaviour of the group bored piles in clayey soil can be investigated. The plan view of the foundation designed in 5 × 3 bored pile group is shown in Figure 3.11.

The group bored pile has a pile cap with a dimension of 9.1 m breadth, 20.8 m length and 1 m thick. Figure 3.12 illustrates the plan view of the foundation designed in 5 × 3 bored pile group arrangement. It must be noted that the parametric study on the group bored piles on the soil was carried out based on the plain strain assumption. The plain strain assumes that the strain in the thickness or *z* direction of the group bored piles 2D model is zero. This assumption is best suit for geometries with thick cross section. With the type of group bored piles under the simulation is arranged as 5 × 3 (5 piles over the length and 3 piles over the width), plain strain assumption can be satisfactorily applied to model the group bored piles on the basis of their thick cross section. In 2D projection, the exact deformation of the group bored piles can be wholly evaluated in plain strain as compared to that of the group bored piles in axis-symmetry. Furthermore, the 2D consolidation settlements of the group bored piles are converted into 3D consolidation settlements based on the theory established by Skempton & Bjerrum (1957) as detailed out in Chapter 2. A summary detail of the variations in the group bored pile design using the software is given in Table 3.3. For the parametric study of the group bored piles in the clayey soil, it is important to evaluate the maximum applied pressure that can be sustained to achieve a consolidation settlement of not more than 25 mm (Allowable consolidation settlement). For that reason, the load tests started in stages at a low applied pressure of 50 kPa and then, the pressure increment was doubled up at each time step until a maximum applied pressure of 800 kPa was achieved.

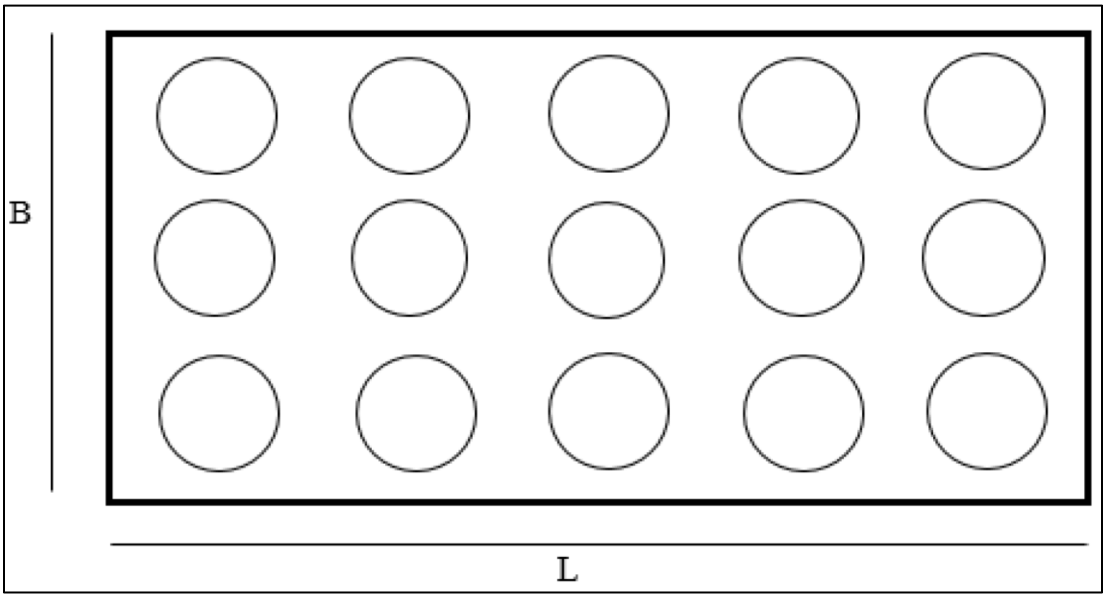


Figure 3.11. Plan view of the foundation designed in 5 × 3 group bored pile arrangement (Note: For the pile cap, *B* = Breadth = 9.1 m; *L* = Length = 20.8 m, *H* = Thickness = 1 m).

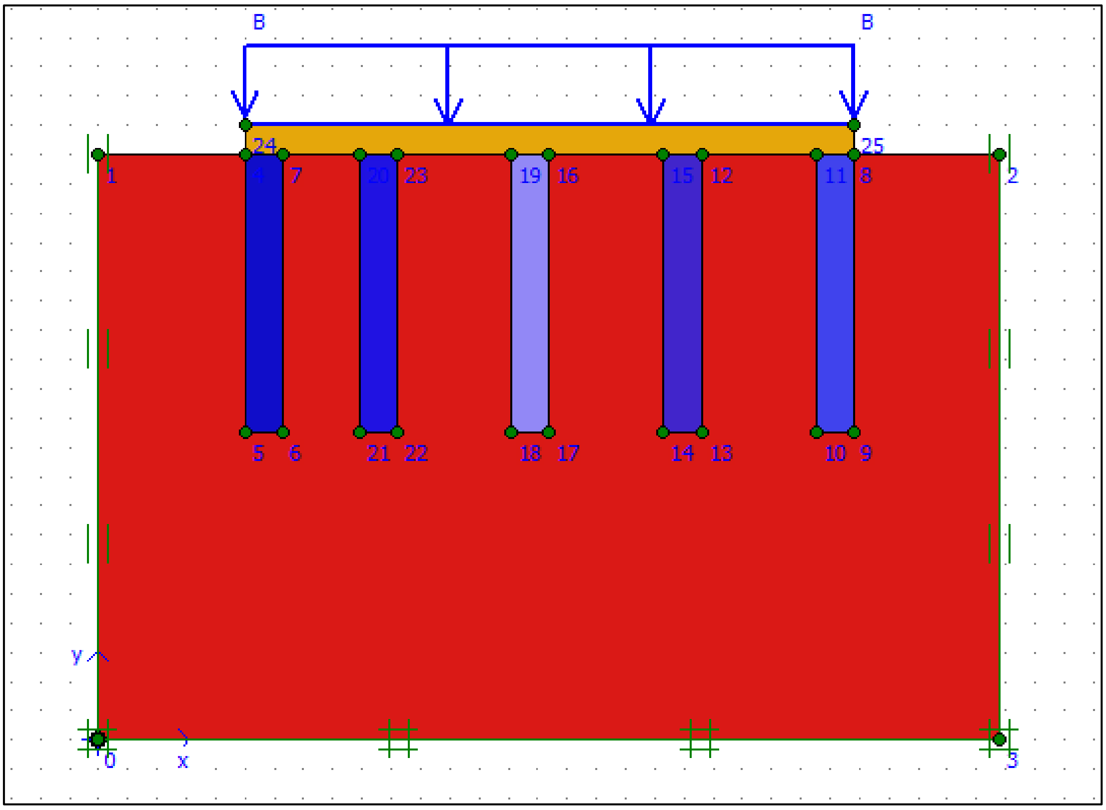


Figure 3.12. Side view of the foundation designed in 5 × 3 group bored pile (Note: *B* = Breadth = 9.1 m; *L* = Length = 20.8 m, Thickness = 1 m).

Table 3.3. Details of parametric study on group bored pile using PLAXIS software.

No.	No. of simulation	Variation of parameters of group bored piles	Purpose
1	5	Pile group of 5 x 3 with 1.30 m pile diameter, 9.5 m pile length, 3D pile spacing and zero slope configuration at pile tip. The simulation is done under various applied pressures as below: i) 50 kPa ii) 100 kPa iii) 200 kPa iv) 400 kPa v) 800 kPa *Note:* Each loading is applied until the excess pore water pressure is fully dissipated from the soil with the pile group. In other words, the time step for each loading is dependent on the full dissipation of excess pore water pressure from the soil with the pile group.	To obtain the design applied pressure to be used from the settlement performance of group bored piles which enables a wide range of parameters to be varied.
2	5	➢ The applied pressure on the pile foundation is 50 kPa. ➢ Pile diameter is 1.30 m. ➢ The pile spacing is varied as below: i) 1D ii) 2D iii) 3D iv) 4D v) 5D	To simulate the pile settlement performance and optimize the bored pile volume with respective to each parametric design.
3	5	➢ The applied pressure on the pile foundation is 50 kPa. ➢ Pile spacing is varied to be 3D. ➢ The pile diameter is varied as below: i) 1.0 m ii) 1.2 m iii) 1.3 m iv) 1.5 m	

		v) 1.7 m	
4	5	➢ The applied pressure on the pile foundation is 50 kPa. ➢ Pile diameter is 1.30 m. ➢ Pile spacing is varied to be 3D. ➢ Pile tip configuration is designed with a slope which varies as below: i) 1:08 ii) 1:2 iii) 1:4 iv) 1:6 v) 1:8	
5	5	➢ The applied pressure on the pile foundation is 50 kPa. ➢ Pile tip configuration is designed with a slope of 1:2. ➢ Pile diameter is 1.30 m. ➢ Pile spacing is set to be 3D. ➢ Soil angle friction (φ) is set at 20°. Soil cohesion (*c*) is varied as below: i) 20 kPa ii) 30 kPa iii) 40 kPa iv) 50 kPa v) 60 kPa	To simulate the pile settlement performance with respect to varying soil cohesions and angle of internal frictions.
6	5	➢ The applied pressure on the pile foundation is 50 kPa. ➢ Pile tip configuration is designed with a slope of 1:2. ➢ Pile diameter is 1.30 m. ➢ Pile spacing is set to be 3D. ➢ Soil cohesion (*c*) is set at 20 kPa. The soil angle of internal friction (ϕ) is varied as below: i) 20° ii) 30°	

		iii) 40° iv) 50° v) 60°	

3.8 The site selected for obtaining the typical values of material parameters of the bored piles under simulation

Site visit was conducted at the incomplete MRT Phase 2 elevated station in Putrajaya. The site is in front of LimKokWing University, Malaysia. Figure 3.13 shows the bored piles at the site. The incomplete MRT station is part of the proposed MRT Phase 2 rail network that connects Sungai Buloh with Putrajaya. It serves a bus hub station, taxi stand, several shop lots and car parks. The depth of the bedrock from the ground surface is 40 m. A typical length of the bored pile at site was discovered to be 31 m. As such, the properties of 31 m length bored pile are used to design the longest pile which is placed at the middle of the pile slope under simulation. The other bored pile parameters obtained from the site and used in the simulation are listed in Table 3.4. It should be clarified that only the properties of the bored piles and their diameters in the parametric study are based on the site conditions. The spacing and length of the bored piles as well as their applied pressure, soil cohesion and angle of internal friction are varied so as to optimize the performance of the group bored piles by setting a maximum allowable consolidation settlement of 25 mm of the clayey soil.

Table 3.4. Parameters of bored pile based on the material properties of the pile from the site.

No	Input	Unit	Parameter
1	Diameter of pile	m	1.3
2	Length of pile	m	31
3	Spacing between each pile	m	3D
4	Applied pressure on pile	kPa	50
5	γ_{pile}	kN/m^3	24
6	E_{pile}	kN/m^2	30000
7	Pile material model	-	Linear elastic

Figure 3.13. Bored piles at the site.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction to results and discussion

This chapter presents the outcomes of the simulation of load tests on bored piles in clayey soil using PLAXIS software. The immediate focus of the results and discussion in this chapter is to ensure the first two research objectives are achieved by validating the soil models applied to single bored pile in clayey soil under the applied pressure with those of the measured results. Through such validation, the most accurate soil model can be applied for simulation of single bored pile in the soil under pressure application. Further to the research development, an optimal parametric design of group bored piles can be determined based on the load-settlement behaviour of the bored piles in various group arrangements. It is necessary to stress that the study on the numerical simulation is rather 'site specific'. This implies that the numerical design is only applicable to the site area under the simulation. Based on the requirement of the deep foundation design, the site data was used for the simulation of group bored piles with 50 kPa applied pressure such that a consolidation settlement of 24.5 kPa was achieved which is just below the tolerable settlement of 25 mm. In line with objective 3, the numerical design of the group bored piles are optimized in order to design the group bored piles as viable friction piles. Friction piles are designed in such a way that their resistance is formulated from skin friction. In the clayey soil, the resistance of the applied pressure is caused by the adhesion and cohesiveness of the clay. This implies that the length of the friction piles is dependent on the shear strength of the clay, the applied pressure and the pile size. Hence, determination on the lengths of friction piles requires a logic understanding of soil-pile interaction, good judgment and experience.

4.2 Numerical simulation of single bored pile under load test

The largest settlement of soil happens at the point underneath bored pile discovered by Randolph (2004). Figure 4.1 shows the point at tip of the single bored pile in clayey soil of which the load-settlement behaviour of the pile under various soil models and mesh fineness was modelled using the software. Thus, it is the point of interest to be studied under the validation of the pile load-settlement behaviour. For that point, the modelled results of the load-settlement behavior of the pile using Mohr-Coulomb (MC), Hardening-Soil (HS), and Soft-Soil (SS) models with Very Fine and Fine mesh were compared and analyzed. For Fine mesh model, there are 500 finite elements with each mesh size is 1 m in the model. For Very fine mesh model, there are 1000 finite elements with each mesh size is 0.6 m in the model.

The load-settlement behaviour of single bored pile in clayey soil using MC model for Very Fine and Fine mesh PLAXIS simulations are shown in Figures 4.2 and Figure 4.3. Aside from that, Figures 4.4 and 4.5 depict the load-settlement behaviour of single bored pile in clayey soil using HS model for Very Fine and Fine mesh PLAXIS simulations. Figures 4.6 and 4.7 show the load-settlement behaviour of single bored pile in clayey soil utilizing SS model for Very Fine and Fine mesh PLAXIS modelling. It must be stressed that the all the PLAXIS simulated results for Figures 4.2, 4.3, 4.4, 4.5, 4.6 and 4.7 are compared to the measured and simulated ones from the findings of Wehnert and Vermeer (2004). The measured results of the pile load-settlement behaviour in the finding of Wehnert and Vermeer (2004) were used for benchmarking with the PLAXIS simulated results in this study through curve fittings. It must be noted that the measured total settlement of the single pile is 71 mm at a failure load of 3250 kN.

By comparing all the figures, it is observable that the load-settlement behaviour of the single bored pile in clayey soil for the PLAXIS simulation in Very Fine Mesh is best fit to the measured curve regardless of the type of the soil model. This is reasonable as the finer the mesh, the more finite element calculation is iterated so as to refine the prediction of load-settlement behaviour of the bored pile in clayey soil. In the modelling work to study the settlement and load transfer mechanism of a pile group adjacent to a deep excavation in soft clay, the soil mesh surrounding the pile was refined by Shakeel and Ng (2018) so as to yield the accurate simulated result of the pile load-settlement behaviour in the soil. Figure 4.8 shows a comparison among the load-settlement curves of single bored pile in clayey soil under the PLAXIS simulation for HS, SS and MC models of Very Fine mesh. It is seen from the figure that all the load-settlement curves for the pile under the soil models are closely gapped among each other, which imply consistency in the simulated pile load-settlement results of Very Fine Mesh regardless of the type of soil model applied.

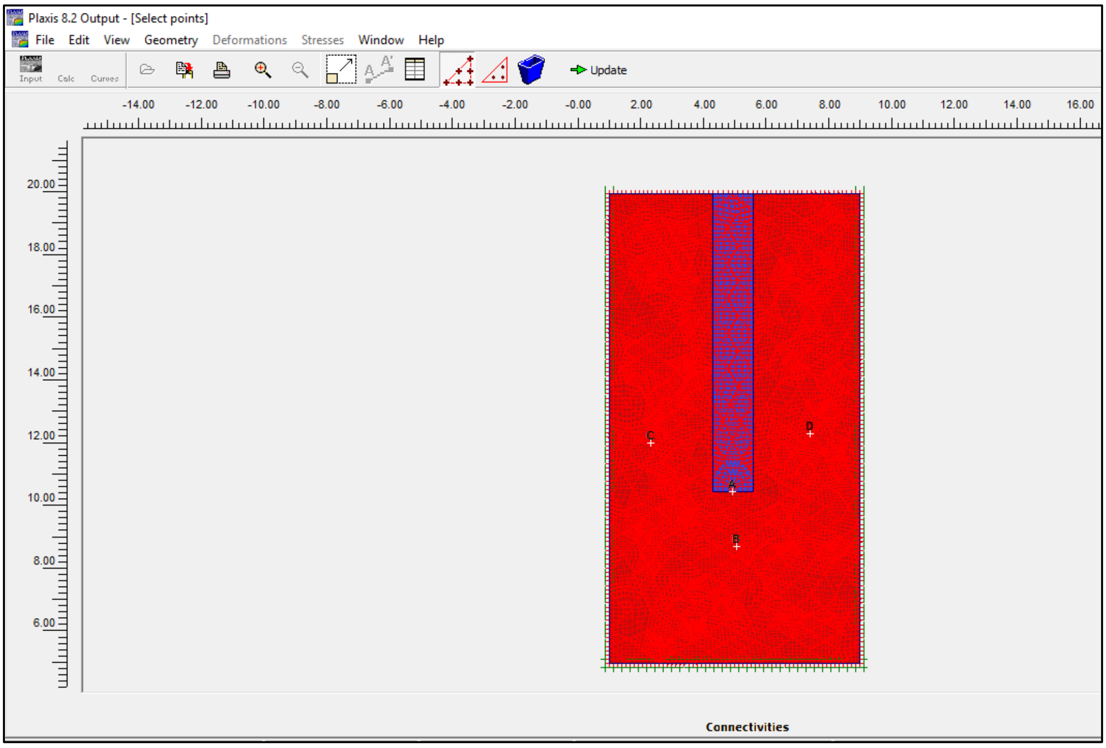


Figure 4.1. Selected tip point of the single bored pile in clayey soil under the PLAXIS simulation.

