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Load-Displacement and Load Transfer Mechanisms of Pile Foundation Using AllPile Software

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Abstract

Numerical analysis has become increasingly important in the design of pile foundations, as it is a concept based on the needs of the project. Various techniques, such as empirical approaches, CPT-based analyses, and pile load tests, have been developed to predict how loads are transferred and how the pile settles along its length. However, these empirical methods may not be suitable for different pile and soil conditions, and they are also costly and time-consuming, leading to higher construction costs. In order to overcome these challenges, numerical analysis using soil properties obtained from field soil tests can easily generate t-z curves and evaluate the performance of pile foundations. In this particular study, a numerical model was created using the affordable software AllPile V6.5.0, which effectively represents the soil-pile interface along the entire pile length. The soil profiles of the area were described using SPT tests. The objective of this research was to assess the allowable bearing capacity, load efficiency, and frictional resistance of BCIS piles using the AllPile software as an alternative to expensive and time-consuming pile load tests and CPT-based methods. This study provides valuable insights into the efficient analysis of BCIS piles for the proper design of pile foundations.

Keywords: *BCIS Piles; SPT; CPT; AllPile Software; Numerical Analysis.*

1 Introduction

Tall buildings are usually built on a pile foundation subjected to a combination of vertical, lateral and overturning forces (Poulos, 2011), with the aim of transferring structural responses through weak and low-bearing soil layers to deeper and harder soil layers. The need for a deep foundation in any given project is usually determined by several factors, including subsurface conditions, foundation loads, and acceptable foundation placement criteria (Bell et al., 2002). All types of piles are invented to meet structural, soil, and local environmental and economic conditions and can be used with two main installation methods: driving or drilling (Day, 2010). The method of activating pile bearing capacity varies and is affected by many factors such as pile types, soil characteristics, drilling or driving method, loading method, etc. The bearing capacity of piles usually consists of two parts: the pile shaft resistance and the pile tip resistance. Pile shaft resistance is the most sensitive factor in the calculation of pile bearing capacity due to pile surface friction and/or cohesive adhesion between pile and soil (Yu, 2009; Hannigan et al., 1998). The calculation method is made for two common types of soil: sandy soil and clay soil. But sometimes, the soil isn't easy to tell apart and can be mixed together in different layers. When water gets soaked up by the soil, it can make the ground weaker and not able to hold as much weight. This makes it difficult to use a standard method to figure out how strong the ground is. Also, the usual methods take a lot of time and money and don't give information about how the soil and piles of stuff on top of it interact with each other. Pile load tests and cone penetration tests are also expensive and time consuming. Many empirical or semi-empirical methods have also been developed to avoid them (Sliwinski & Fleming, 1984). This is basically defined as the allowable stress and ultimate limit design approach. The allowable stress-based method is traditional, well-established and mostly used, but conservative and uses a high overall safety factor of 2 to 4 (Becker, 1997). The ultimate boundary design method is more rational, but is still considered unsafe and unacceptable to many designers, so it is not included in many codes and standards (Becker, 1997). Today's situation clearly shows that there are unresolved uncertainties in pile bearing capacity calculations around the world (Christian & Baecher, 2011). Therefore, the only approach for researchers and designers to obtain reliable estimates of pile bearing capacity is to provide inexpensive, time-efficient numerical analysis values for piles in different types of soils, along with surface influence factors. The interaction between piles and the surrounding soil is complex, making generalizations about pile behavior unrealistic. The insertion of piles changes the properties of the soil, resulting in intense strains locally near the piles (Rao & Supriya, 2015). Soil heterogeneity makes it even more difficult to understand soil-pile interactions, beyond the effects of pile diameter and pile depth (Rao & Supriya, 2015). In such cases, successful pile foundation design requires an understanding of pile capabilities and other soil-pile interfacial properties. Therefore, it is of great interest for researchers and designers to know the pile capacity, shear stress, displacement along the soil-pile interface, and load settlement under vertical loading.

