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Settlement Analysis of Modeled Wooden Piles in Clay

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***Abstract*— This paper presents the results of recent experimental study on the settlement analysis of modeled wooden piles of circular and square cross sections in clay. The modeled piles were carved from strong wood. The configurations of the circular section consist of 20mm and 200mm for diameter and length respectively. The square piles also have a surface width and overall length of 20mm and 200mm respectively. Single pile as well as pile groups of 2x2 (4 piles) with centre to centre spacing (a) of 4d, and 3x3 (9 piles) with centre to centre (a) of 3d, were driven into clearly marked layered clay soils differentiated by moisture and density of w = 20%, γ = 17 kN/m^3 for the weak; w = 10%, γ = 19 kN/m^3 for the strong), and a third layer of reinforced weak soil having reinforcing bars placed in it. The tests were conducted in a specially designed testing equipment/tank. The modeled piles were subjected to axial compressive loads and the effect on the soils in the inter-pile spacing, as well as those under and around the piles were evaluated as the loading increases. The pile axial capacity increases with the loading rate. The load-settlement curves show exponential formats. The tests revealed a maximum shaft resistance at the pile tip. Also, the relationship between applied load and pile displacement within the load bearing limit was observed to be linear. The initial settlements of circular piles are generally lower than those for square piles, but the former gave a higher overall settlement than the latter. The load-settlement curves were also similar to that predicted by CAPWAP analysis which has been employed by many analysts. A failure bulb of deformation of roughly 3 zones with depths of 3d, 2.5d and 2d along the pile length downward has been identified.**

***Keywords*- Compressive Loads, Clay, Deformation, Pile displacement; Settlement, Wooden Piles.**

I. INTRODUCTION

Pile foundations are structural members used to carry the applied loads from the superstructures to deep stronger stratum, as well as reinforced the soil [1]. Vertical piles resist lateral loads or moments by deflecting laterally until the necessary reaction in the surrounding soil is mobilized [2]. The technique most commonly used for the analysis and design of piles is based on the theory of beam on elastic foundation. Rational analyses of pile group displacements were pioneered by Poulos [3]. The rate of application of external load affects the strength of cohesive soils [4]. The pile driving process can potentially generate large stresses and deformations in the nearby soils. Soil within a few pile diameters can undergo large shear deformations [5].

The key geotechnical parameter in the estimation of pile settlement is the stiffness of the soil. One of the common mean of analyzing pile group behavior is by use of interaction factor method which was described by [6], otherwise known as the principle of superposition. However, a simplified expression for the interaction factor, which enables easier computational analysis of group settlement of piles, was later developed by [7].

The settlement of a pile group can differ significantly from that of a single pile at the same loading rate. The presence of soft compressible layers below the pile tips can result in substantial increase in the settlement of a pile group, despite the fact that the settlement of a single pile may be largely unaffected by the compressible layers. The larger the group (i.e. the width of the pile group), the greater is the effect of the underlying compressible layer on settlement [8] and [9].

A review of literatures on pile behavior among others revealed that, as the loading increases, the axial capacity of single piles in clay soils increases [10], [11] and [12]. Settlement and deformation of piles have been reported to correspond to the applied load [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 [15] - [18]. An elasto-plastic model was used to obtain the response of laterally loaded piles by [19], while earth pressure theory was used to obtain pile deflection for both short and long piles by [20].

In the design of pile foundations, it is usually necessary to evaluate the pile deflection, which is closely related to its settlement, in addition to estimating the ultimate pile capacity to satisfy the serviceability aspects [21]. Obtaining the settlements of piles under loads is a key factor to understanding its behavior and response to deformation and utmost functionality. The foregoing therefore, explains the relevance of this work.

Hence, this paper presents the results of a series of modeled pile tests on the settlements of wooden piles of square and circular cross sections. The tests were conducted in the research laboratory, Geotechnical and Environmental Engineering department, Belorussian National Technical University, Minsk, Belarus. The model piles were subjected to axial compressive loads at incremental rates of 0.01, 0.05, 0.1 and 1mm/min respectively. The load-displacement responses, as well as settlement of these piles were investigated. This investigation is essential in the calibration and validation of analytical techniques to predict the changes in the properties of the soils around the piles.

II. EXPERIMENTAL INVESTIGATIONS

The soil samples investigated in this work was wet clay samples taken from a site around Uruccha, at the outskirt of Minsk province of Belarus. Detailed laboratory investigations were then carried out on the conditioned clay in order to determine its settlement and response to incremental axial compressive loading when modeled wooden piles of circular and square cross sections were driven through it.

The clay soil was pulverized and mixed to desired water contents of 10%; bulk densities of 17 kN/m^3 and 19 kN/m^3 for weak modeled and strong modeled layers of clay respectively. The weak layers were also reinforced with reinforcing bars.

The soil samples were consolidated in a specially constructed 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 (Fig. 1). 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. 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).