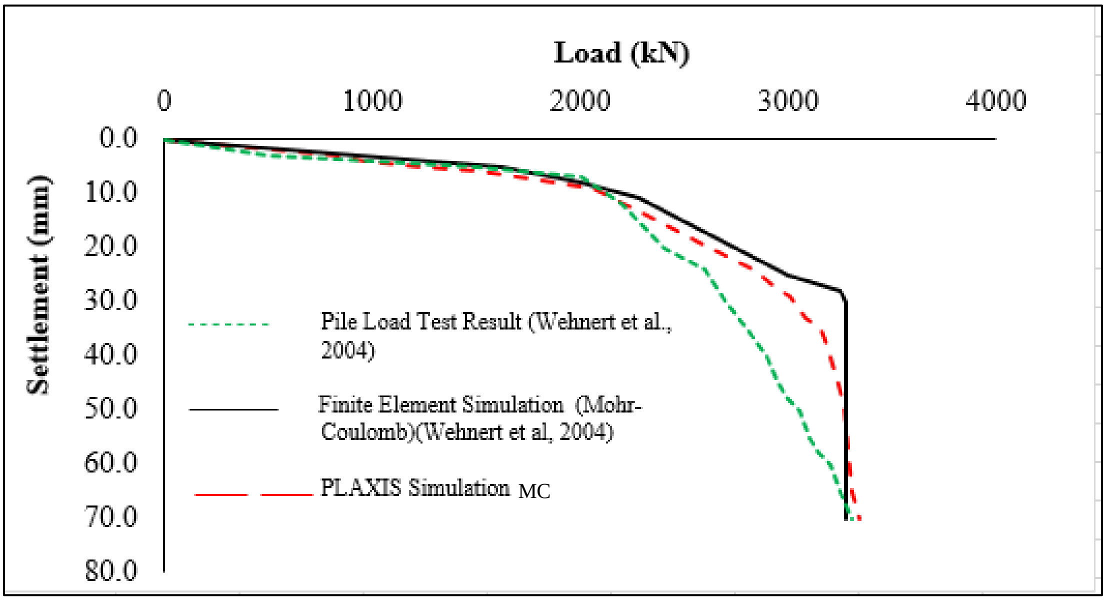


Figure 4.2. Load-settlement behaviour of single bored pile in clayey soil using MC model for Very Fine mesh PLAXIS simulation in comparison to the measured and simulated ones from Wehnert and Vermeer (2004).

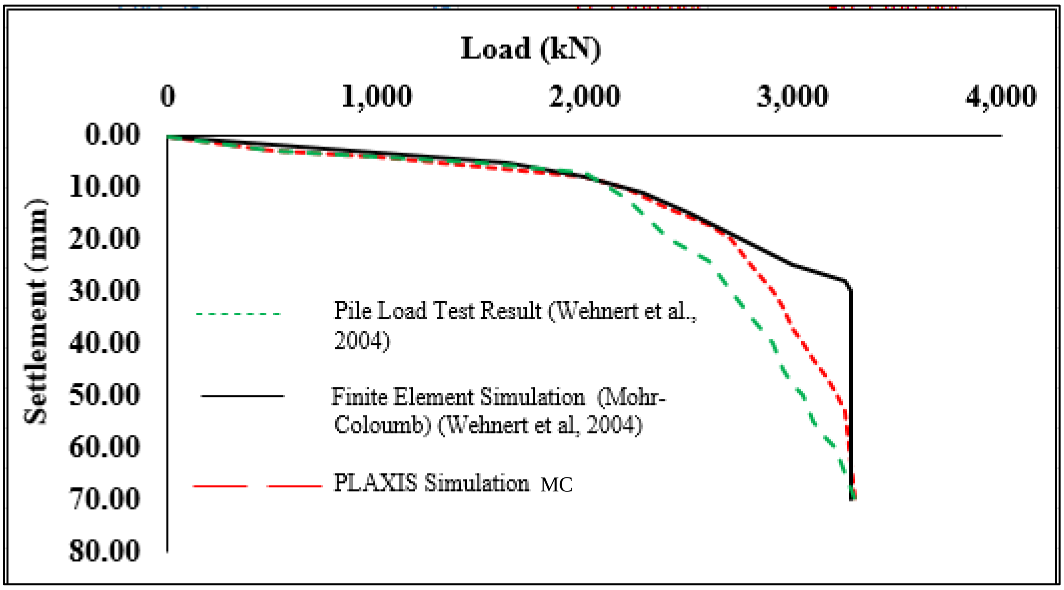


Figure 4.3. Load-settlement behaviour of single bored pile in clayey soil using MC model for Fine mesh PLAXIS simulation in comparison to the measured and simulated ones from Wehnert & Vermeer (2004).

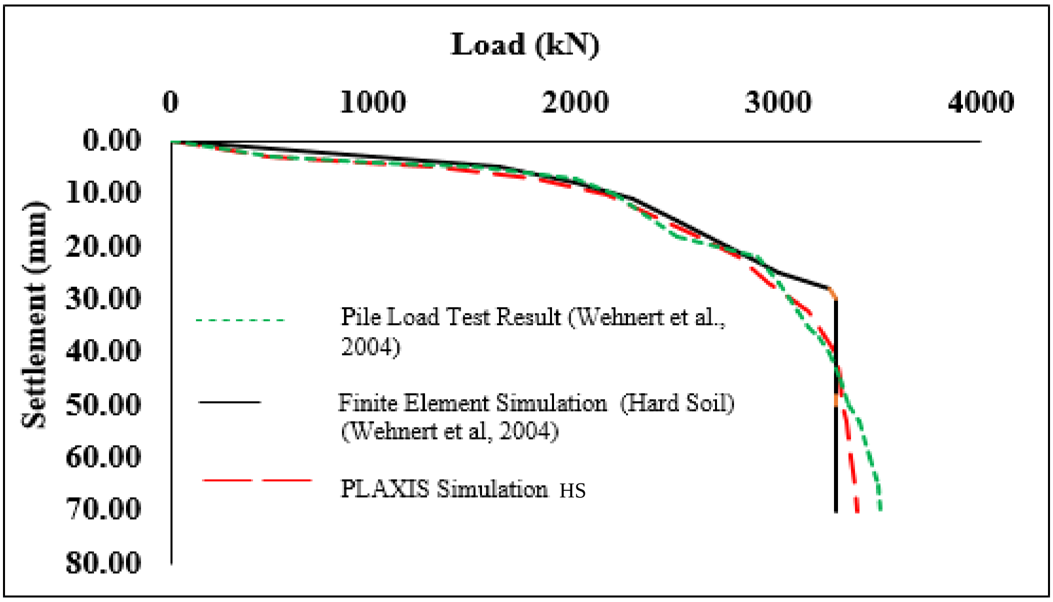


Figure 4.4. Load-settlement behaviour of single bored pile in clayey soil using HS model for Very Fine mesh PLAXIS simulation in comparison to the measured and simulated ones from Wehnert & Vermeer (2004).

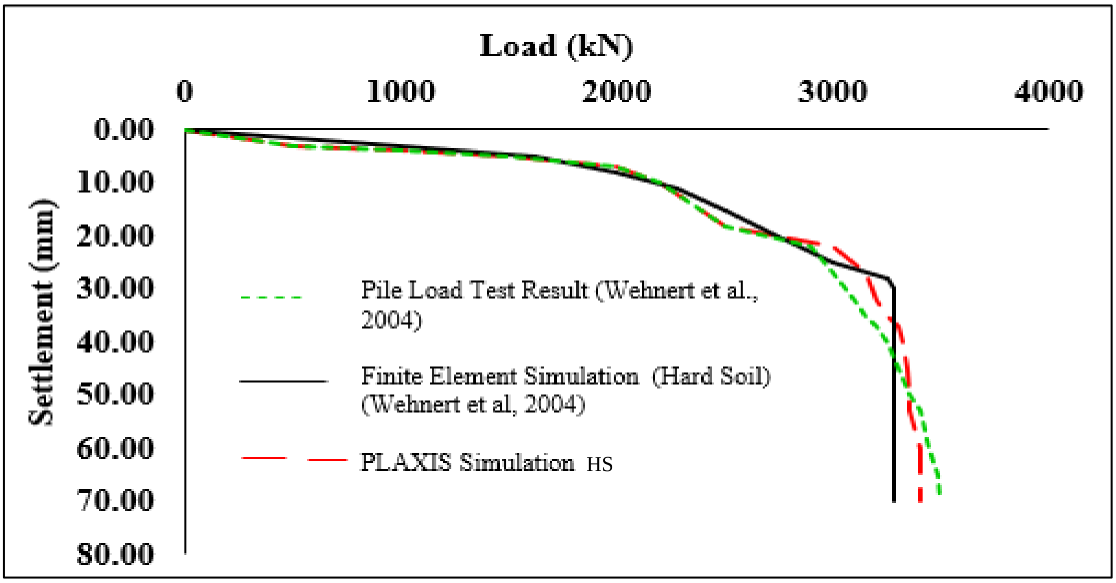


Figure 4.5. Load-settlement behaviour of single bored pile in clayey soil using HS model for Fine mesh PLAXIS simulation in comparison to the measured and simulated ones from Wehnert & Vermeer (2004).

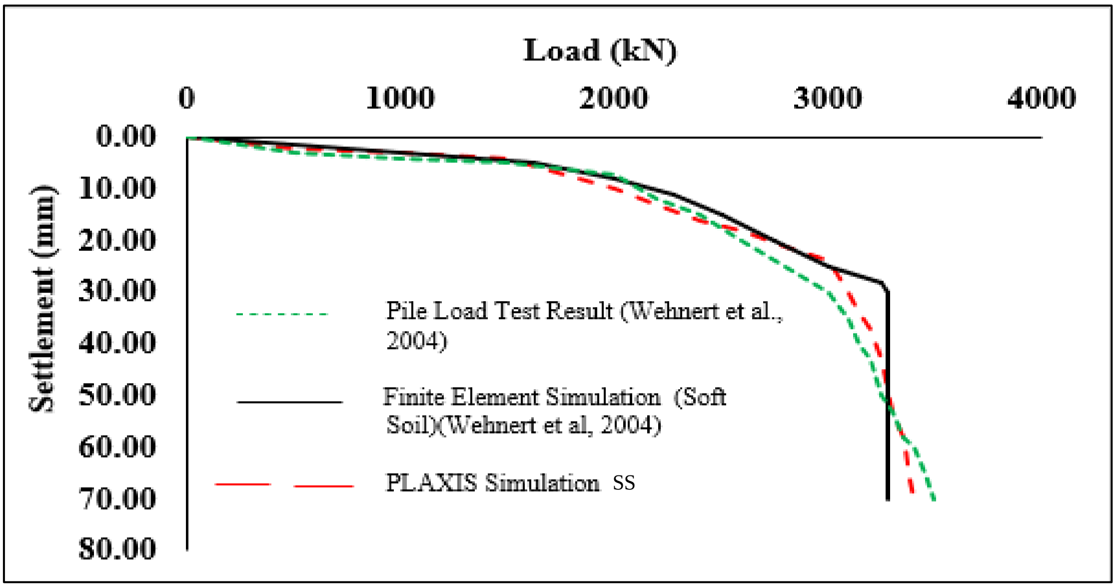


Figure 4.6. Load-settlement behaviour of single bored pile in clayey soil using SS model for Very Fine mesh PLAXIS simulation in comparison to the measured and simulated ones from Wehnert & Vermeer (2004).

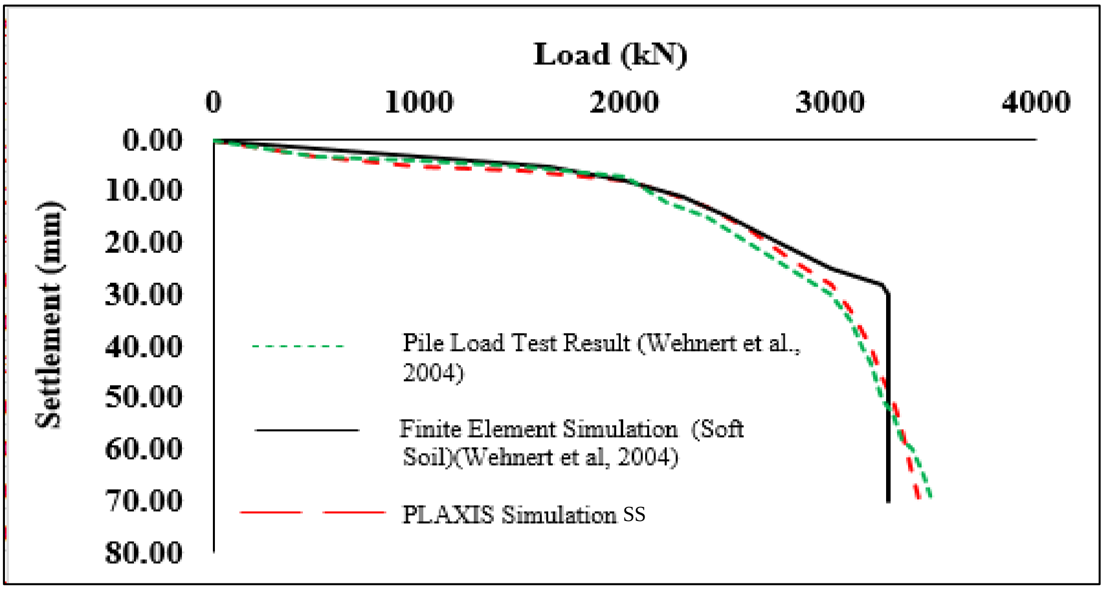


Figure 4.7. Load-settlement behaviour of single bored pile in clayey soil using SS model for Fine mesh PLAXIS simulation in comparison to the measured and simulated ones from Wehnert & Vermeer (2004).

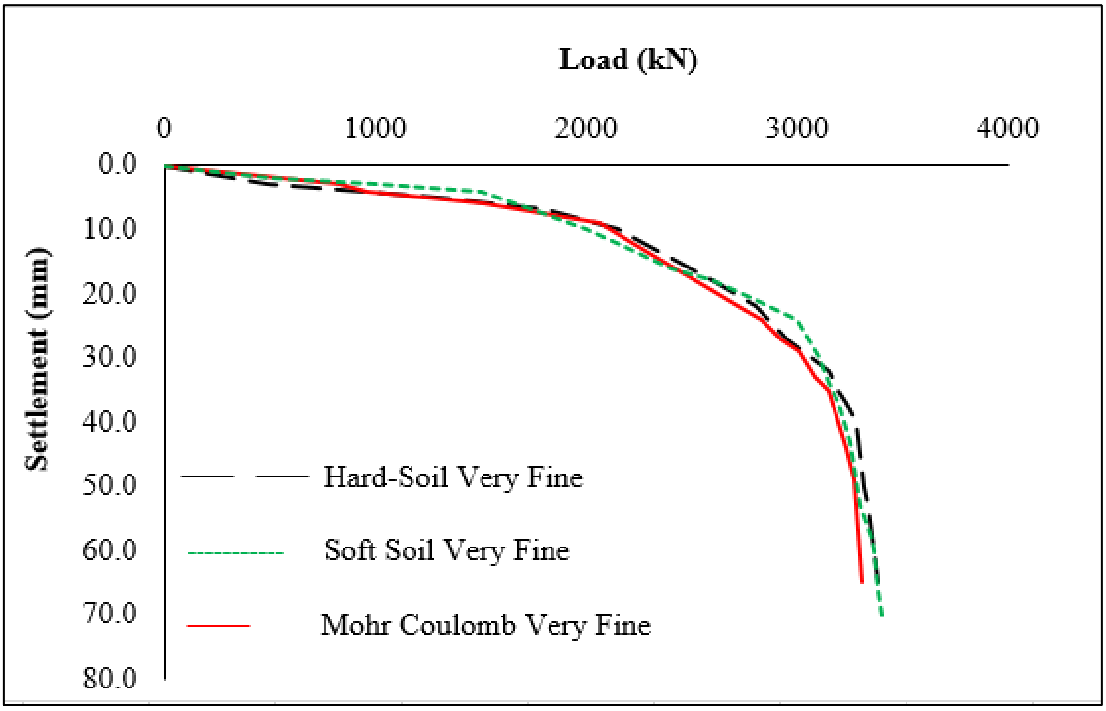


Figure 4.8. Comparison among the load-settlement curves of single bored pile in clayey soil under the PLAXIS simulation for MC, HS and SS models of Very Fine mesh.

Coefficient of determination (R^2) is used as the parameter to measure the degree of closeness of the PLAXIS simulated result with the measured one. At the respective total settlement of the single bored pile in clayey soil, the corresponding simulated load result was plotted against the measured one in order to determine the value of R^2. The R^2 values for the single bored pile simulated with various soil models in very fine mesh were compared and analyzed with those of the measured ones. This is necessary in order to justify the accuracy of the PLAXIS simulated results in comparison to those of Wehnert and Vermeer (2004).

Figures 4.9 and Figure 4.10 compare the R^2 values for the simulated load versus measured load for the single bored pile in clayey soil using Mohr-Coulomb model in Very Fine mesh by Wehnert and Vermeer (2004) and the PLAXIS simulation respectively. In Figures 4.11 and Figure 4.12, the R^2 value for the simulated load versus measured load for the single bored pile in clayey soil using Hard Soil model in Very Fine mesh by Wehnert and Vermeer (2004) was compared to that modelled using the PLAXIS software. Figures 4.13 and Figure 4.14 show the evidence of R^2 values for the simulated load versus measured load for the single bored pile in clayey soil using Soft Soil model in Very Fine mesh by Wehnert and Vermeer (2004) and the PLAXIS simulation. A summary of the R^2 values for the single bored pile in clayey soil simulations of all the soil models is given in Table 4.1.

