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ANALYSIS OF BEHAVIOR OF PILE GROUPS IN LAYERED CLAY

Taiye W. Adejumo
Department of Geotechnics and Ecology in Civil Engineering, Faculty of Civil Engineering
Belorussian National Technical University - Minsk, Belarus.
elisha4exploit@yahoo.com (Tel: +37533 601 94 28)

Abstract

This paper presents the results of recent experimental investigation on the analysis of behavior of pile groups in layered clay. It’s a laboratory modeled experiment with the square and circular prototype test piles carved to shape from strong wood. The configurations of circular section consist of 20mm and 200mm for diameter and length respectively. The square section is 20 x 20 mm, with a length of 200 mm. Four modeled soil conditions were investigated: Strong modeled clay; weak modeled clay; weak on top of strong modeled clay; and reinforced weak modeled clay. Single pile as well as pile groups of 2x2 (4 piles) with centre to centre spacing a = 4d, and 3x3 (9 piles) with centre to centre a = 3d, were driven into clearly marked layered clay soils differentiated by moisture and density of $w = 20\%$, $\gamma = 17$ kN/m^3 for the weak; $w = 10\%$, $\gamma = 19$ kN/m^3 for the strong). The tests were conducted in a specially designed testing equipment/tank. The loadings were applied gradually at the rates of 0.01, 0.05, 0.1 and 1mm/min. The test results showed that pile displacement increases with increase in applied load. Increment in loading significantly affects the compressive axial capacity of modeled pile group in clay The initial settlements of square piles are generally higher than in circular piles, but the latter gives higher over-all settlement than the former. Lateral deformations decrease with increase in distance from the pile, and outward radial deformations around the pile decrease downwards along the pile depth. A pressure bulb of roughly three zones of deformation of length 3d, 2.5d and 2d respectively from the pile cap was identified after unloading.

KEYWORDS: Pile behavior; Settlement; Compressive Loads; Deformation; Wooden Piles; Clay.

Introduction

The presence of soft compressible layers below the pile tips can result in substantial increases in the settlement of a pile group, whereas the settlement of a single pile may be largely unaffected by the compressible layers [1], [2]. As might be expected, the larger the group (the width of the pile group), the greater is the effect of the underlying compressible layer on the group settlement [3] - [5].

The process of installation of driven (i.e. displacement) piles is well known to cause substantial changes to the in situ effective stress regime, which subsequently undergoes further significant changes as pore pressures dissipate and total stresses equalize [6] and [7]. After equalization, the stress regime, which controls the long term pile performance, is difficult to estimate with any degree of certainty because of its dependence on a large variety of clay properties as well as on the pile type and pile installation procedure [8].

Soil within a few pile diameters can undergo large shear deformations. The pile driving process can potentially generate large stresses and deformations in the nearby soils [9]. For many cohesive clay soils which tend to be highly sensitive to remolding, this leads to significant loss of strength in the short term.

Lateral loads and moments are resisted by vertical piles by deflecting laterally until the necessary reaction in the surrounding soil is mobilized [10]. The piles penetration depth (length) depends on the magnitude of the applied load and type of soil. The rate of application of external load affects the strength of cohesive soils [11]. The response of pile group during loading is also influenced significantly by the degree of interaction between piles of shear stresses acting on their shafts and normal stresses at their bases [12].

The behaviors of piles are usually investigated with pile load test in the field. However, the high cost of conducting full-scale pile tests in the field and the inherently high variability of the field conditions make them impractical for research purposes. Therefore, model tests are usually used for investigating the behavior of piles [11], [13] and [14].

Due to the interaction of neighboring piles in group, the behavior of pile group is geometrically different from that of single pile under applied load. Investigating the magnitude and pattern of deformation, settlement and interactions of layered clay soil under axially loaded modeled piles in clay therefore, will be of practical importance.