After layer by layer densities were achieved, consolidation pressure was applied through the upper surface layer. The testing tank was then made rigid and ready for pile driving. Modeled circular and square 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 modeled piles were subjected to axial compressive loads until the allowable pile settlement of 0.1d (10% of pile diameter i.e. 2 mm) is reached or exceeded in line with the submission of [22] and [12], also commented on by [8] and [23]. The settlement of the clay was measured by means of a dial gauge, which was connected to the upper plate (Fig. 1). The load was then increased 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, the tests were repeated for the three soil conditions separately and the three combined.

Figure 1. Tank set up and load application on the Soil

Figure 2. Pile driven into Clay Soil in the Tank

Figure 3. Settlement measurement on Dial gauge

III. DISCUSSION OF TEST RESULTS

Pile group efficiencies as well as pile spacing were pre-determined for the chosen test pile configurations of 2 x 2 (4 piles) and 3 x 3 (9 piles). Group efficiencies and pile spacing of 0.85; 4d and 0.99; 3d for 2 x 2 and 3 x 3 configurations respectively were adopted. A total of 30 tests (15 each for the circular and square piles) were conducted in the laboratory. The results of critical cases were evaluated and thus presented.

The result of some of the geotechnical properties of the tested clay samples is shown in Table 1. The samples can be described as slightly over consolidated soft clay, having 0 cohesion in it wet state and less than zero liquidity index.

Table 1. Some Geotechnical Properties of the Clay Sample

Parameters	**Modeled strong clay** (γ = 19 kN/m^3, *w* = 10%)	**Modeled weak clay** (γ = 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
Angle of internal friction (φ^o)	25	33
Modulus of Deformation E (kPa)	8.5	5.4

The Load-settlement curves at different loading conditions for both circular and square piles are shown in figures 4 - 7. Generally, pile displacements increased with increment in loading. 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. The reinforced weak clay behaved similar to strong modeled clay in it response to deformation and pile displacement under axial loadings.

From the testing tank transparent panel (fig. 8), a careful visible observation showed eaves, depression and total settlement of modeled test piles, which varies with the differences in pile spacing. The failure bulb and deformation zones produced can clearly be seen in figs. 9 and 10. Averagely, 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 pile diameter).

Lateral deformations decrease with increase in distance from the pile, and outward radial deformations recorded around the pile decreases downwards as shown in figs. 11 and 12.

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

The initial settlement of square piles is higher than that of circular piles. This is due to wider surface area in contact and less negative friction. However, as the loading rate increases, circular piles penetrate further with higher settlement and deformation than square piles, figs. 11 and 12. Fig. 7 clearly shows that for a given loading rate, the settlement of circular piles is higher for a corresponding load. This was practically proven in the three modeled soil conditions investigated.