It is seen in Table 4.1 that the R^2 value for the PLAXIS simulated load versus the measured load on the single bored pile in clayey soil using Mohr-Coulomb model in Very Fine mesh is 0.9840 which is the highest among all the soil models evaluated. The value of R^2 is also 0.0462 higher when compared to that simulated by Wehnert and Vermeer (2004). This is attributable to the well-clustered result of the simulated load-measured load relationship for the pile in Mohr-Coulomb model in Very Fine mesh as shown in Figure 4.10. Although the R^2 values of the single bored pile for the HS and SS models are lower than that of the MC model, the results are satisfactory considering the fact that all the R^2 values are greater than 0.9. This verifies the fact that it is most accurate to perform PLAXIS simulation on the bored pile in clayey soil using MC model in Very Fine mesh. For that reason, the soil model in Very Fine mesh are applied for parametric study on loading of group bored piles in clayey soil. The numerical results proved that the combination of mesh fineness and the type of soil model played a crucial role in providing accurate prediction of the load-settlement relationship of the single pile in the clayey soil. The application of Very Fine mesh in the finite element analysis allowed for more discrete finite elements to be evaluated in the PLAXIS software. Such fact, when combined with the utilization MC model provide the most accurate prediction to the load-settlement behaviour of the single pile in the soil since the Mohr-Coulomb failure criteria, which consider the parameters such as shear stress on the failure plane, cohesion, normal stress on the failure plane, angle of internal friction and pore water pressure fit well in clay modelling.

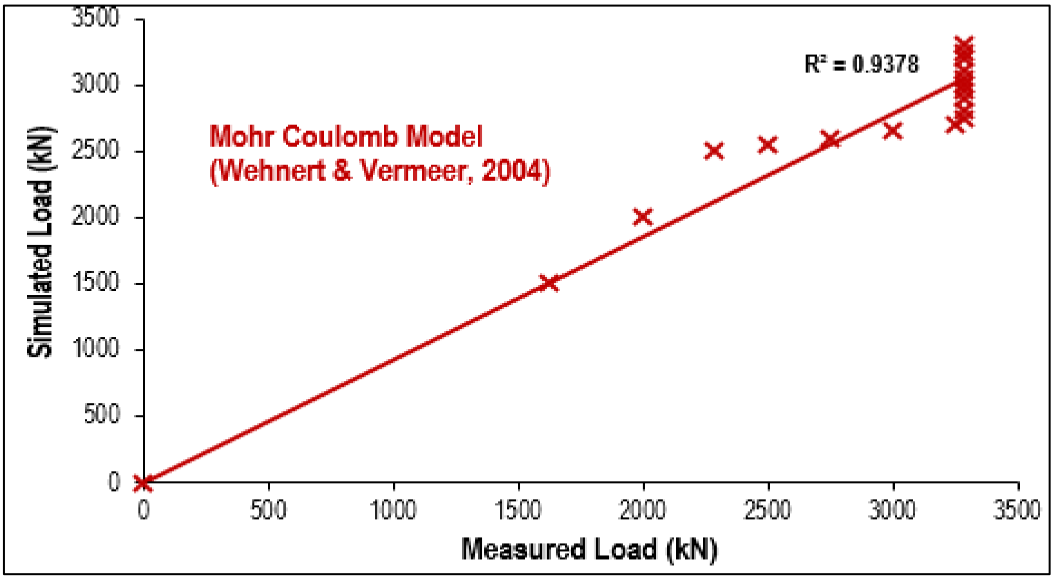


Figure 4.9. The result of R^2 for the simulated load versus measured load for the single bored pile in clayey soil using Mohr-Coulomb model in Very Fine mesh by Wehnert and Vermeer (2004).

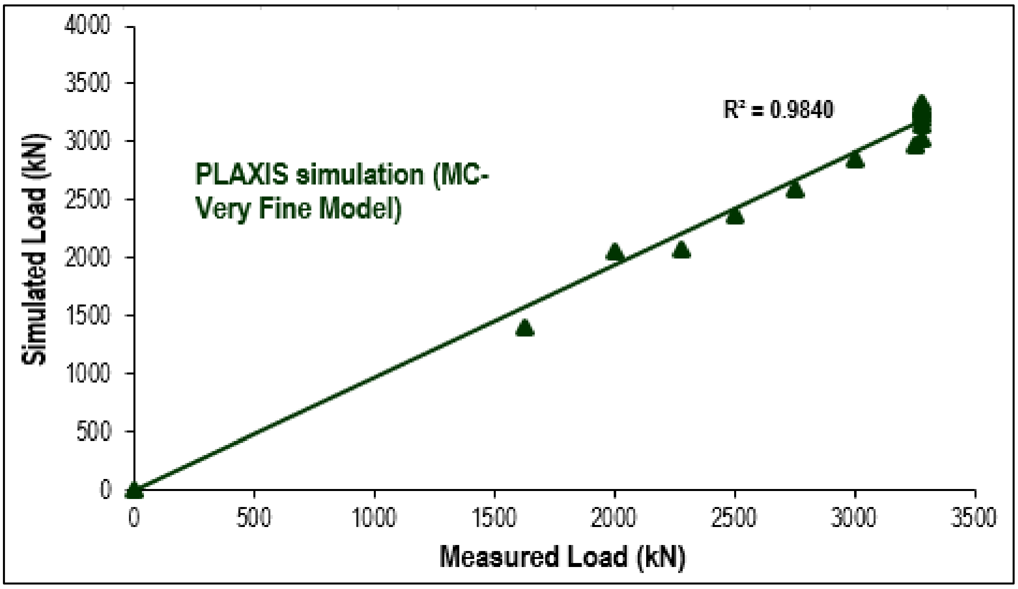


Figure 4.10. The result of R^2 for the simulated load versus measured load for the single bored pile in clayey soil using Mohr-Coulomb model in Very Fine mesh by the PLAXIS simulation.

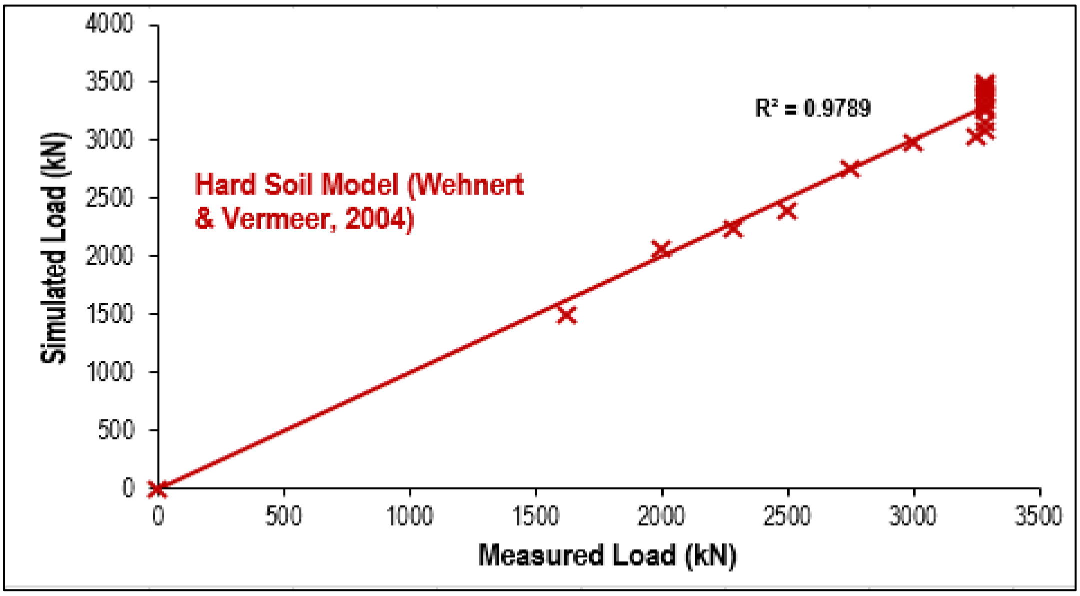


Figure 4.11. The result of R^2 for the simulated load versus measured load for the single bored pile in clayey soil using Hard Soil model in Very Fine mesh by Wehnert and Vermeer (2004).

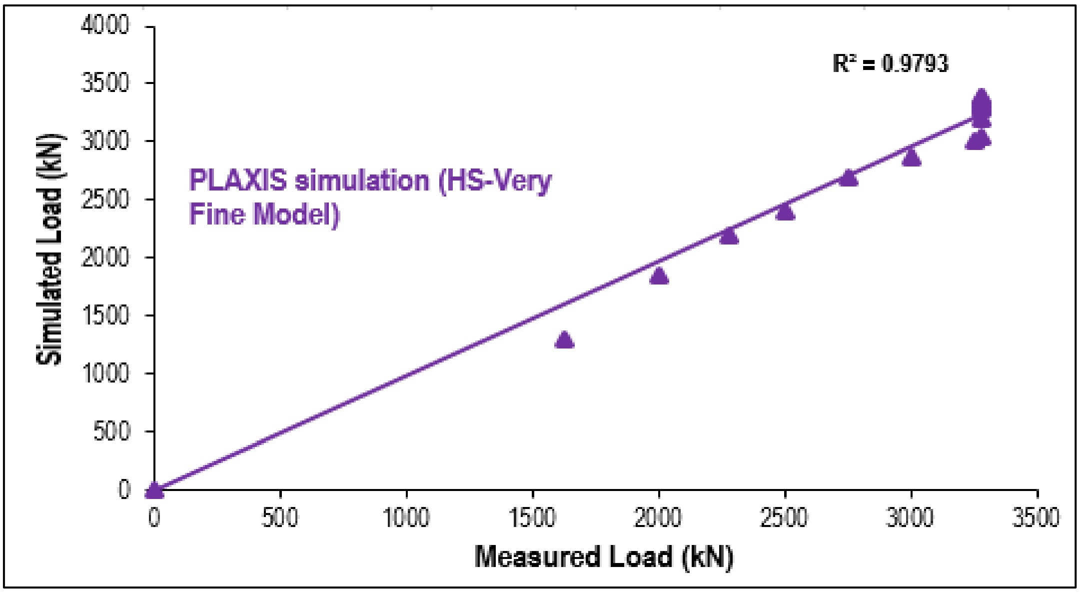


Figure 4.12. The result of R^2 for the simulated load versus measured load for the single bored pile in clayey soil using Hard Soil model in Very Fine mesh by the PLAXIS simulation.

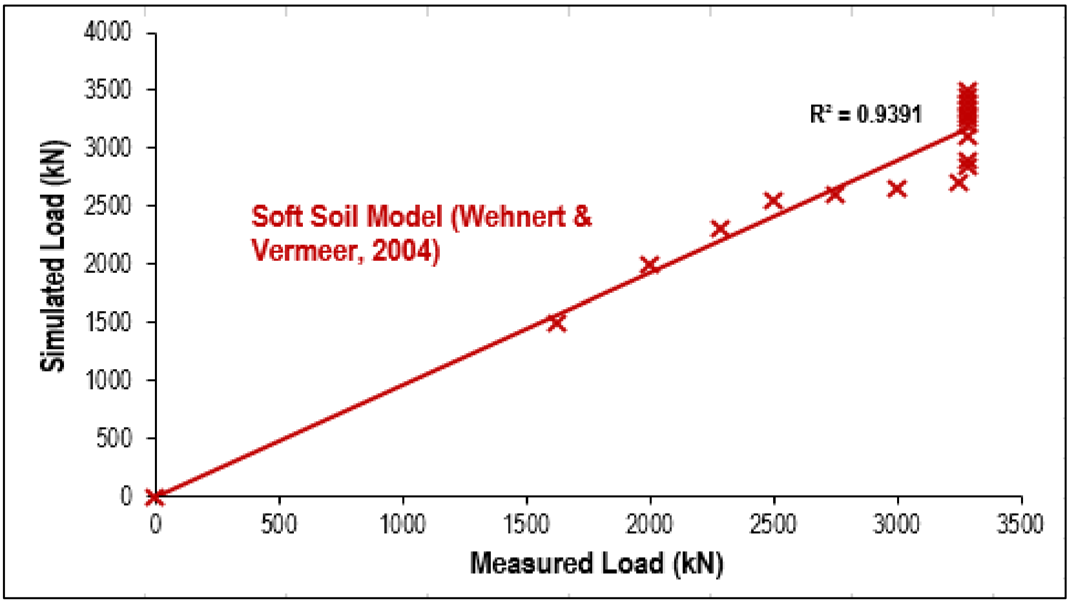


Figure 4.13. The result of R^2 for the simulated load versus measured load for the single bored pile in clayey soil using Soft Soil model in Very Fine mesh by Wehnert and Vermeer (2004).

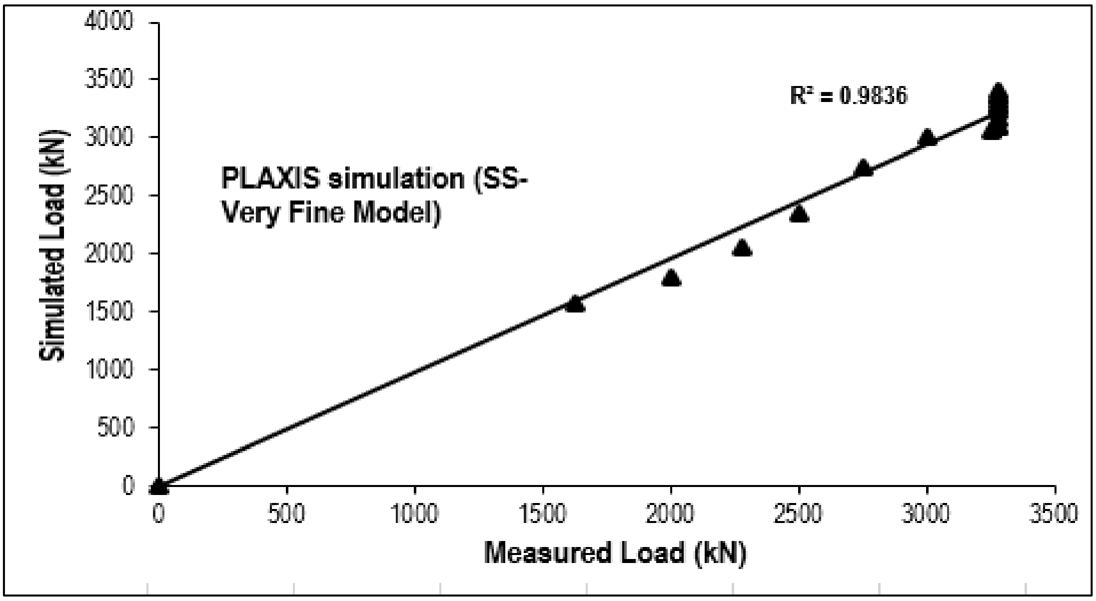


Figure 4.14. The result of R^2 for the simulated load versus measured load for the single bored pile in clayey soil using Soft Soil model in Very Fine mesh by the PLAXIS simulation.

Table 4.1. Summary of R^2 values for the simulated load versus measured load under various soil models in Very Fine mesh for the single bored pile in clayey soil based on the results from Wehnert and Vermeer (2004) and the PLAXIS simulation.

Simulation type		Coefficient of Determination, R^2		
		Soil Model		
		MC	HS	SS
Pile load test	Wehnert & Vermeer (2004)	0.9378	0.9789	0.9391
	PLAXIS simulation	0.9840	0.9793	0.9836

4.3 Parametric study of group bored piles in clayey soil

Based on the MC soil model in Very Fine Mesh, a set of parametric study was done in order to evaluate the settlement performance of the group bored piles in clayey soil for the purpose of optimizing the pile parametric design. The effects of pile pressure, diameter, spacing and slope were taken into account for the pile parametric design. To evaluate the effect of pile parametric design on various conditions of the clayey soil on the total settlement, the cohesion (c) and angle of internal friction (ϕ) were varied with the material parameters of the group bored piles in the PLAXIS simulation. According to Braja (2016), the allowable consolidation settlement for foundation is 25 mm. It must be highlighted details in the variations of the bored piles and soil parameters are discussed in Chapter 3. The tip point of the middle bored pile in the group was chosen as the focus of settlement evaluation because the centric load of the group bored is the greatest when they are subjected to uniformly distributed load in the clayey soil.

4.3.1 Effect of pile pressure

Applied pressure plays a very important role at influencing the settlement behaviour of group bored piles in clayey soil. Pressure of 50, 100, 200, 400 and 800 kPa were applied on the group bored piles and the settlements of the mid pile tip point at full dissipation of excess pore water pressure in the clayey soil under the PLAXIS simulation were evaluated. It is important to note that primary consolidation due to the loading and bored piles ended at the full dissipation of excess pore water pressure from the soil. Figure 4.15 shows a typical graphical illustration on the determination of the simulated consolidation settlement of the bored pile in the soil based on dissipation of excess pore water pressure under the applied pressure of 50 kPa. The data of pore water pressure distribution over the consolidation settlement of the group bored piles in the clayey soil for the consolidation pressures of 50, 100, 200, 400 and 800 kPa are shown in the Appendix. Figure 4.16 shows the graph of applied pressure at 50 kPa when it reaches a settlement of 24.5 mm by 1.89 days. Figure 4.17 shows the relationship between consolidation settlement of the mid pile tip point and the applied load on the group bored piles in the soil under the PLAXIS simulation. Figure 4.18 shows the relationship between time and applied pressure for the mid pile tip point of the group bored piles in the clay soil under the PLAXIS simulation. It is noticed from the figure that the higher the applied pressure on the bored piles, the greater is the consolidation settlement of the mid bored pile. It is realized that only the consolidation settlement of the mid bored pile under an applied pressure of 50 kPa is below the tolerable limit of 25 mm. This implies that a maximum applied pressure of 50 kPa can be applied on the group bored piles so as to ensure that the consolidation settlement is within the tolerable range. As such, an applied pressure of 50 kPa is chosen for the parametric study on the effects pile diameter, spacing and slope as well as cohesion and angle of internal friction of the clay.