Therefore, presented in this work are the results of a series of pile tests with prototype modeled wooden piles axially loaded in clay soil. The tests were conducted in the research laboratory, Geotechnical and Environmental Engineering department, Belorussian National Technical University, Minsk, Belarus. The clay soil was pulverized and mixed to desired water content of 10%; bulk densities of 17 kN/m^3 and 19 kN/m^3 for the weak modeled and strong modeled layers of clay respectively. The piles were subjected to axial compressive loads at incremental rates of 0.01, 0.05, 0.1 and 1mm/min respectively, and the behavior in terms of deformation, settlement and interaction were studied and presented.

Experimental Investigation

Wet clay soil sample obtained from a site around Uruccha, at the outskirt of Minsk province of Belarus, were investigated in this study. Comprehensive laboratory investigations were carried out on the conditioned clay in order to analyze its behavior in relation to settlement, deformation pattern and response to incremental loading under axially loaded modeled wooden prototype piles.

The clay samples were consolidated in a specially fabricated multipurpose steel tank with the dimensions of 1100 x 250 x 600 mm for length, width and depth respectively. It has a relatively rigid steel framework support. It has a one sided steel panel having open and close apertures for drained and undrained tests. The frontal panel (other side) is made with transparent plastic fiber, which is strong enough to withstand consolidation pressure and strikes (Fig. 1). The transparent strong plastic allows proper monitoring of sample's state during the test as well as ensures visual observation of failures in the tested soils in terms of depression, heaving or wobbles. Temporary makings can be made on the transparent plastic panel depending on the desired volume of work. Thereafter, the pulverized, air-dried and conditioned clay was placed in the test tank in three layers; strong, weak and reinforced weak layers. The weight of clay required to obtain a unit weight of 19 kN/m^3 (strong) or 17 kN/m^3 (weak) were packed into the test tank in lifts, with the interface between the lifts being made uneven, to reduce the bedding effects, and clearly marked to give room for proper monitoring during loading and unloading.

The load is transferred to the soil by a weight hanger with a lever arm. The hanger consists of a lower and upper cross beams and a cantilevered beam with a pin connection at one end and a cradle for weights at the free end. The load is applied by placing slotted dead weights on the cradle. The cantilever beam connecting end is designed with a load factor of 10 i.e. the actual load transferred to the soil through the connecting plate being 10 times the load on the cradle (Fig. 1).

To achieve the desired densities layer by layer, consolidation pressure was applied through the upper surface layer. The testing tank was then made rigid and ready for pile driving. Modeled square and circular piles were then driven through the soil, and the pile cap was put in place (Figs. 2 and 3). The pile cap was then connected by the fulcrum under the loading arm. Soil deformation was monitored and readings of settlement were taken at certain time intervals until the relationship between settlement and the logarithm of time became nearly horizontal.

The prototype wooden test piles were subjected to axial compressive loads until the allowable bearing capacity corresponding to pile settlement of 0.1d (10% of pile diameter) or 25mm, whichever is less, in line with the submission of [15] - [20], also commented on by [21] and [22]. The settlement of the clay was measured by means of a dial gauge, which was connected to the upper plate (Fig. 3). The load was then increased steadily at the rate of 0.01, 0.05, 0.1 and 1mm/min. The settlement was taken with time until the time when the settlement change was insignificant. For each pile group, (2x2 i.e. 4 piles and 3x3 i.e. 9 piles) the tests were repeated for the three soil conditions separately and also for the single pile. The general behavior, settlement, deformation and soil-pile interaction were observed and recorded.

Figure 1. Test tank and load application on the Soil

Figure 2. Prototype piles driven into clay in the tank

Figure 3. Settlement measurement on the Dial gauge

Discussion of Test Results

For the convenience of investigation with the testing tank, group efficiencies were pre-determined and the spacing 3d, and 4d adopted for the 3 x 3 (9 piles) and 2 x 2 (4 piles) respectively.

Table 1 shows the result of some of the geotechnical properties of the clay investigated. The samples used can be described as soft clay which is slightly normally consolidated in it its wet state having less than zero liquidity index and 0 cohesion (weak modeled), but with a cohesion of 20 kPa at a stiffer state (strong modeled). Overall, the properties of this clay are typical and similar to that of soft clay found in Sokoto, north-western Nigeria as reported by Ola [23-25].

