

MODELING OF AXIALLY LOADED PILE GROUP SETTLEMENT IN SOFT COMPRESSIVE CLAY

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Abstract

This paper presents the results of recent experimental investigation on modeling of settlement of pile group under axial load in soft compressible clay. The prototype test piles in the model were axially loaded until failure. Three modeled soil conditions were investigated: strong modeled clay; weak modeled clay; weak clay between strong modeled clay layers. 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 soft compressible clay soils (differentiated by moisture and density of $w = 20\%$, $\gamma = 17 \text{ kN/m}^3$ for the weak; $w=10\%$, $\gamma = 19 \text{ kN/m}^3$ for the strong). Using Mohr-Coulomb constitutive model, a one-dimensional non-linear Load transfer model for the settlement of pile group in compressible clay was developed. The model produced a handy load-settlement curves and settlement similar to those obtained by a number of conventional settlement analysis models.

KEYWORDS: Axial load; Compressive clay; Deformation; Modeled piles; Settlement.

Introduction

Resistance of axial load as well as lateral load is of critical importance in the design of pile foundation carrying large vertical loads as well as loading from earthquake, soil movement, waves etc. [1].

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 [2], [3]. 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 [2] and [6].

In geotechnical engineering, soils with properties that cannot be safely and economically used for the construction of civil engineering structures without adopting some stabilization measures are referred to as weak or problematic soils. Soft compressible clay falls into this category [7].

Under axial loads, soil within a few pile diameters can undergo noticeable settlement which may lead large shear deformations. The pile driving process can potentially generate large stresses and deformations in the nearby soils [8]. For many cohesive clay soils which tend to be highly sensitive to remolding, this leads to significant loss of strength in the short term [9] and [10].

The piles penetration depth (length) depends on the magnitude of the applied load and type of soil around the pile. 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] and [13].

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 [12], [14] and [15].

The settlement and deformation of soils around loaded piles are among other indications of the long-term behavior of the structure [16] – [19]. Therefore, analysis of settlement arising from deformation of modeled piles especially in soft compressible clay, would not only present scientific interest for the geotechnical engineers, but a guide, construction as well as monitoring of the project.

Therefore, presented in this paper is the result of tests on modeling of pile group settlement in soft compressible clay, conducted in the research laboratory, Geotechnical and En-

vironmental Engineering department, Belorussian National Technical University, Minsk, Belarus. The settlement of pile group for the three soil conditions was modeled using Mohr-Coulomb model to develop a one-dimensional non-linear Load transfer model for settlement of pile group axially loaded until failure with soil parameters: internal friction angle (ϕ), cohesion coefficient (C), elastic modulus (Es) and Poisson's ratio (ν s).

Experimental Investigation

Wet clay soil sample obtained from a site around Uručcha, at the outskirts of Minsk province of Belarus, were investigated in this study. 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 pulverized, air-dried and conditioned clay was placed in the test tank in layers, according to the proposed modeled soil conditions; strong modeled clay; weak modeled clay; weak clay between strong modeled clay layers. The strong clay was modeled with a unit weight of 19 kN/m³ and 10% moisture content, while the weak clay has 17 kN/m³ and 20% moisture content.

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).

The test piles are of circular and square shapes, having 20mm diameter and sides and 200mm length for both circular and square respectively. The 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 [20] - [24], also commented on by [25] and [26].

The settlement of the clay was measured by means of a dial gauge, which was connected to the upper plate (Figs. 1 and 2). This and other tests were carried out to determine the geotechnical properties of the soft clay needed for the model.



Figure 1. Testing tank and load application on soft clay



Figure 2. Testing tank and load application on soft clay

Mohr-Coulomb elasto-plastic criteria (Model)

The Mohr-Coulomb Model (MCM) is a linear elastic and perfectly plastic model. Unlike other complex models, it enables the user to specify the strength, and stress-strain properties of the element through the input of the constituent parameters namely; internal friction angle (ϕ), cohesion coefficient (C), Young modulus (Es) and Poisson's ratio (ν). The shear modulus can be obtained through ν and E, $\{G = E / (1 + \nu)\}$. Using Mohr-Coulomb model may also reduce the time of the analysis in comparison with other approaches having complex constitutive models.