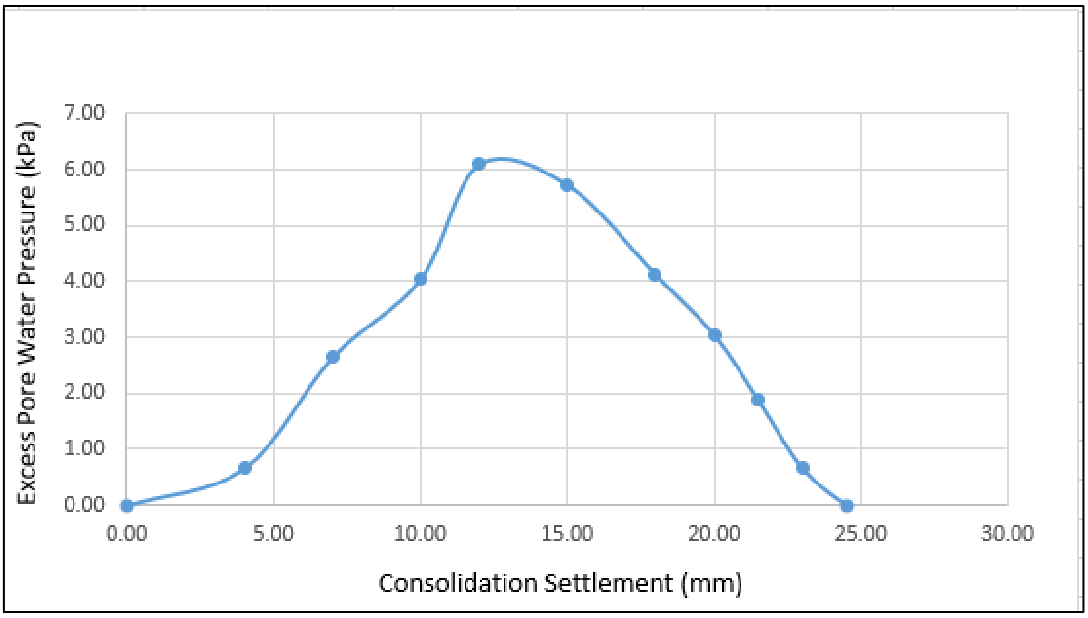


Figure 4.15. The relationship between excess pore water pressure and consolidation settlement for the mid pile tip point of the group bored piles subjected to 50 kPa applied pressure in the clayey soil under the PLAXIS simulation.

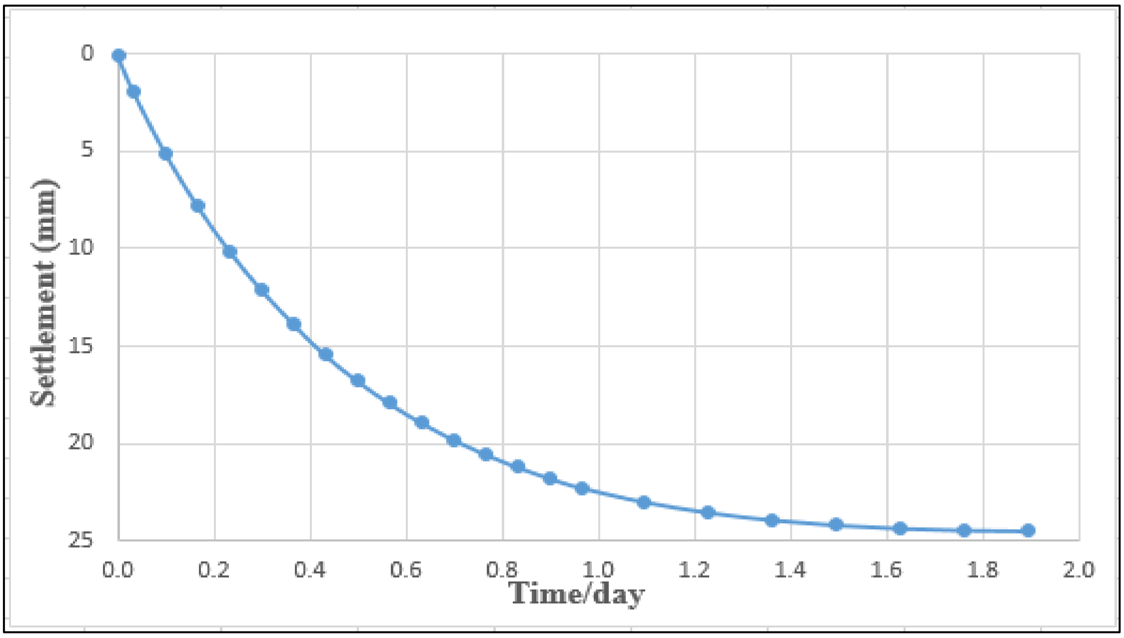


Figure 4.16. The relationship between settlement and time for the mid pile tip point of the group bored piles subjected to 50 kPa applied pressure in the clayey soil under the PLAXIS simulation.

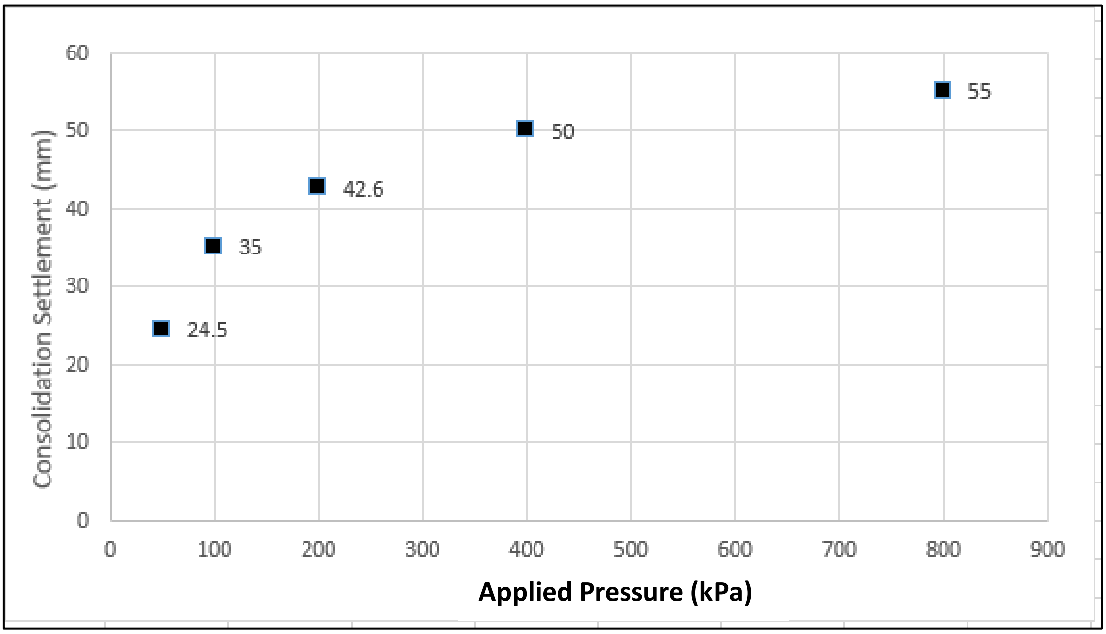


Figure 4.17. The relationship between consolidation settlement and applied pressure for the mid pile tip point of the group bored piles after the dissipation of excess pore water pressure in the clayey soil under the PLAXIS simulation.

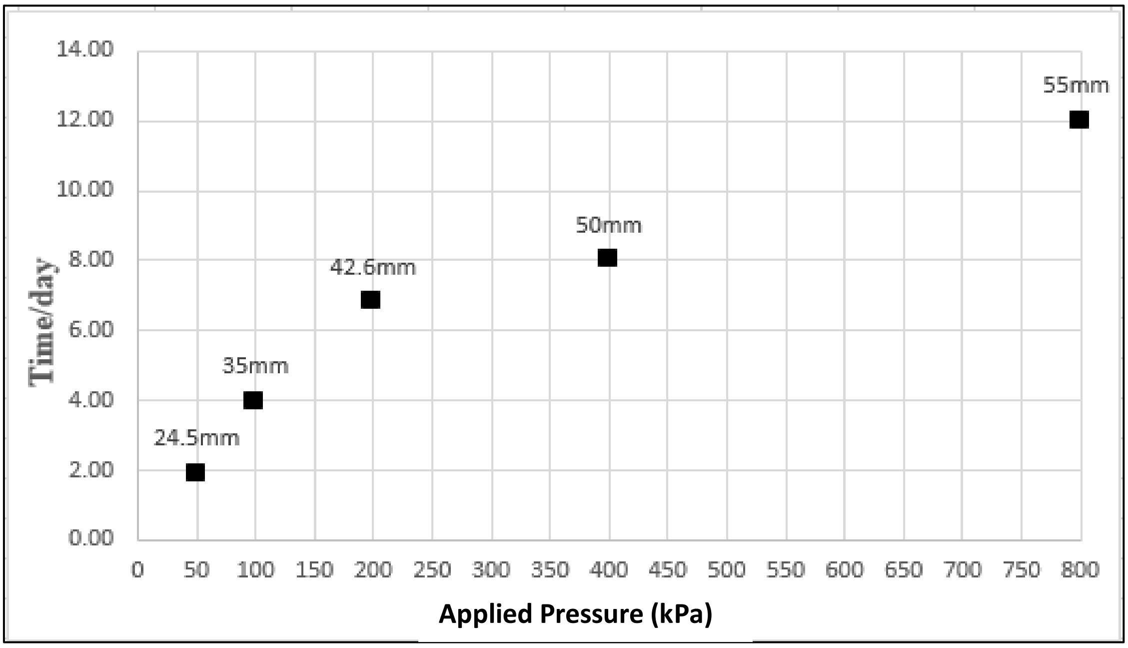


Figure 4.18. The relationship between time and applied pressure for the mid pile tip point of the group bored piles in the clayey soil under the PLAXIS simulation.

4.3.2 Effect of pile diameter

Basically, the larger the bored pile diameter, the lesser is the consolidation settlement of the group bored piles in the clayey soil. However, for economic reason, the bored pile diameter needs to be optimized. Figure 4.19 illustrates typical graphical plot to show the relationship between pore water pressure and consolidation settlement for the mid pile tip point of the group bored piles subjected to 50 kPa applied pressure and pile diameter of 1.3 m in the clayey soil under the PLAXIS simulation. At the end of the primary consolidation it was discovered that the consolidation settlement of the pile is 24.9 mm which below 25 mm tolerable limit of consolidation settlement. Figure 4.20 shows the graph of pile diameter of 1.3m when it reaches the settlement of 24.9mm by 80 days. Figure 4.21 indicates the relationship between consolidation settlement of the mid pile tip point and pile diameter in the clayey soil under the PLAXIS simulation. It is shown in the figure that the greater the pile diameter, the lesser is the consolidation settlement of the mid pile. Figure 4.22 shows the relationship between time and pile diameter for the mid pile tip point of group bored piles in the clay soil under PLAXIS simulation. At a pile diameter of 1.3 m, a consolidation settlement of below 25 mm was achieved for the mid pile tip point in the clayey soil. As such, pile diameter of 1.3 m was selected for the further study on the group bored piles in clayey soil with respect to the effects of pile spacing and slope.

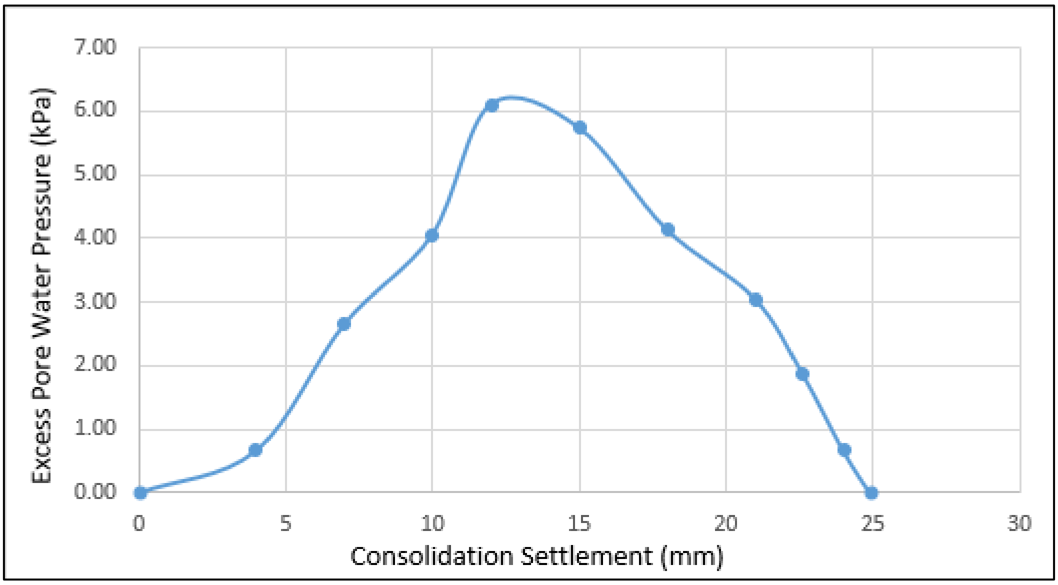


Figure 4.19. The relationship between excess pore water pressure and consolidation settlement for the mid pile tip point of the group bored piles subjected to 50 kPa applied pressure and pile diameter of 1.3 m in the clayey soil under the PLAXIS simulation.

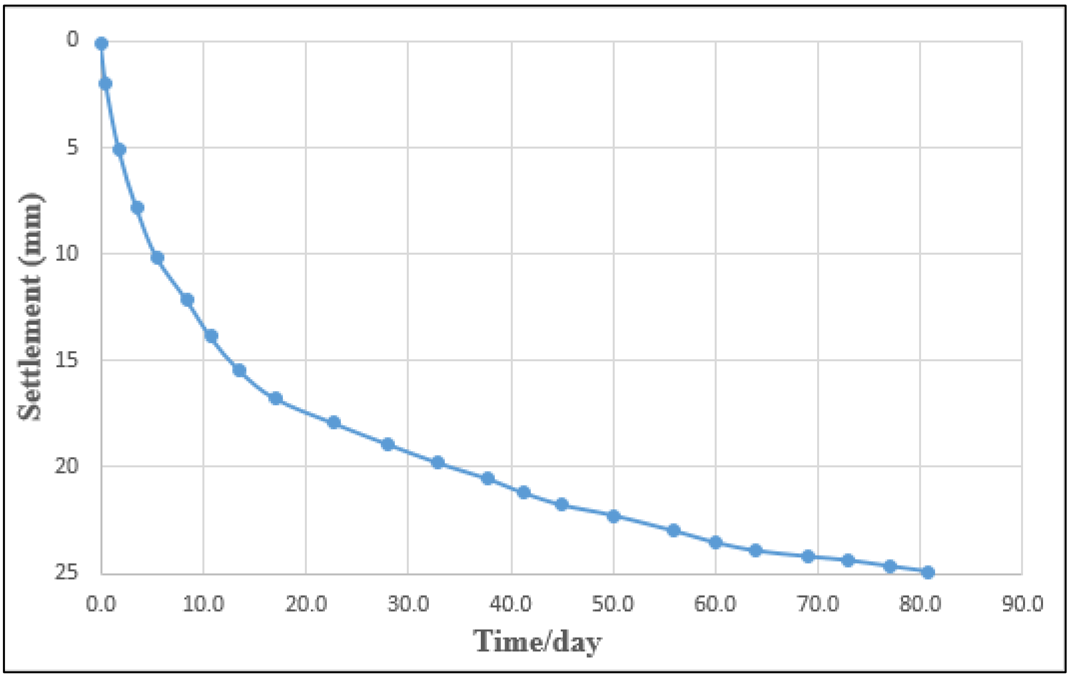


Figure 4.20. The relationship between settlement and time for the mid pile tip point of the group bored piles subjected to pile diameter of 1.3 m in the clayey soil under the PLAXIS simulation.

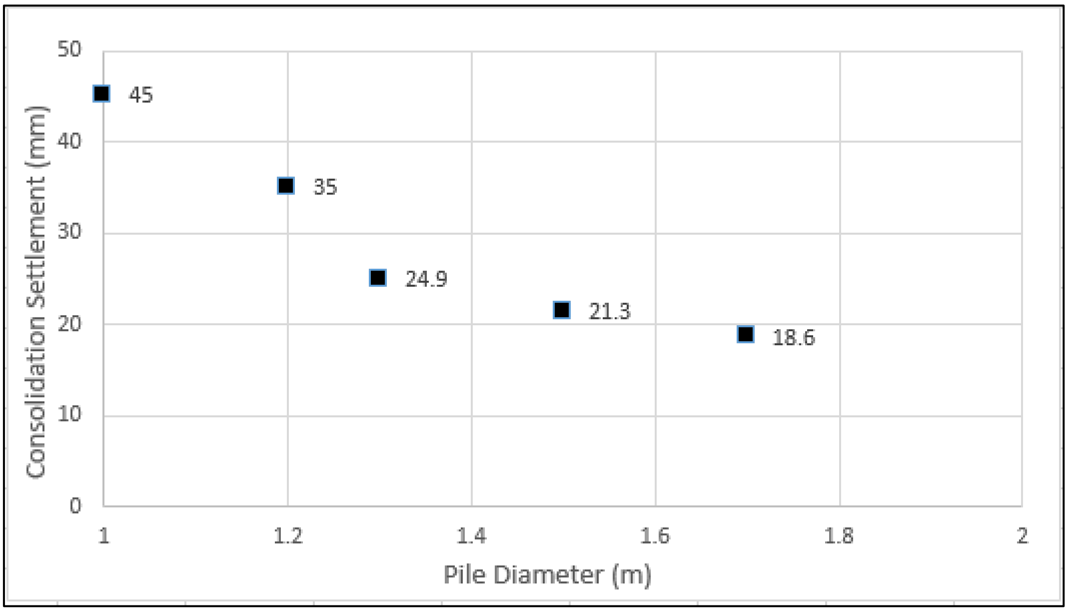


Figure 4.21. The relationship between consolidation settlement for the mid pile tip point of the group bored piles and pile diameter in the clayey soil under the PLAXIS simulation.