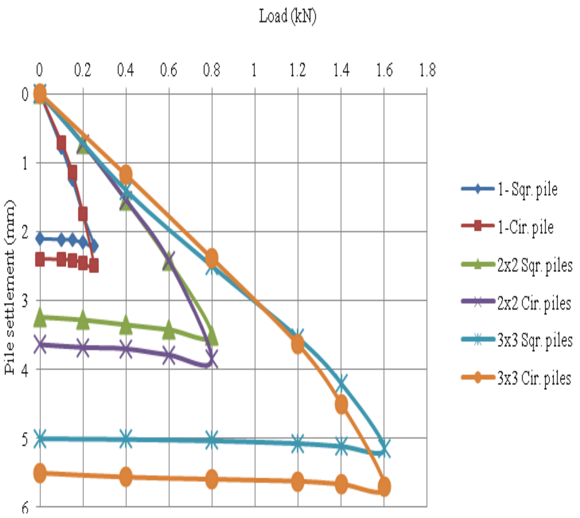

Figure 4. Load-Settlement curve @ 0.01 mm/ min loading rate

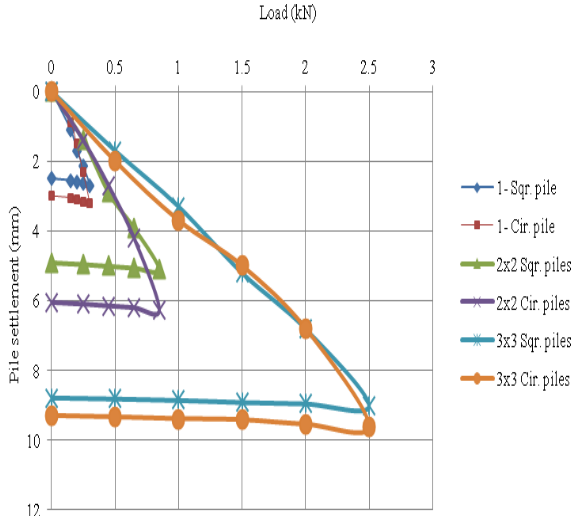

Figure 5. Load-Settlement curve @ 0.05 mm/ min loading rate

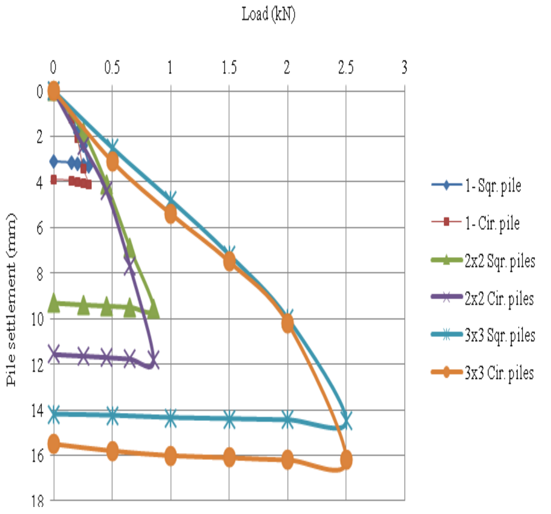

Figure 6. Load-Settlement curve @ 0.1 mm/ min loading rate

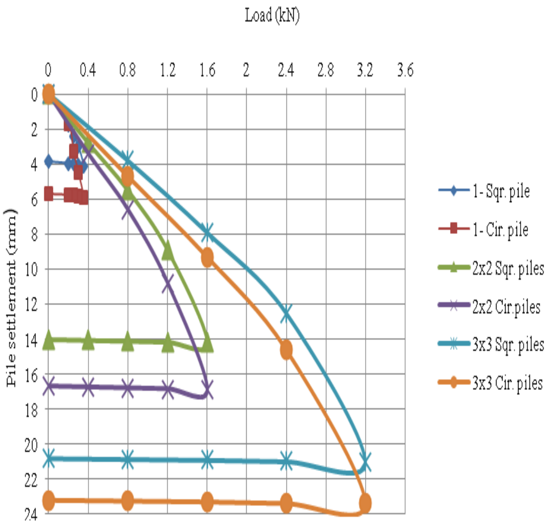

Figure 7. Load-Settlement curve @ 1.0 mm/ min loading rate

Figure 8. Testing Tank showing eaves, depression and settlement of piles

Figure 9. Failure bulb and Deformation Zones under load

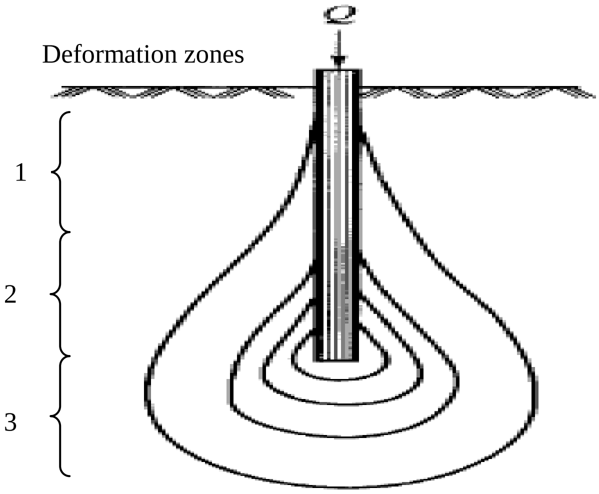

Figure 10. Failure bulb and Deformation Zones of a Single Pile

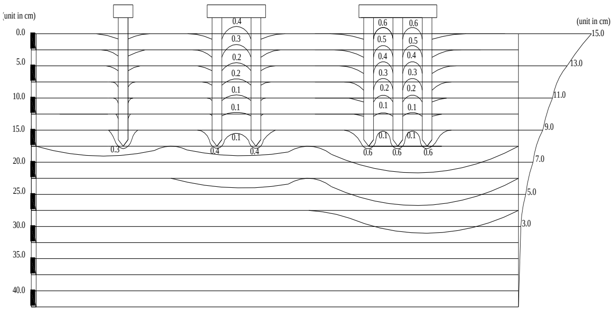

Figure 11. Deformation of Soils around Square Piles

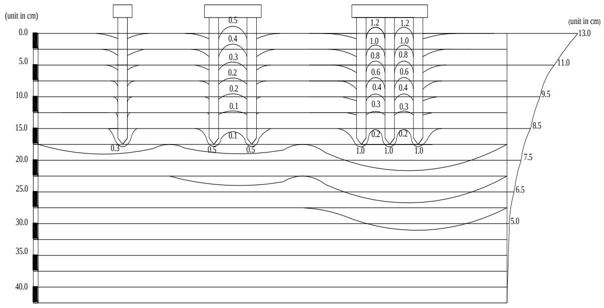

Figure 12. Deformation of Soils around Circular Piles

In conclusion, it can be deduced from the study that, the settlement of modeled test piles increases with axial load. The lateral deformation of pile decrease with increase in distance from the pile centre line, while the outward radial deformations around the pile shaft decreases with depth. Also pile displacements increase linearly with the applied load.

The initial settlement of circular piles is lower than that of square piles. However, as the load increases circular piles produce a larger overall settlement than the square piles.

Furthermore, a failure bulb of deformation of roughly 3 zones with depths of 3d, 2.5d and 2d along the pile length downward has been identified.

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