Mohr-Coulomb elasto-plastic criteria, partially shown in Fig. 2 which has been used for the medium sandy soil to overcome the difficulties arising from the need to perform more complex shear test and back analysis associated with

complex models [27]. The relationship of the failure shear stress can be modeled with the Mohr-Coulomb and described using Mohr-circles. Before applying the load to the system, the model equilibrium under initial state was controlled.

Discussion of Test Results

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 normally consolidated in 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). To a large extent, the properties of this clay are typical and similar to that of soft clay found in Sokoto, north-western Nigeria, and a few other places as reported by Ola [28] - [29].

The ultimate bearing capacities (factored) of test piles in the three modeled soil conditions are shown in Table 2. Modeled 1 with stiffer and stronger clay has the highest ultimate bearing capacities of 641 kPa and 630 kPa for square and circular piles respectively. The lowest bearing capacities of 363 kPa and 355 kPa were recorded for the square and circular test piles respectively. Model 3 with weak clay between strong clay layers produced higher bearing capacities, as shown in the table, since pile shafts projected through and beyond the weak layers.

Table 1. Some Geotechnical Properties of the soft clay sample

Parameters	Modeled weak clay ($\gamma = 17 \text{ kN/m}^3$, $w = 20\%$)	Modeled strong clay ($\gamma = 19 \text{ kN/m}^3$, $w = 10\%$)
Specific gravity of solids	2.66	2.66
Liquid Limit (%)	24	23
Plastic Limit (%)	18	17
Plasticity Index (%)	6	6
Liquidity Index (%)	0.3	$I_L < 0$
Void ration (e)	0.84	0.51
Cohesion (kPa)	0	20
Relative consistency	2.37	2.31
Angle of internal friction (ϕ) degree	34	25

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

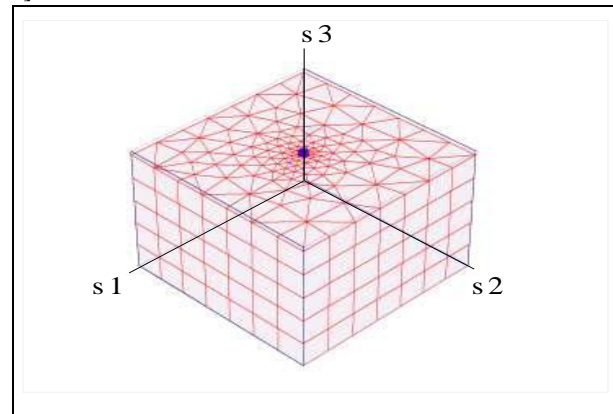
Pile Foundation Prototype shape	Ultimate Bearing Capacity (kPa)		
	Model 1	Model 2	Model 3
Square	641	363	496
Circular	630	355	482

Model 1- Modeled soil condition for strong clay

Model 2- Modeled soil condition for weak clay

Model 3- Modeled soil condition for weak between strong clay layers

Employing Mohr-Coulomb constitutive model, the failure envelope generated (Fig. 3), with S3 i.e. σ_3 on y-axis, S2 i.e. σ_2 on x-axis, S1 i.e. σ_1 on z-axis, shows, that the failure behavior of the soil, and its dependence on principal stress, Poisson's ratio, cohesion, angle of internal friction and average elastic modulus. The square shape piles have a higher shaft resistance and lower settlement at corresponding load compared with circular shape pile as shown in the load-settlement curves for the three modeled conditions in Figs. 4-6. Fig. 5 shows a wider variation of 3x3 pile group for weak soil condition. Fig. 4 and 6 exhibited similarity, but the weak-strong model soil condition, fig. 6 underwent a higher settlement than the purely strong model condition in Fig. 4. From the results, using elasto-plastic criteria of Mohr-Coulomb model, from which the model was generated, the computed settlement obtained largely agreed with one measured on the test platform, and also with the one obtained using Polous-David-Randolph (PDR) method. The internal angle of friction (ϕ), cohesion coefficient (C), Poisson's ratio (ν_s) and the average elastic modulus of deformation (E_s) were obtained to be 30 degree, 19.7 kPa, 0.26 and 8.2 kPa respectively, which is similar to the one obtained by [27].