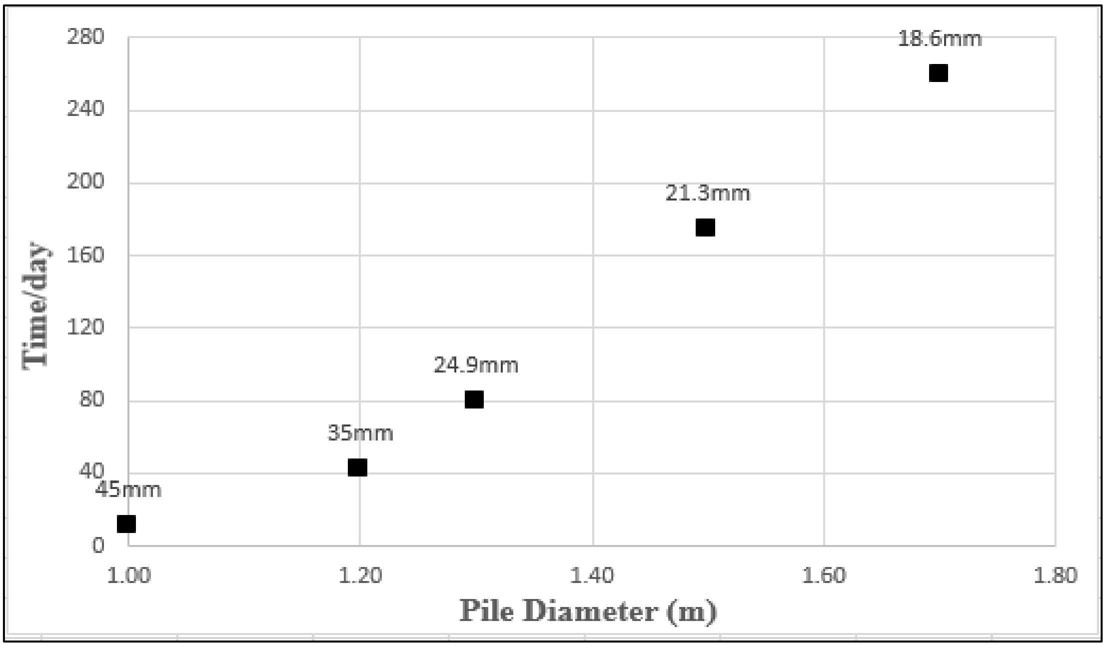


Figure 4.22. The relationship between time and pile diameter for the mid pile tip point of the group bored piles in the clayey soil under the PLAXIS simulation.

4.3.3 Effect of pile spacing

Aside from pile applied pressure and diameter, pile spacing is an important aspect of parametric study for optimization of the group bored piles numerical design in the clayey soil. For the parametric study, spacing of the bored piles was varied in 2D, 3D and 4D with D is referred as the diameter of the bored pile which is 1.3 m. Figure 4.23 shows a typical relationship between pore water pressure and consolidation settlement for the mid pile tip point of the group bored piles subjected to 50 kPa applied pressure, pile diameter of 1.3 m and pile spacing of 3D in the clayey soil under the PLAXIS simulation. Under such condition, the consolidation settlement for the pile was found to be 25 mm which is still within the tolerable consolidation settlement for the bored piles. Figure 4.24 shows the graph of pile spacing 3D when it reaches settlement of 25mm by 19.8 days. Figure 4.25 depicts the relationship between consolidation settlement for the mid pile tip point of the group bored piles and pile spacing PLAXIS simulation. Basically, the large the pile spacing, the greater is the consolidation settlement of the group bored piles in the clayey soil. This is logical as large pile space tends to reduce the foundation support by creating wider gaps among the group bored piles in the soil. Thus, pile spacing of 5D could not produce the settlement since the spacing are wider. Figure 4.26 show the relationship between time and pile spacing for the mid pile tip point of group bored piles in the clay soil under the PLAXIS simulation. Based on the results in Figure 4.25, the acceptable pile spacing for the group bored piles is 3D since the consolidation settlement at that point is within the tolerable limit.

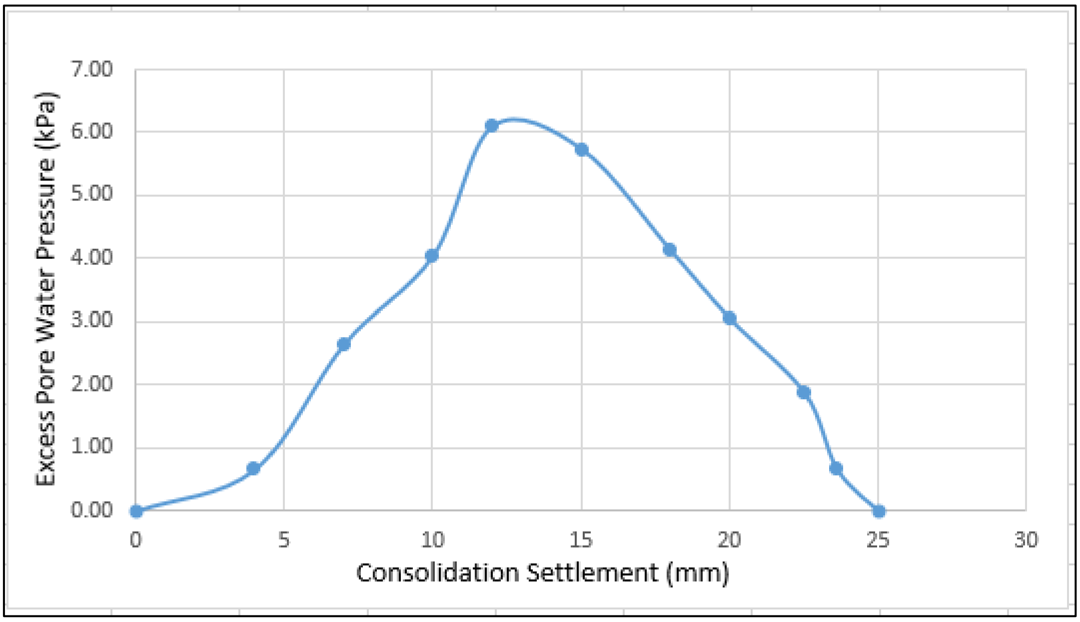


Figure 4.23. The relationship between excess pore water pressure and consolidation settlement for the mid pile tip point of the group bored piles subjected to 50 kPa applied pressure, pile diameter of 1.3 m and pile spacing of 3D in the clayey soil under the PLAXIS simulation.

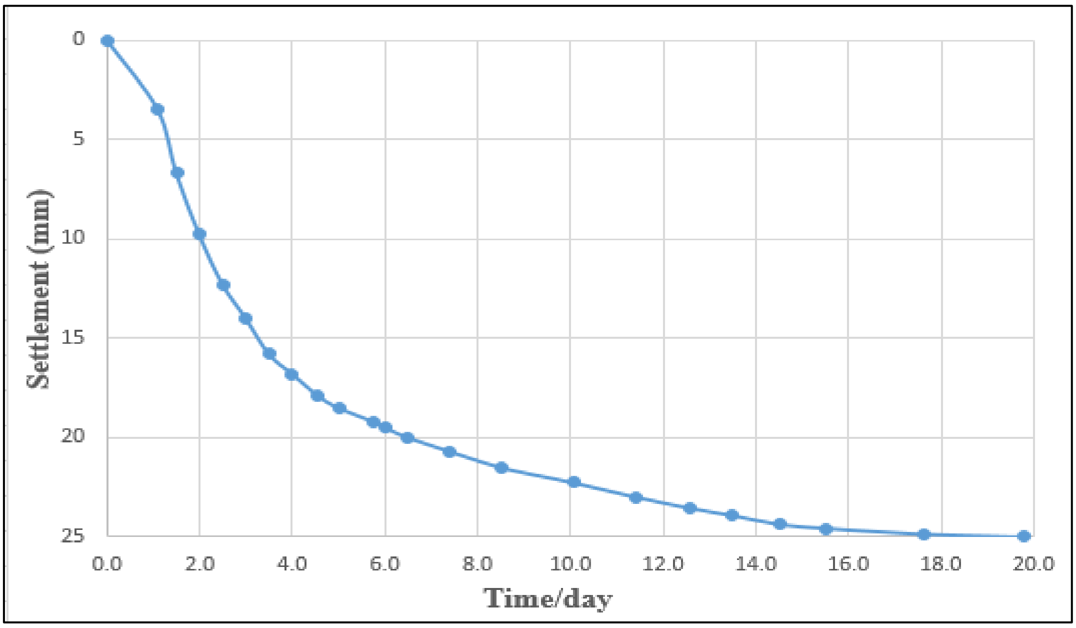


Figure 4.24. The relationship between settlement and time for the mid pile tip point of the group bored piles subjected to pile spacing of 3D in the clayey soil under the PLAXIS simulation.

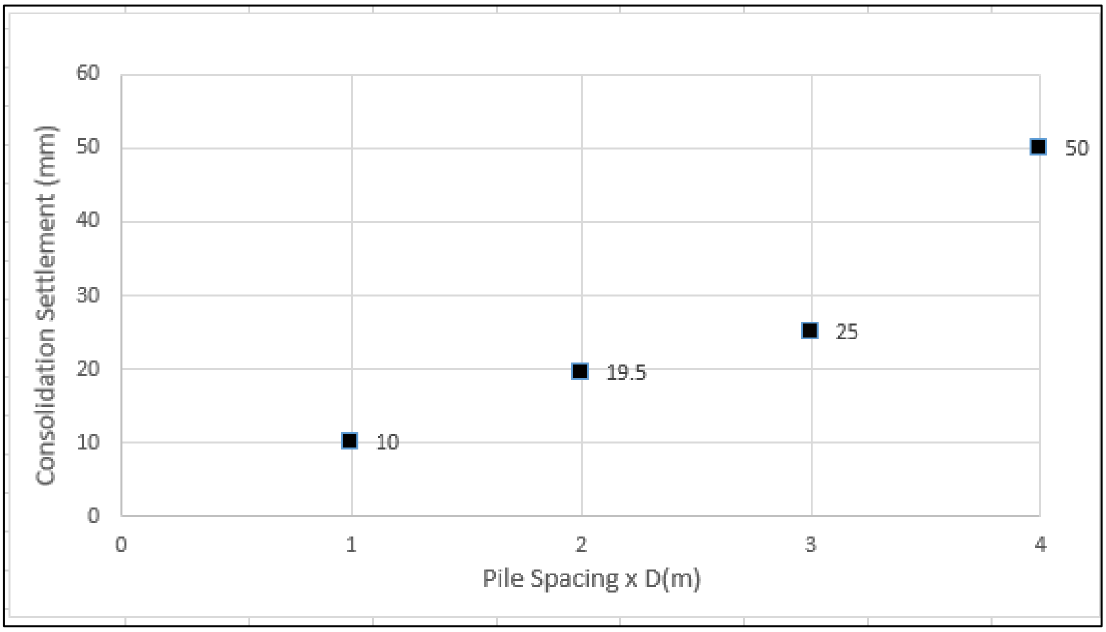


Figure 4.25. The relationship between consolidation settlement for the mid pile tip point of the group bored piles and pile spacing in the clayey soil under the PLAXIS simulation.

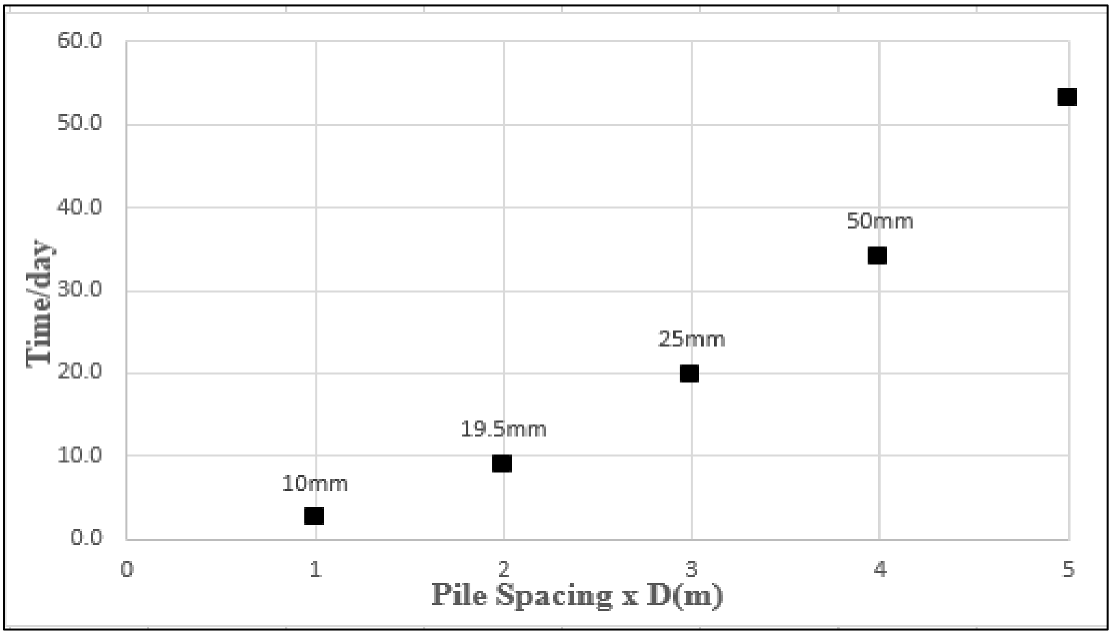


Figure 4.26. The relationship between time and pile spacing for the mid pile tip point of the group bored piles in the clayey soil under the PLAXIS simulation.

4.3.4 Effect of pile slope ratio

In order to optimize the materials required for the making of the bored piles, it is of great importance to evaluate the effect of pile slope ratio on the group bored piles in clayey soil under the PLAXIS simulation. Under the condition of 50 kPa applied pressure, 1.3 m pile diameter and 3D pile spacing, PLAXIS simulation was done on the group bored piles in the clayey soil with pile slope ratios that vary among 1:0.8, 1:2 and 1:4. Figure 4.27 indicates the group bored piles arrangement in the clayey soil with zero slope ratio. By comparison, Figure 4.28 shows the group bored piles' arrangement in the clayey soil with slope ratios of 1:0.8, 1:2, 1:4, 1:6 and 1:8. Figure 4.29 illustrates typical relationship between pore water pressure and consolidation settlement for the mid pile tip point of the group bored piles subjected to 50 kPa applied pressure, pile diameter of 1.3 m, pile spacing of 3D and pile slope ratio of 1:2 in the clayey soil under the PLAXIS simulation. Under the condition, consolidation settlement of the bored pile was discovered to be 24.8 mm which is still below the 25 mm allowable limit of consolidation settlement. Figure 4.30 shows the graph of pile slope ratio at 1:2 when it reaches settlement of 24.8mm by 4000 days.

In Figure 4.31, the relationship between consolidation settlement for the mid pile tip point of the group bored piles and pile spacing in the clayey soil under the PLAXIS simulation is shown. It is seen from the Figure 4.31 that the greater the pile slope ratio, the lesser is the consolidation settlement of the bored pile in the soil. With respect to pile slope, the optimal pile slope design is 1:2 as the consolidation settlement for the bored pile is 24.8 mm which is below the tolerable limit of the settlement. This implies that based on the optimized pile slope ratio in the numerical simulation, it is possible to shorten the length of the group bored piles without compromising with the allowable consolidation settlement of the piles of 25 mm. Figure 4.32 show the relationship between time and pile slope for the mid pile tip point of group bored piles in the clay soil under the PLAXIS simulation. Therefore, it can be ascertained from such finding that the optimal group bored piles' arrangement can be set at 50 kPa applied pressure, pile diameter of 1.3 m, pile spacing of 3D and pile slope ratio of 1:2 in the clayey soil under the PLAXIS simulation (Figure 4.33).