Several previous studies have investigated the effect of foundation geometry (Garcia and Albuquerque, 2019; Bezerra et al., 2005), the contribution of raft bottom contact and the load distribution between elements and their variables (Butterfield and Banerjee, 1971). As reported by Poulos and Davis, 1980, the parameters of foundation geometry, number of piles and material properties affect foundation behavior. Most researchers primarily focus on how the shape, number, and material of foundation piles affect their performance. However, none have used the AllPile V6.5.0 software to analyze pile foundations. This study presents a numerical model using AllPile V6.5.0 to predict the capacity of BCIS piles and gain insights into their performance. The study also demonstrates how AllPile 6.5.0V can be used to measure soil-pile interface behavior and accurately predict load displacement and transfer mechanisms.

2 Materials and Methods

2.1 Properties of Soil Used

This study focuses on the behavior of silty clay soil particles, which are in between sand and clay in terms of their characteristics. Understanding this behavior is crucial for geotechnical design. The researchers used soil stratification to model silty clay soils and provided the corresponding parameters in Table 1.

Table 1. Properties of Soil Used in this Analysis.

Zg (m)	Soil Data Input	G (kN/m^3)	Phi (deg)	C (kN/m^2)	K (MN/m^3)	Strain (E50)	Nspt
0	Soft Clay	5.3	0.00	4.2	2.6	4.38	1
2	Sand/Gravel [W]	6.0	27.2	0.00	1.2	8.69	2
3.1	Silt (Phi+C) [W]	8.9	27.6	15.0	25.9	1.33	5
4	Silt (Phi+C) [W]	9.8	28.6	20.9	48.9	1.08	7
6	Silt (Phi+C) [W]	10.8	30.9	38.9	123.6	0.74	13
11	Silt (Phi+C) [W]	10.1	29.1	24.5	62.9	0.98	8
12	Stiff Clay [W]	10.8	0.00	77.8	123.6	0.74	13
15	Stiff Clay [W]	10.5	0.00	59.9	85.0	0.87	10

2.2 Properties of Pile Used

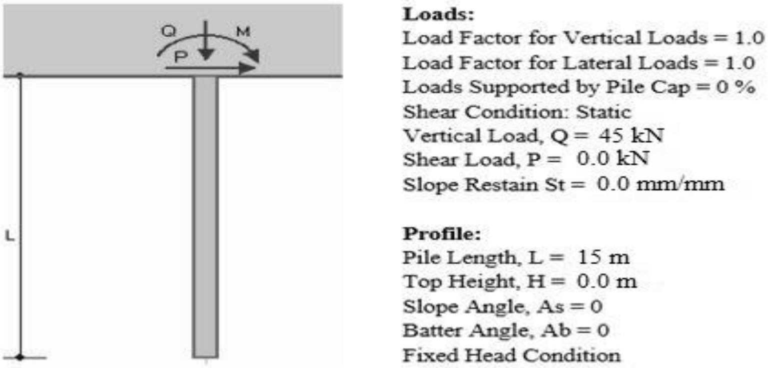
This study employed the advanced software program AllPile V6.5.0 to model a sophisticated 15-meter long, 40-centimeter diameter boring pile situated within silty clay soil. The meticulous characteristics of the piles utilized in this investigation are meticulously delineated in Table 2.

Table 2. Properties of Piles Used in this Investigation.

Depth (m)	Width (cm)	Area (cm^2)	Perimeter (cm)	I (cm^4)	E (MP)	Weight (kN/m)
0.0	40	1256.6	125.7	125663.7	20683	2.963
15.0	40	1256.6	125.7	125663.7	20683	2.963

2.3 Numerical Modeling

The software program AllPile 6.5.0V was used for numerical modeling of drilled concrete piles (Fig. 1) and is compatible with various types of piles and shallow foundations. It stands out from other pile software because it can handle multiple types of pile analysis in one program, including compression, uplift, lateral capacity, and group analysis. AllPile 6.5.0V is suitable for engineers of all levels of experience and helps with selecting soil parameters and pile properties. It is a valuable tool for civil, geotechnical, and structural engineers for analyzing different types of piles and shallow foundations.