Simulations: s for stress; $\sigma_1 = \sigma_2 = \sigma_3$; $\phi = 25$, $\nu = 0.25$; $C = 0$, $C = 20 \text{ kPa}$
Figure 3. Load-Settlement curve @ 0.01 mm/ min loading rate

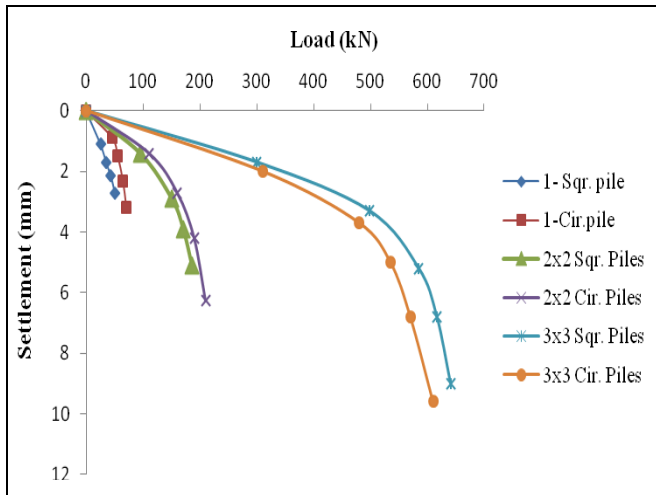


Figure 4. Load-Settlement curve for strong clay model

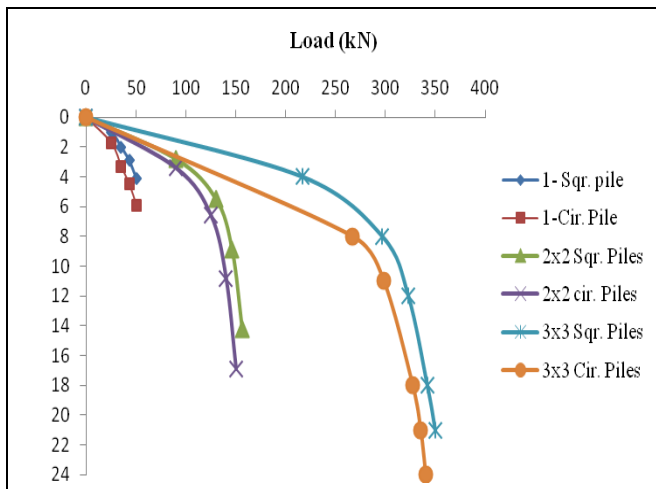


Figure 5. Load-Settlement curve for Weak clay model

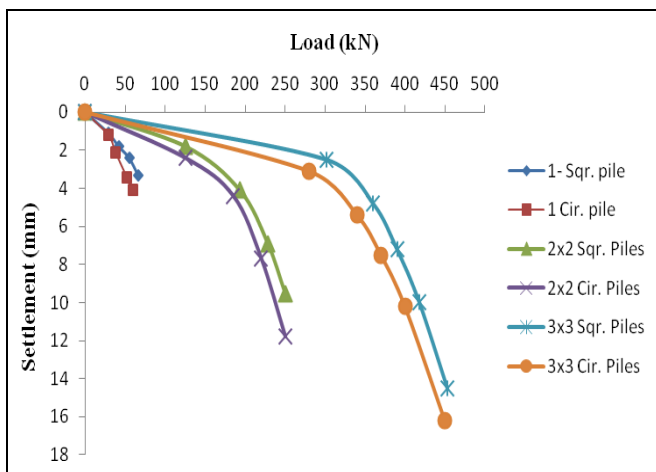


Figure 6. Load-Settlement curve for weak-strong clay model

Conclusions

From the results of modeling of settlement of axially loaded pile group in compressive clay, the following conclusions may be drawn:

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. Therefore, the higher contact area between the square pile and surrounding soils plays a greater role in its less settlement and high shaft resistance than the circular piles

The higher the pile component (number of pile) in the group, the more pronounce may be the effect on settlement and lateral deformation in weaker clay soils.

As the result agreed with most conventional models, laboratory investigation on modeling of settlement analysis of pile group when properly conducted provides a reliable in understanding of pile group behavior, especially in soft compressible clay.

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