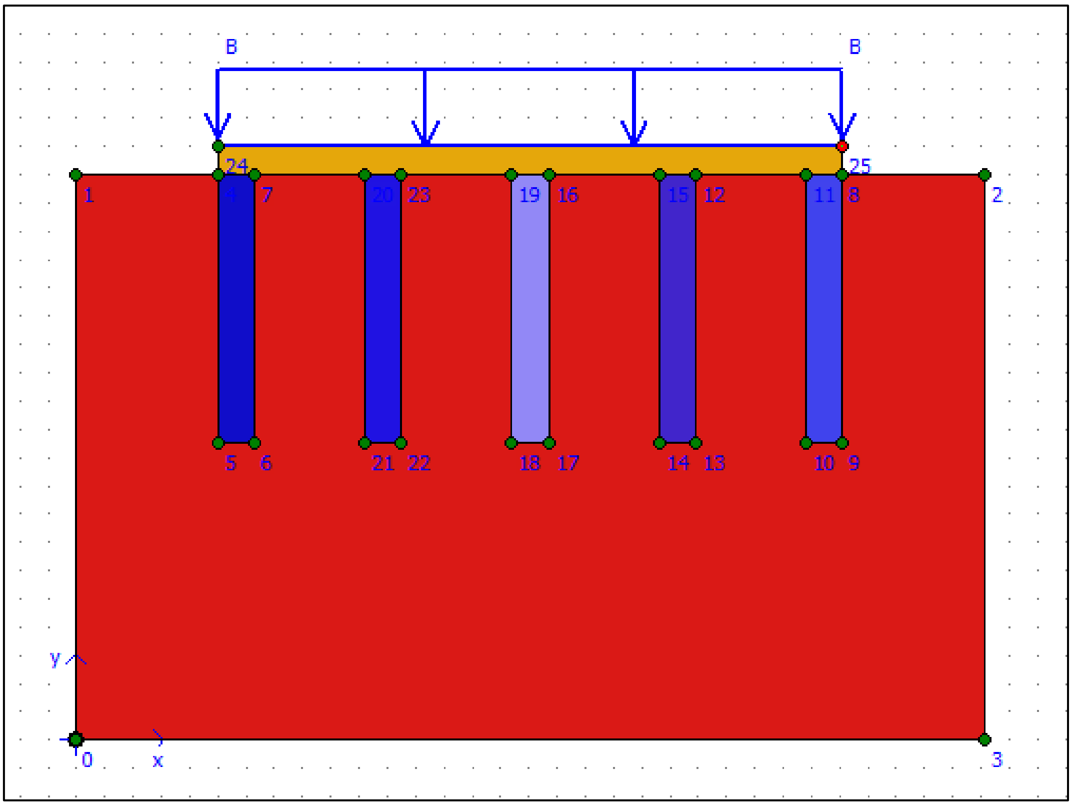
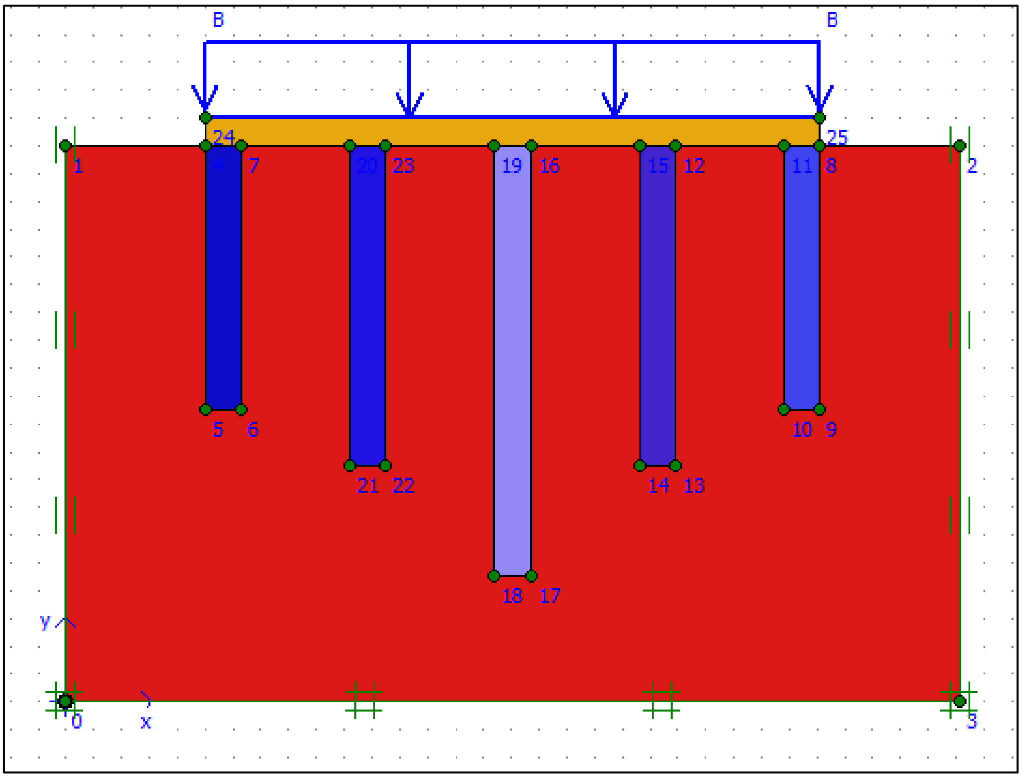
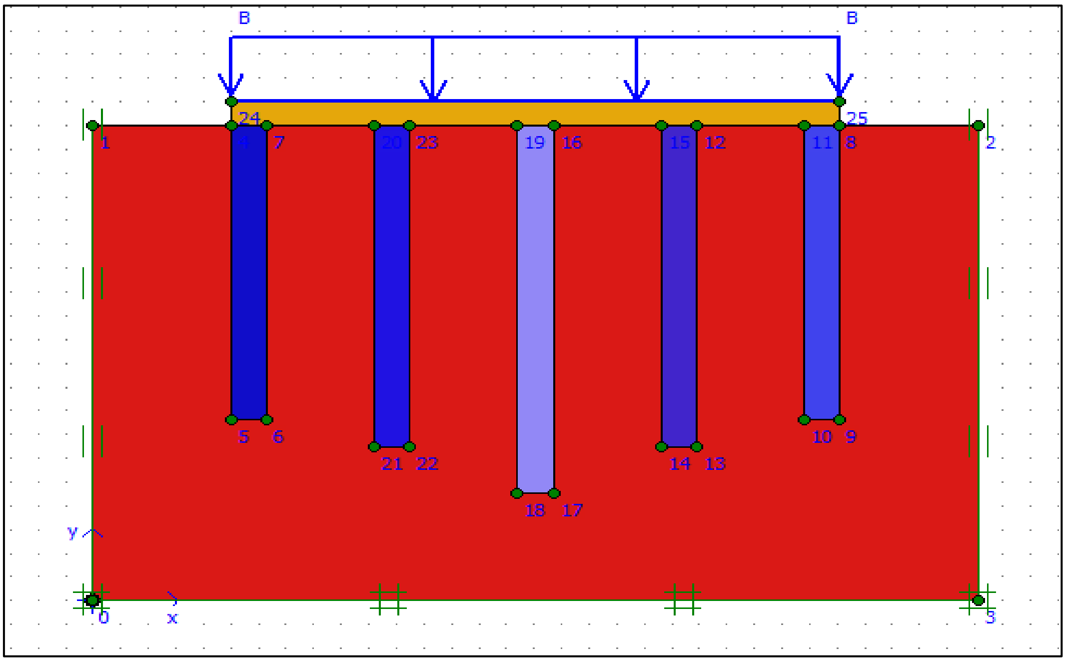


Figure 4.27. The group bored piles arrangement in the clayey soil with zero slope ratio.



(a)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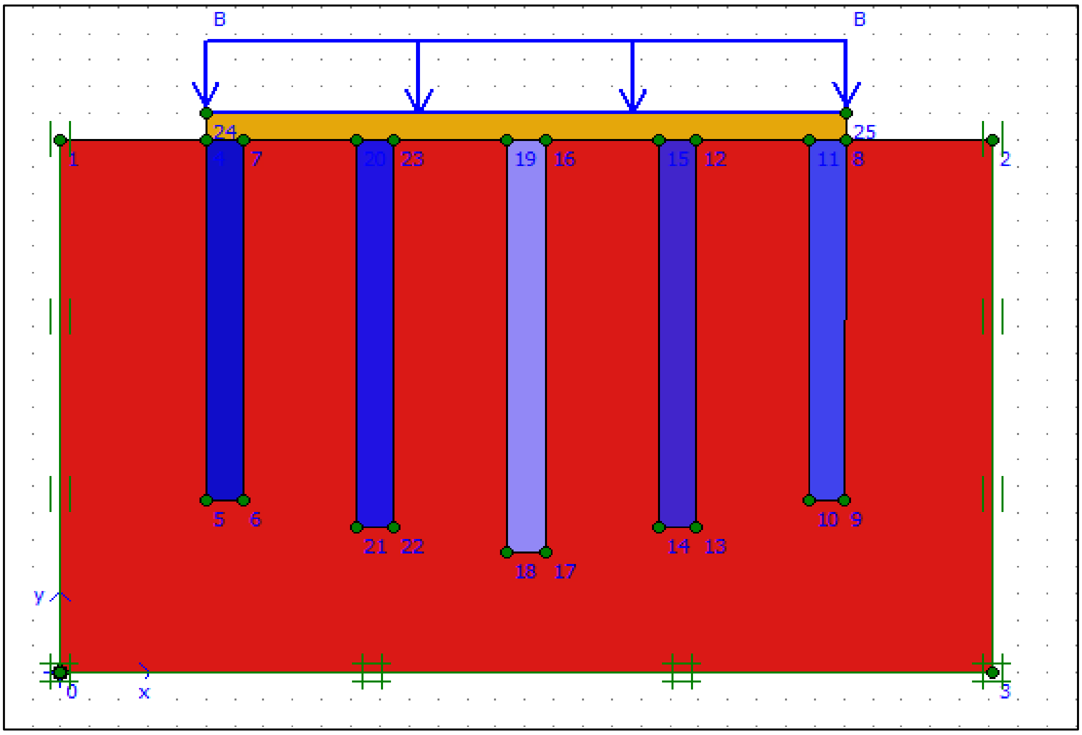
(b)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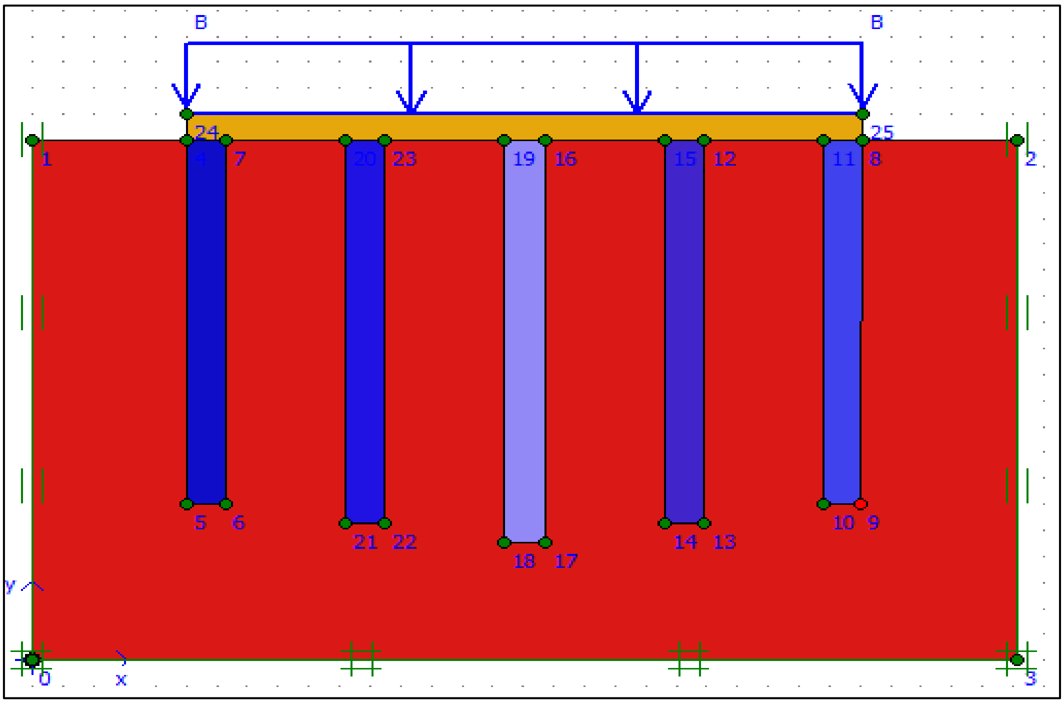
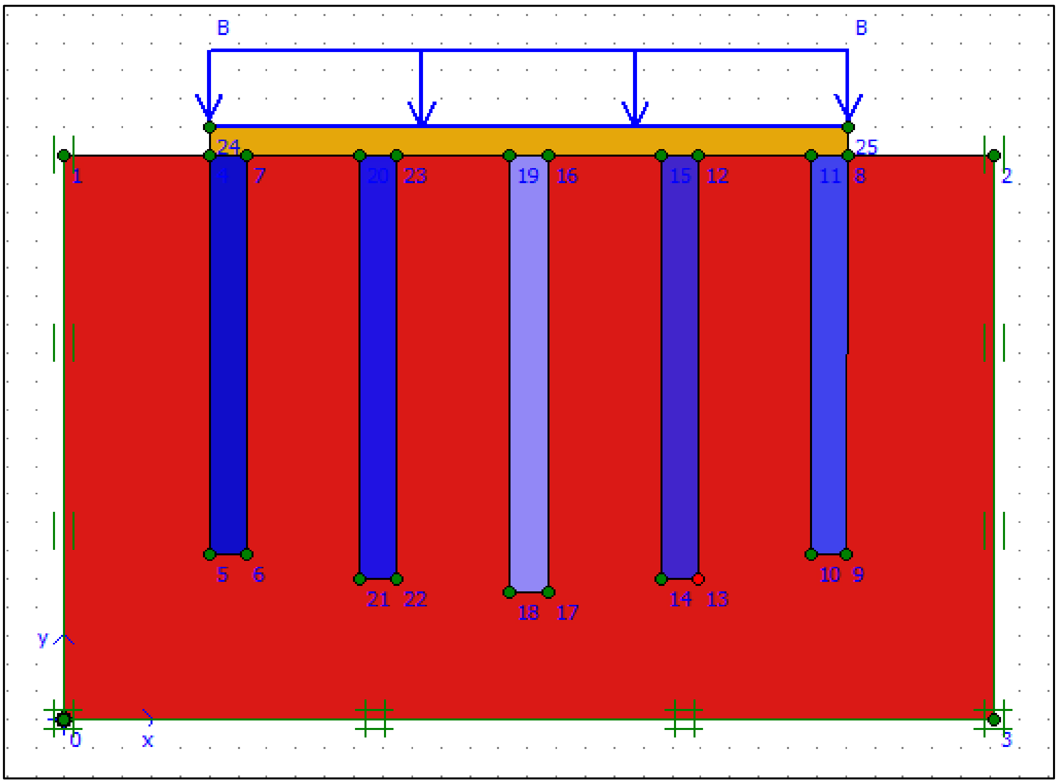


(d)



(e)

Figure 4.28. The group bored piles arrangement in the clayey soil with slope ratio (a) 1:0.8, (b) 1:2, (c) 1:4, (d) 1:6, (e) 1:8

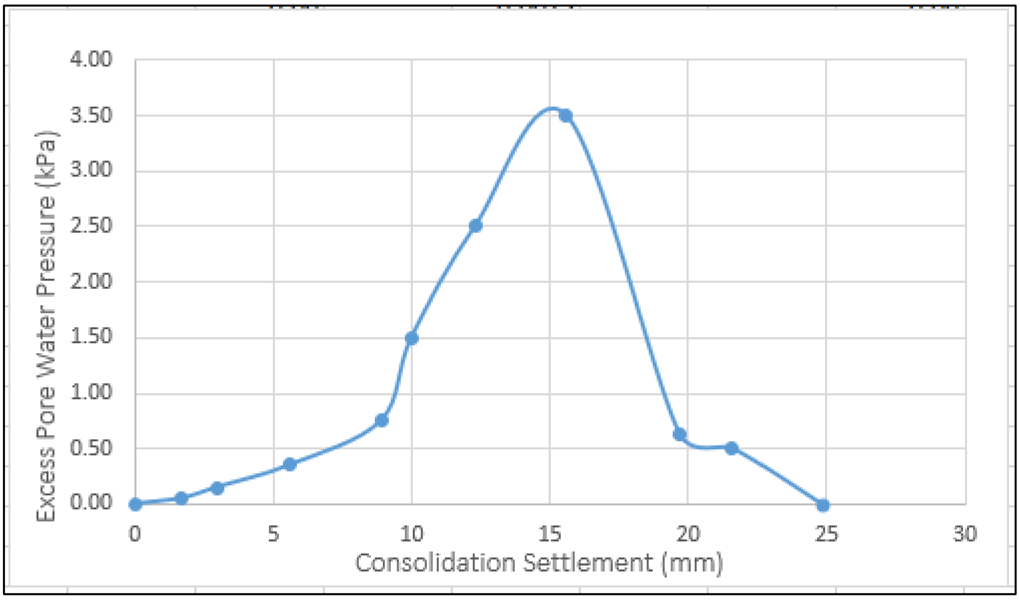


Figure 4.29. The relationship between excess pore water pressure and consolidation settlement for the mid pile tip point of the group bored piles subjected to 50 kPa applied pressure, pile diameter of 1.3 m, pile spacing of 3D and pile slope ratio of 1:2 in the clayey soil under the PLAXIS simulation.

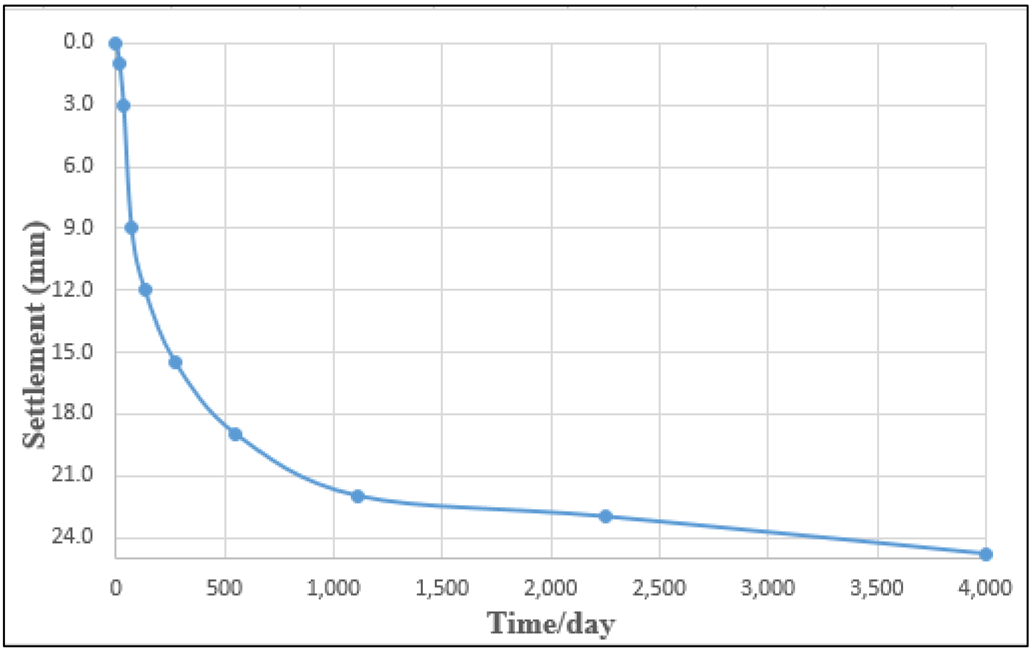


Figure 4.30. The relationship between settlement and time for the mid pile tip point of the group bored piles subjected pile slope ratio of 1:2 in the clayey soil under the PLAXIS simulation.