Table 2 shows the ultimate bearing capacities of circular and square prototype piles in different modeled soil conditions. Modeled 1 with stiffer and stronger clay has the highest ultimate bearing capacities of 634 kPa and 640 kPa for circular and square piles respectively. Having stiffer clay under weak as well as reinforcing weak clay layers produced higher bearing capacities since pile shafts projected through and beyond the weak layers. The lowest bearing capacities of 358 kPa and 365 kPa were recorded for the circular and square prototype piles respectively.

Table 1. Some Geotechnical Properties of the Clay Sample

Parameters	**Modeled strong clay** ($\gamma = 19$ kN/m^3, $w = 10\%$)	**Modeled weak clay** ($\gamma = 17$ kN/m^3, $w = 20\%$)
Specific gravity of solids	2.66	2.66
Liquid Limit (%)	23	24
Plastic Limit (%)	17	18
Plasticity Index (%)	6	6
Liquidity Index (%)	$I_L < 0$	0.3
Void ration (e)	0.51	0.84
Cohesion (kPa)	20	0
Relative consistency	2.32	2.38
Angle of internal friction (φ^o)	25	33
Modulus of Deformation E (kPa)	8.5	5.4

Table 2. Ultimate Bearing Capacity of prototype piles in modeled soil conditions

Pile Foundation Prototype shape	Ultimate Bearing Capacity (kPa)			
	Model 1	Model 2	Model 3	Model 4
Circular	634	358	486	510
Square	640	365	495	516

Model 1- Modeled soil condition for strong clay
Model 2- Modeled soil condition for weak clay
Model 3- Modeled soil condition for weak on strong clay
Model 4- Modeled soil condition for reinforced weak clay

The Load-settlement curves at different loading conditions for the prototype test piles are shown in figures 4 - 7. From these figure, pile displacements increased with increase in loading generally. The single pile showed an isolation effect, although with smaller settlement, while the 2 x 2 (4 piles) group with 4d spacing and 3 x 3 (9 piles) with 3d spacing behaved similarly as a result of group efficiency influence. Under axial loadings, the reinforced weak clay (Model 4) behaved similarly to strong clay (Model 1) in its response to deformation and pile displacement.

A careful physical observation from the testing tank transparent panel (fig. 8), showed eaves, depression and total settlement of modeled test piles, which varies with the differences in pile spacing. The pressure bulb and deformation zones produced can clearly be seen in figs. 9 and 10. On the average, the depth of zone 1 is about 3d from the lateral surface of pile; zone 2 has a depth of 2.5 d, while zone 3 ends at about 2d from the pile tip, (d is diameter of pile).

Also, the lateral deformations of soil around the piles decrease with increase in distance from the pile, while the outward radial deformations around the pile decreases downwards as shown in figures 11 and 12.

The initial settlement of circular piles is lower than that of square piles. This is due to wider surface area in contact and less negative friction of the latter. However, as the loading rate increases, circular piles penetrate further with higher settlement and deformation than square piles, figs. 11 and 12. Practically shown in the four modeled soil conditions, for a given loading rate, the settlement of circular piles is higher for a corresponding load.

The axial compressive loading capacity of the pile group, in terms of axial load applied, increase linearly with loading rate as the loading regime is gradually increased up to 100 percent from 0.01-1.0 mm/min. The deformation in the bearing soil also increases as shown in figures 4 - 7. For a single pile, increase in loading rate produced a quicker deformation and increase pile displacement.