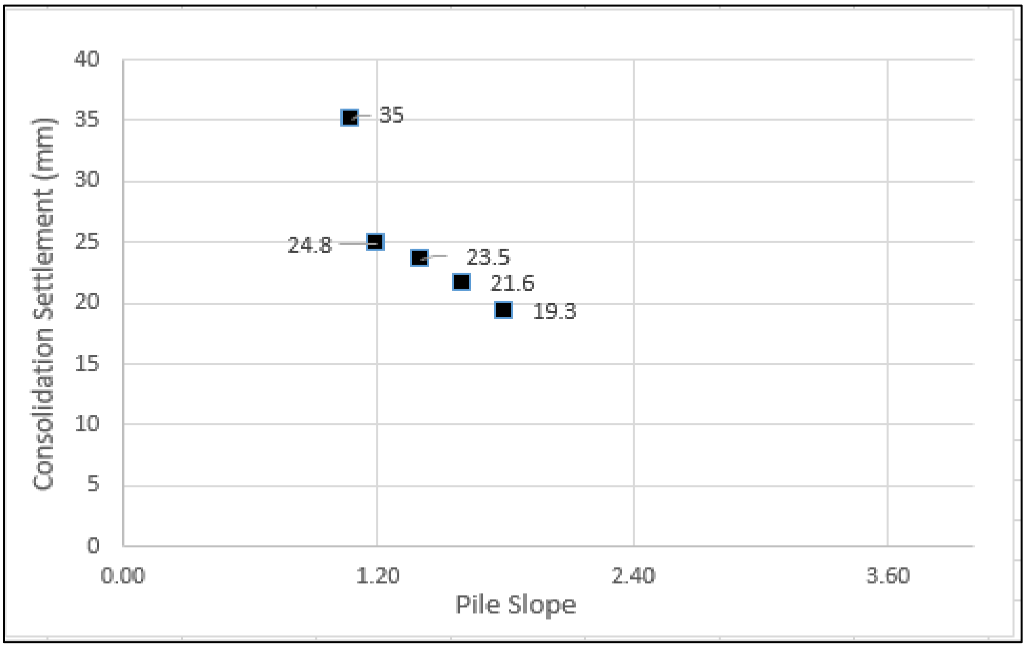


Figure 4.31. The relationship between consolidation settlement for the mid pile tip point of the group bored piles and pile slope ratio in clayey soil under the PLAXIS simulation.

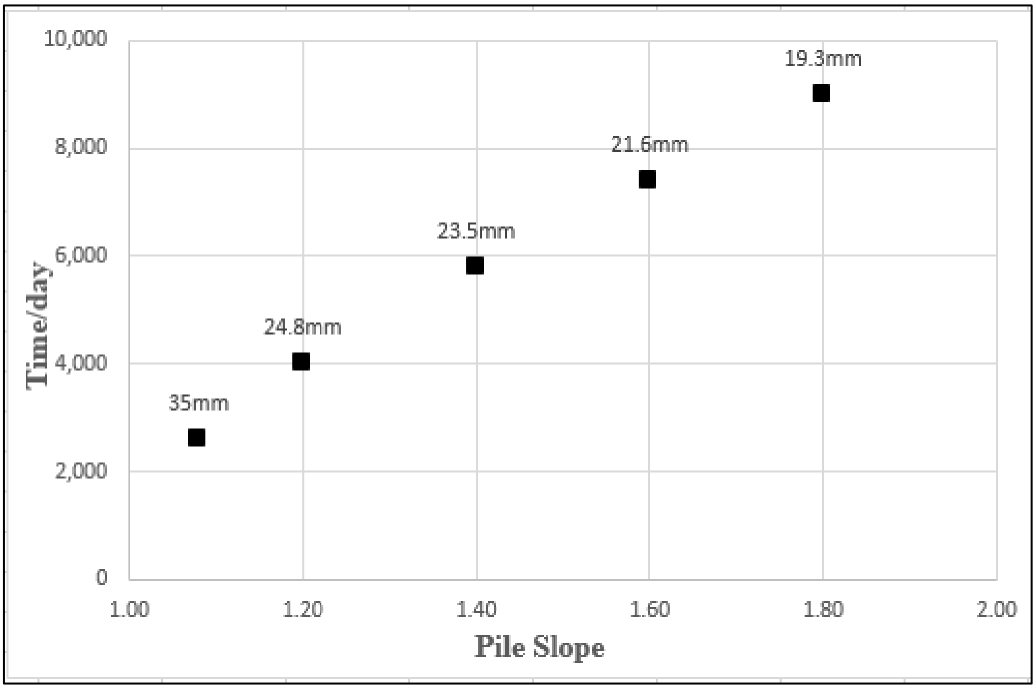


Figure 4.32. The relationship between time and pile slope for the mid pile tip point of the group bored piles in clayey soil under the PLAXIS simulation.

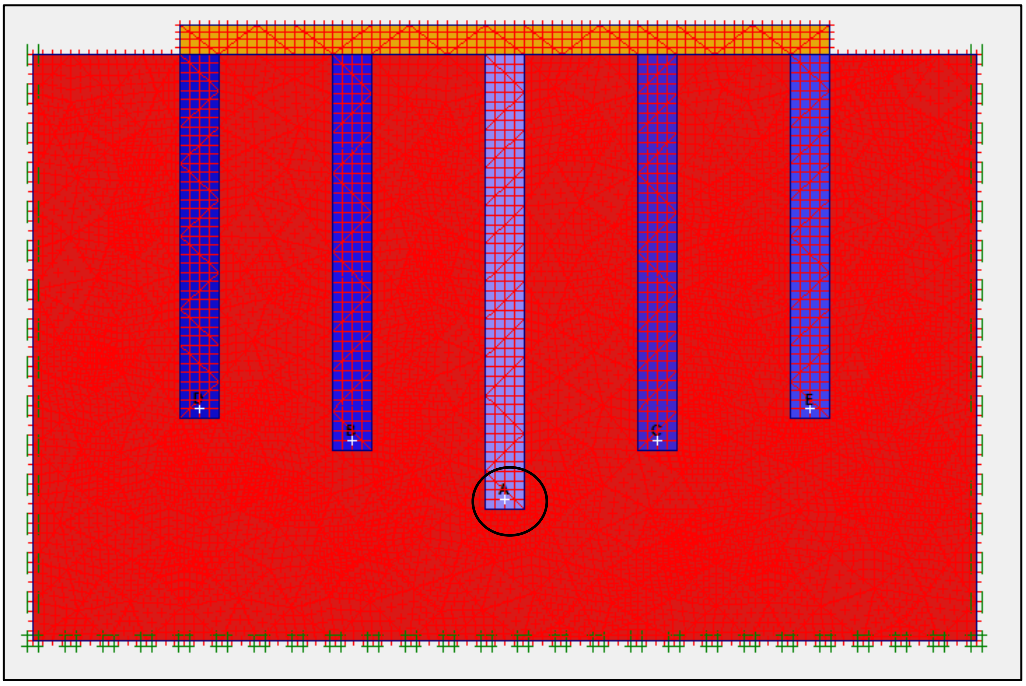


Figure 4.33. Proposed optimal numerical design of the group bored piles in the clayey soil with 50 kPa applied pressure, 1.3 m pile diameter, 3D pile spacing and pile slope ratio 1:2.

4.3.5 Effect of soil cohesion

In order to assess the suitability of the clayey soil in term of cohesion for the optimal group bored piles arrangement in term of consolidation settlement, the clay cohesion under study was varied among 20, 30, 40, 50 and 60 kPa for the PLAXIS simulation. Figure 4.34 indicates a typical relationship between pore water pressure and consolidation settlement for the mid pile tip point of the group bored piles subjected to 50 kPa applied pressure, pile diameter of 1.3 m, pile spacing of 3D, pile slope ratio of 1:2 and soil cohesion of 20 kPa in the clayey soil under the PLAXIS simulation. At the end of primary consolidation, a consolidation settlement of the bored pile was achieved at 24.3 mm which is below the tolerable limit of consolidation settlement. Figure 4.35 show the graph of soil cohesion at 20 kPa when it reaches settlement of 24.3mm by 3153 days. Figure 4.36 shows the relationship between consolidation settlement for the mid pile tip point of the group bored piles and soil cohesion in the clayey soil under the PLAXIS simulation. It is seen from the figure that the higher the soil cohesion, the higher is the consolidation settlement of the bored pile in the numerical simulation. Figure 4.37 shows the relationship between time and soil cohesion for the mid pile tip point of group bored piles in the clay soil under PLAXIS simulation.

At a soil cohesion of 20 kPa, the consolidation settlement of the group bored piles arrangement under the optimal design was found to be 24.3 mm. When the soil cohesion is greater than 20 kPa, the consolidation settlement of the bored piles increased above 25 mm tolerable limit of consolidation settlement. This points to the fact plasticity of the clay is an important aspect that influences the consolidation settlement of the group bored piles.

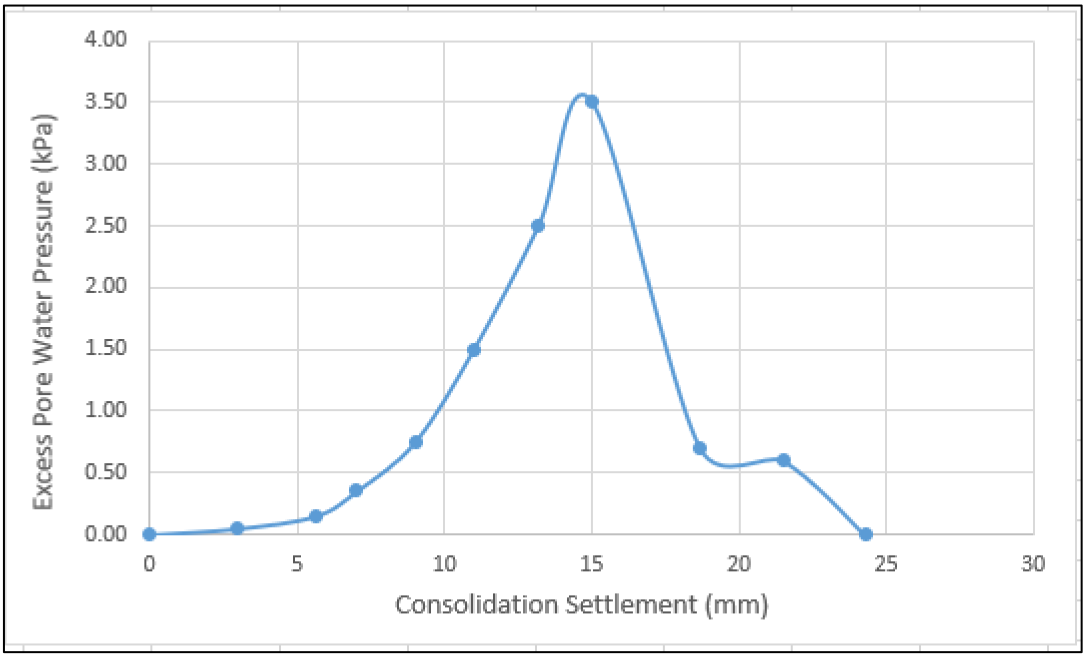


Figure 4.34. The relationship between excess pore water pressure and consolidation settlement for the mid pile tip point of the group bored piles subjected to 50 kPa applied pressure, pile diameter of 1.3 m, pile spacing of 3D, pile slope ratio of 1:2 and soil cohesion of 20 kPa in the clayey soil under the PLAXIS simulation.

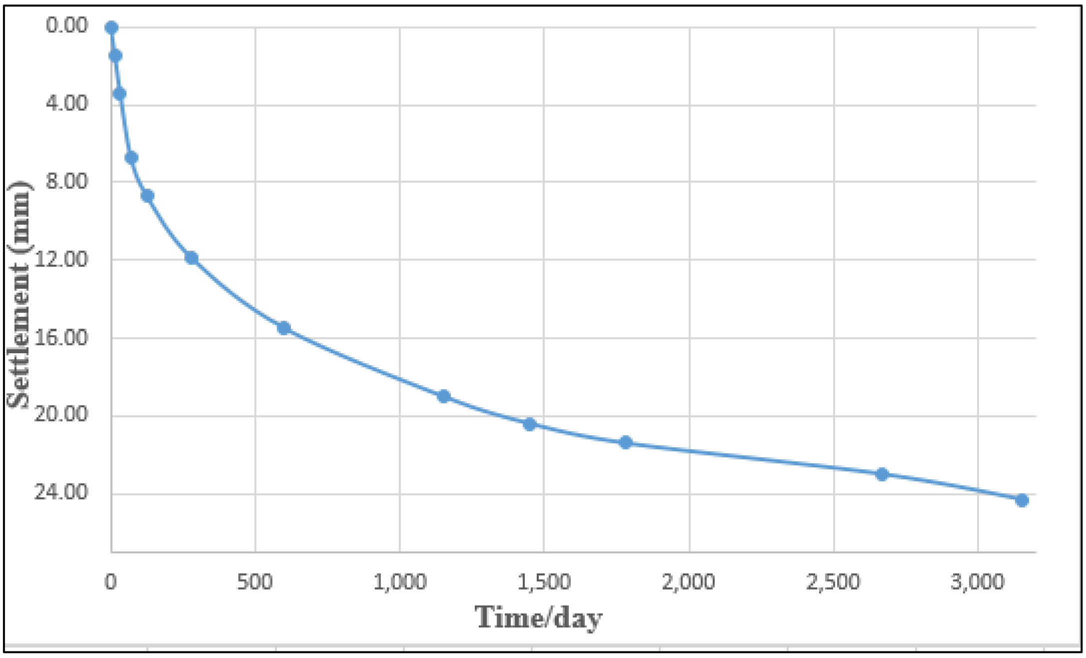


Figure 4.35. The relationship between settlement and time for the mid pile tip point of the group bored piles subjected to soil cohesion of 20 kPa in the clayey soil under the PLAXIS simulation.

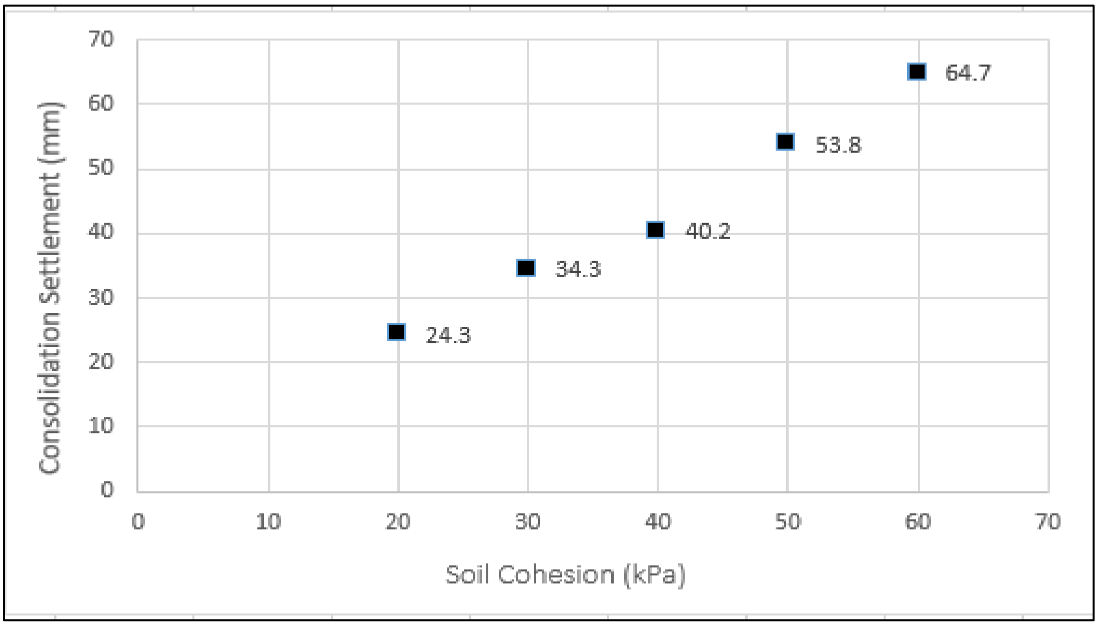


Figure 4.36. The relationship between consolidation settlement for the mid pile tip point of the group bored piles and soil cohesion in the clayey soil under the PLAXIS simulation.

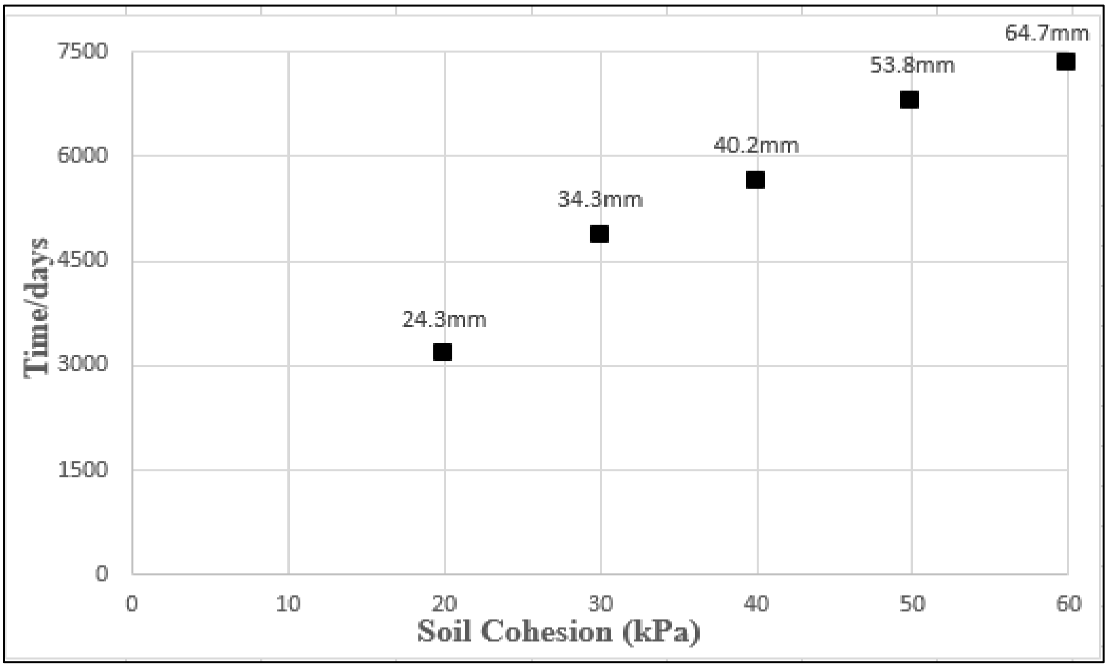


Figure 4.37. The relationship between time and soil cohesion for the mid pile tip point of the group bored piles in the clayey soil under the PLAXIS simulation.

4.3.6 Effect of soil angle internal friction

Under the optimal design of the group bored piles and at 20 kPa soil cohesion, the soil angle of internal friction was varied among 20°, 30° and 40° in the numerical simulation. The soil angle of internal friction is a critical parameter in the Mohr-Coulomb model adopted for the parametric study of group bored piles in the clayey soil. Figure 4.38 illustrates a typical relationship between pore water pressure and consolidation settlement for the mid pile tip point of the group bored piles subjected to 50 kPa applied pressure, pile diameter of 1.3 m, pile spacing of 3D, pile slope ratio of 1:2, soil cohesion of 20 kPa and soil angle of internal friction of 20° in the clayey soil under the PLAXIS simulation. Under such arrangement of the group bored piles, the consolidation settlement of the pile was found to be 24.7 mm which is below 25 mm. Figure 4.39 shows the graph of soil angle internal friction at 20° when it reaches settlement of 24.7mm by 3889 days. Figure 4.40 indicates the relationship between consolidation settlement for the mid pile tip point of the group bored piles and soil angle of internal friction in the clayey soil under the PLAXIS simulation.

It is seen in the figure that only at the soil angle of internal friction of 20°, the consolidation settlement of the pile is 24.7 mm which is less than 25 mm under the optimal group bored piles arrangement. Based on the Skempton-Bjerrum modification (1957) for consolidation settlement calculation and taking the pore water pressure parameter, A as 0.6, and H_c/B as 0.99 in Figure 2.13; the settlement ratio, K_{cir} is determined to be 0.75. With reference to Equation 2.6, the corresponding three dimensional consolidation settlement, $S_{c(p)}$ for the group bored pile foundation can be calculated as 18.5 mm. The three dimensional consolidation settlement of the group bored pile is still below 25 mm which is the allowable limit for the consolidation settlement. Figure 4.41 show the relationship between time and soil angle friction for the mid pile tip point of group bored piles in clay soil under PLAXIS simulation. When the soil angle of internal friction is more than 20°, the consolidation settlement of the bored pile was discovered to be above 25 mm which is more than the tolerable value. Although high soil angle of internal friction implies high soil shearing resistance, effective interaction between the optimal group bored piles arrangement and the soil cohesion and angle of internal friction is essential in order to minimize the consolidation settlement induced by the group bored piles in the clayey soil.

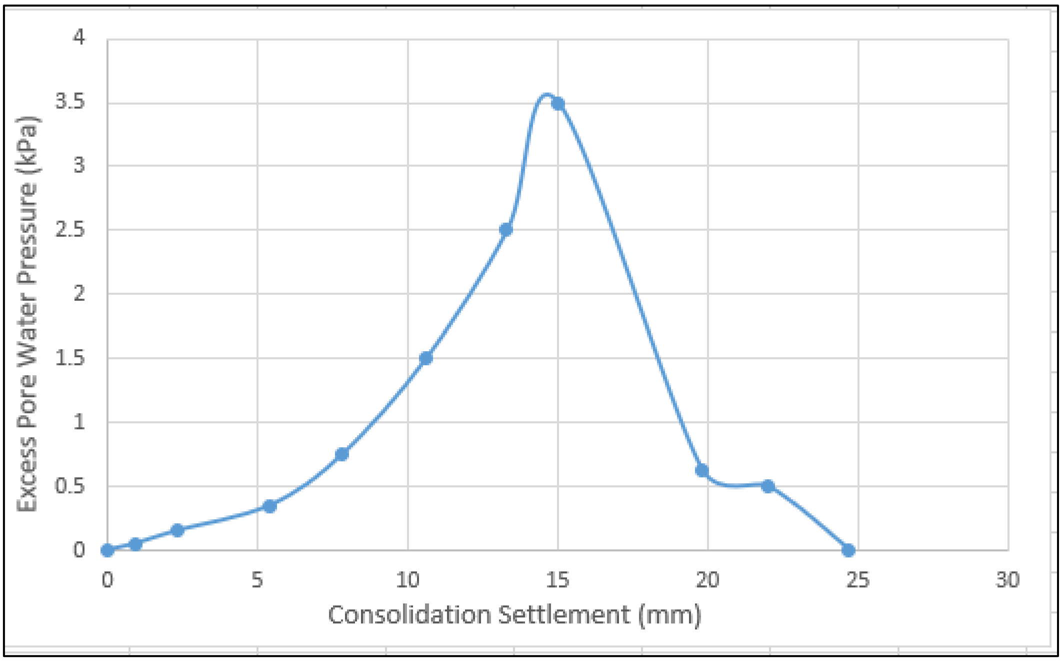


Figure 4.38. The relationship between excess pore water pressure and consolidation settlement for the mid pile tip point of the group bored piles subjected to 50 kPa applied pressure, pile diameter of 1.3 m, pile spacing of 3D, pile slope ratio of 1:2, soil cohesion of 20 kPa and soil angle of internal friction of 20° in the clayey soil under the PLAXIS simulation.

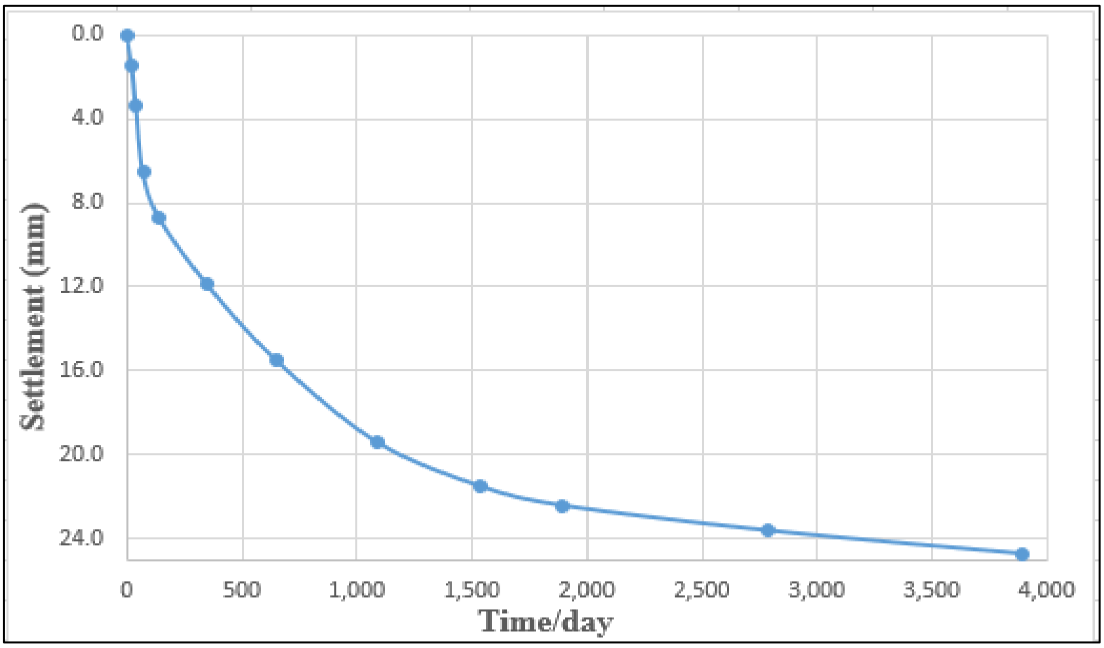


Figure 4.39. The relationship between settlement and time for the mid pile tip point of the group bored piles subjected to soil angle of internal friction of 20° in the clayey soil under the PLAXIS simulation.

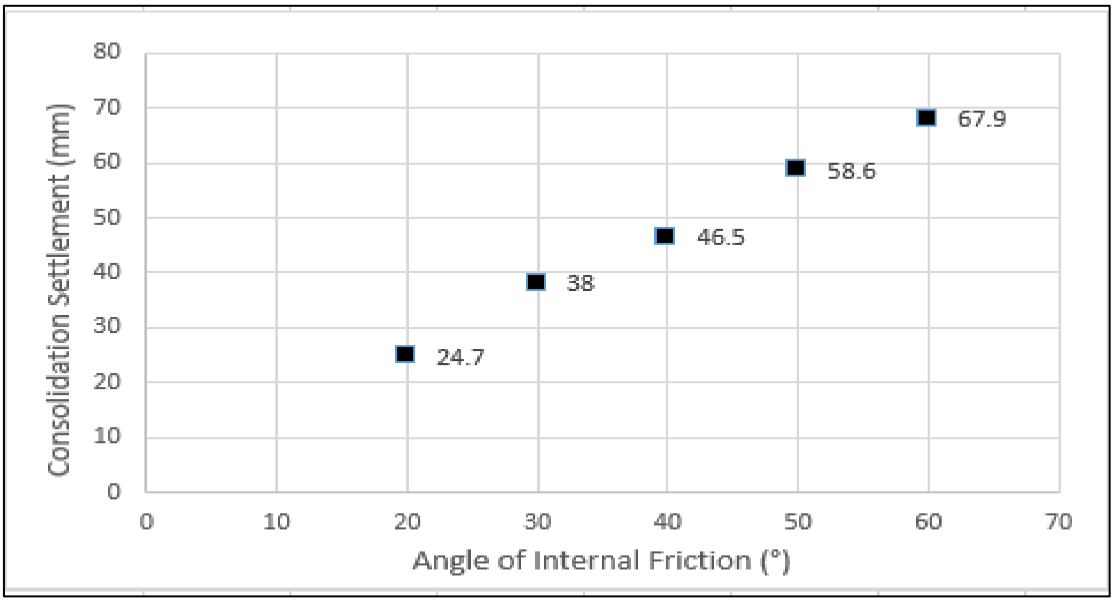


Figure 4.40. The relationship between consolidation settlement for the mid pile tip point of the group bored piles and soil angle of internal friction in the clayey soil under the PLAXIS simulation.

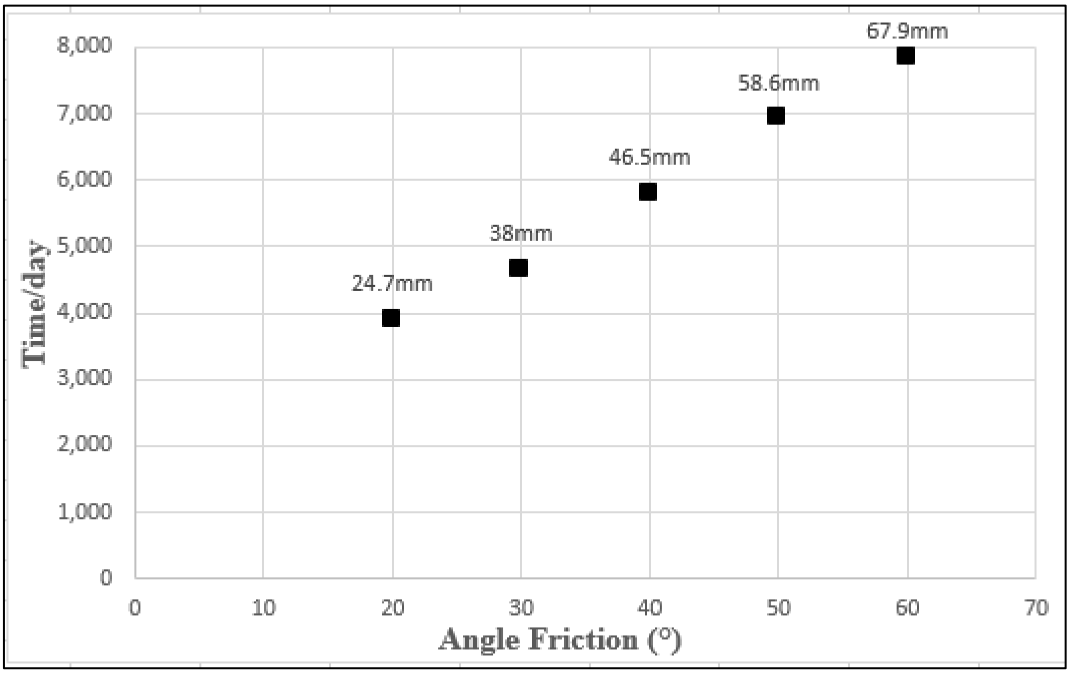


Figure 4.41. The relationship between time and soil angle friction for the mid pile tip point of the group bored piles in the clayey soil under the PLAXIS simulation.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATION FOR FUTURE WORK

5.1 Conclusions

Based on the finite element analysis using the PLAXIS software, the following conclusions can be drawn.

a) The results of PLAXIS simulation of single bored pile in clayey soil were compared and validated with those from Wehnert & Vermeer (2004). Three types of soil models were evaluated under the simulation namely Mohr-Coulomb (MC), Hardening Soil (HS) and Softening Soil (SS) models. The modelling works were done in Fine and Very Fine Mesh. Based on the PLAXIS simulation result, it was found that the single bored pile simulation with Mohr-Coulomb (MC) soil model in Very Fine mesh has the highest coefficient of determination (R^2) which is 0.9840 for the simulated load in comparison to measured load. This implies that the soil model best fit the data of measured load-settlement of the single bored pile in clayey soil as documented by Wehnert & Vermeer (2004). As such, Mohr-Coulomb model in Very Fine mesh was selected for the parametric study of the group bored piles in clayey soil.
b) Based on the Mohr-Coulomb soil model in Very Fine mesh, the results of the parametric study revealed that the optimal group bored piles' arrangement is subjected to 50 kPa applied pressure, 1.3 m pile diameter, 3D pile spacing and 1:2 pile slope ratio. Optimization of the parameters for the group bored piles is based on 25 mm tolerable consolidation settlement based on Meyerhoff theory for foundation in clayey soil. It was further discovered that at the optimal group bored pile design, the cohesion and angle of internal friction of the clay should be 20 kPa and 20° respectively in order to induce consolidation settlement of

the group bored piles of not exceeding 25 mm. This reflects the importance of the PLAXIS numerical study in order to assess the most suitable interaction mechanism of the floating group bored piles in the clayey soil under applied pressure.

The main contribution of the research work is that through the finite element modelling of the pile-soil interaction under the various loading increments and time steps, a viable design of the group bored piles can be established. Since modelling the pile-soil behaviour is complex, it requires a reasonable degree of accuracy to predict the settlement resulting from the pile-soil interaction. So, the best way to study the soil-structure behaviour based on the finite element model is to evaluate the frictional interaction between the piles and soil by using the PLAXIS software.

5.2 Recommendation for future work

Based on the outcomes of the research work, it is recommended for future study to be expanded to three dimensional modelling on the validation and parametric study of the bored piles in clayey soil so as to provide detailed in depth comprehension on the three-dimensional deformation of the clayey soil under the application of pressure on the bored piles. Through such three dimensional simulation, it is interesting to evaluate the three-dimensional dissipation of excess pore water pressure in the soil as a result of the bored piles' installation. It is also interesting to recommend that finite element development of the three dimensional modelling of the group bored piles in clayey soil needs to be established to include seismic impact on the deep foundation in the soil. Such knowledge will be valuable in order to come out with a viable solution to the group bored piles' design that takes into account ground vibration induced by earthquakes.

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APPENDIX

Table A1. The data of excess pore water pressure versus consolidation settlement for the mid pile tip point of the group bored piles subjected to 50 kPa applied pressure in the clayey soil under the PLAXIS simulation.

Consolidation settlement (mm)	Excess pore water pressure (kPa)
0.00	0.00
4.00	0.66
7.00	2.65
10.00	4.05
12.00	6.10
15.00	5.73
18.00	4.13
20.00	3.05
21.50	1.88
23.00	0.66
24.50	0.00

Table A2. The data of excess pore water pressure versus consolidation settlement for the mid pile tip point of the group bored piles subjected to 100 kPa applied pressure in the clayey soil under the PLAXIS simulation.

Consolidation settlement (mm)	Excess pore water pressure (kPa)
0.00	0.00
11.00	8.00
14.00	13.25
17.00	20.25
19.00	30.50
22.00	28.67
25.00	20.65
27.00	15.25
28.50	10.90
30.00	8.50
35.00	0.00

Table A3. The data of excess pore water pressure versus consolidation settlement for the mid pile tip point of the group bored piles subjected to 200 kPa applied pressure in the clayey soil under the PLAXIS simulation.

Consolidation settlement (mm)	**Excess pore water pressure (kPa)**
0.00	0.00
19.00	40.80
22.00	79.50
25.00	121.50
27.00	183.00
30.00	172.02
33.00	123.90
35.00	101.50
36.50	80.40
38.00	70.30
42.60	0.00

Table A4. The data of excess pore water pressure versus consolidation settlement for the mid pile tip point of the group bored piles subjected to 400 kPa applied pressure in the clayey soil under the PLAXIS simulation.

Consolidation settlement (mm)	**Excess pore water pressure (kPa)**
0.00	0.00
28.00	150.71
31.00	180.92
34.00	255.15
36.00	384.30
39.00	361.25
42.00	260.19
44.00	213.15
45.50	168.84
47.00	147.63
50.00	0.00

Table A5. The data of excess pore water pressure versus consolidation settlement for the mid pile tip point of the group bored piles subjected to 800 kPa applied pressure in the clayey soil under the PLAXIS simulation.

Consolidation settlement (mm)	**Excess pore water pressure (kPa)**
0.00	0.00
35.00	331.43
38.00	385.76
41.00	510.30
43.00	768.60
46.00	722.50
49.00	520.38
51.00	426.30
52.50	337.68
54.00	295.26
55.00	0.00