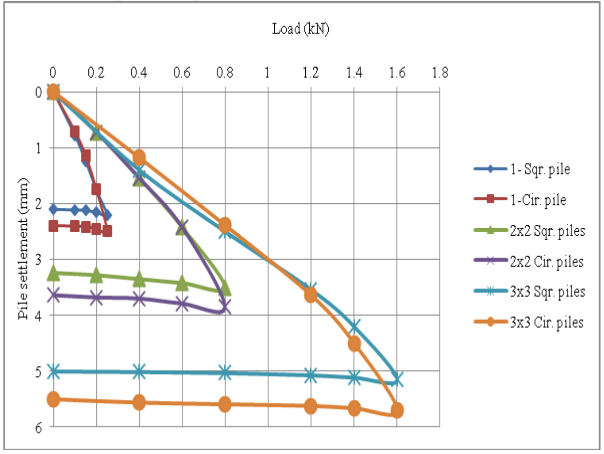

Figure 4. Load-Settlement curve @ 0.01 mm/ min loading rate

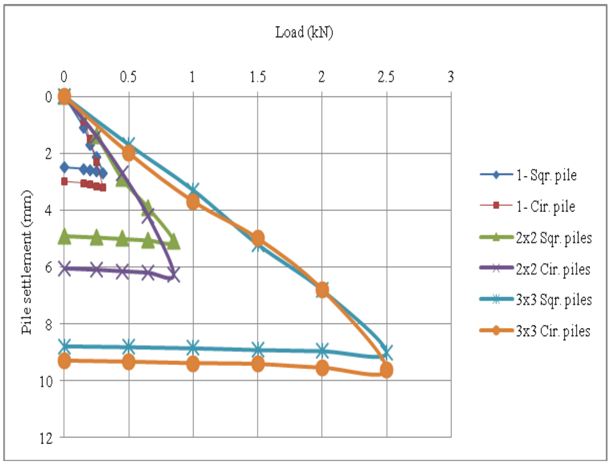

Figure 5. Load-Settlement curve @ 0.05 mm/ min loading rate

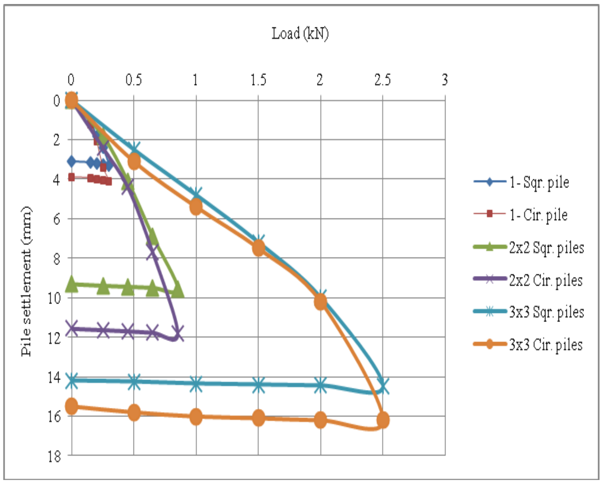

Figure 6. Load-Settlement curve @ 0.1 mm/ min loading rate

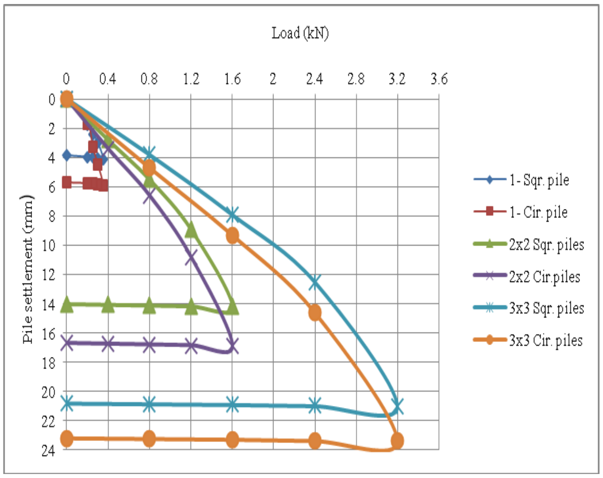

Figure 7. Load-Settlement curve @ 1.0 mm/ min loading rate

Figure 8. Eaves, depression and settlement of pile

Figure 9. Pressure bulb and Deformation Zones under load

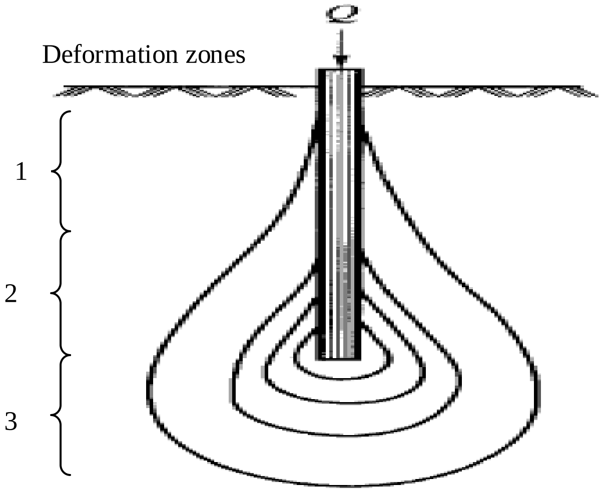

Figure 10. Failure bulb and Deformation Zones of a Single Pile

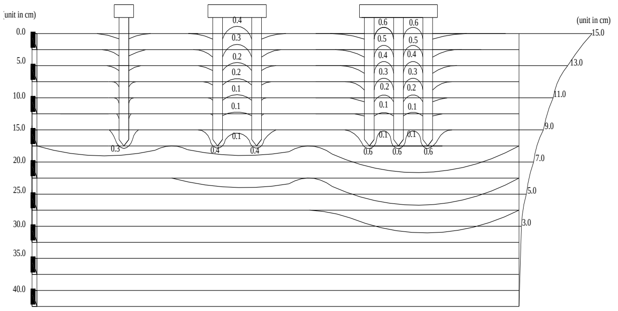

Figure 11. Deformation of Soils around Square Piles

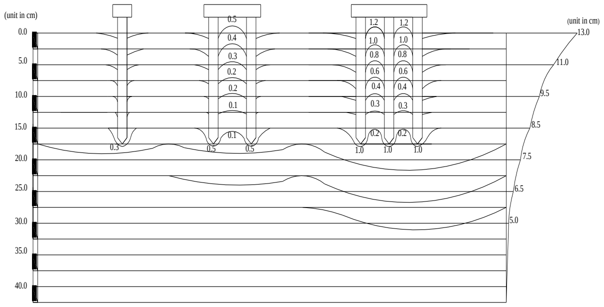

Figure 12. Deformation of Soils around Circular Piles

Conclusions

From the results of laboratory investigation of analysis of behavior of pile groups in layered clay under axially loaded modeled square and circular piles, the following conclusions are drawn:

Pile displacement increases with increase in applied load. Increment in loading significantly affects the compressive axial capacity of modeled pile group in clay.

The initial settlement of square piles is higher than that of circular piles. However, as the load increases circular piles produce a larger overall settlement than the square piles. Although installation of square piles may be more demanding in terms of handling for accuracy and efficiency

Outward radial deformations around the pile shaft decreases with depth. Lateral deformation of pile decrease with increase in distance from the pile centre.

Three zones of deformation are clearly shown in the tested loaded piles; zone 1 of about 3d from pile lateral surface under the pile cap; zone 2 of about 2.5d along the pile length; and zone 3 around and under the pile tip with a depth of about 2d. Hence the deformation zones of soil around axially loaded piles decreases in length, but increases in radius downward from the pile cap.

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Biography

TAIYE W. ADEJUMO received the B.Eng. degree in Civil Engineering from the Federal University of Technology, Minna, Niger State - Nigeria, in 1998, the M.Eng. degree in Civil Engineering from the Bayero University Kano, Kano State - Nigeria, in 2006, and commenced Ph.D. degree in Civil Engineering at the Belorussian National Technical University, Minsk, Belarus in 2010, respectively. He's expected to round up the Ph.D. after the summer of 2013.Currently; He is a Lecturer at the Federal University of Technology, Minna, Niger State – Nigeria (on study leave) and a research fellow at the Department of Geotechnics and Ecology in Civil Engineering, Faculty of Civil Engineering
Belorussian National Technical University - Minsk, Belarus. His teaching and research areas include Soil mechanics, Geotechnics and Foundation Engineering. He has a few publications in Electronic Journal of Geotechnical Engineering (EJGE), Volume 17, 2012; Bundles J, L, M, N, O, Q and S. Engr. Adejumo may be reached at elisha4exploit@yahoo.com