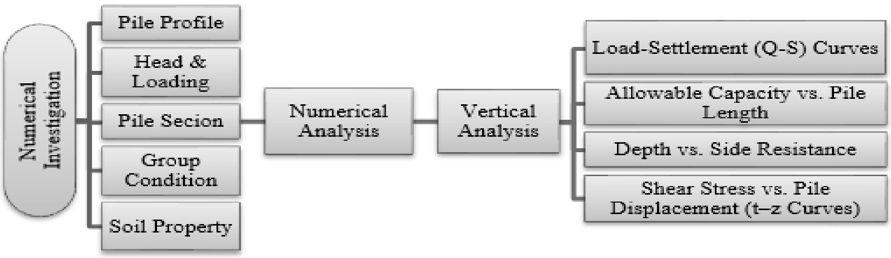
Loads:
Load Factor for Vertical Loads = 1.0
Load Factor for Lateral Loads = 1.0
Loads Supported by Pile Cap = 0 %
Shear Condition: Static
Vertical Load, Q = 45 kN
Shear Load, P = 0.0 kN
Slope Restain St = 0.0 mm/mm

Profile:
Pile Length, L = 15 m
Top Height, H = 0.0 m
Slope Angle, As = 0
Batter Angle, Ab = 0
Fixed Head Condition

Figure 1. Numerical Modeling of Pile in AllPile Software.

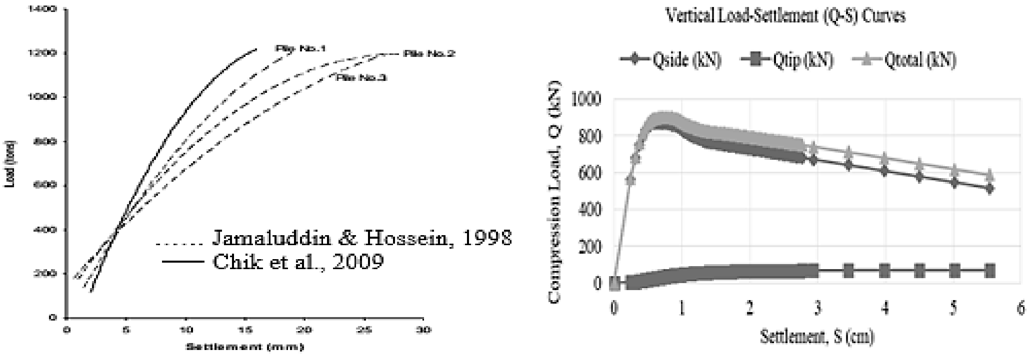
2.4 Methodology

The step-by-step procedures of the analysis are shown in the following flowchart –



3 Validation of this Study Using Experimental Results

To validate this study, the experimental results (Chik et al., 2009) are compared with the numerical model of this study.



(a) Load-Settlement Curves (Chik et al., 2009)

(b) Load-Settlement Curves (Present Study)

Figure 2. Comparison of Load-Settlement Curves between the Present Study and the Measured Results Reported by Chik et al., 2009.

Chik et al., 2009, investigated pile load testing of 75 m long piles used in the construction of a new 2.2 km two-lane road project in Port Klang, Malaysia. The subsurface was characterized by a soft silty clay about 20m deep, under which is a layer of soft silty clay 10m thick, followed by medium to dense silty sand and medium silty sand followed by a layer of hard silty clay. The numerical analysis results showed the consistency of the model with the reality and have the greatest similarity between the numerical and experimental results as shown in Figure 2.

4 Results and Discussions

4.1 Shear Stress at the Pile Shaft (t) and Pile Displacement (z) along the Pile Shaft

Figure 3 shows the relationship between shear stress and displacement (t-z curves) at the soil-pile interface at certain depths (1.9 m, 3.8 m, 5.6 m, 7.5 m, 9.4 m, 11.3 m and 13.1 m) along the length. The highest lateral resistance (t) was found at a depth of 13.1 meters and the lowest lateral resistance (t) at a depth of 1.9 meters. The analysis results also showed that the maximum displacement (Zm) at the pile head at fully mobilized shear strength was approximately 3.0 to 5.0 mm.

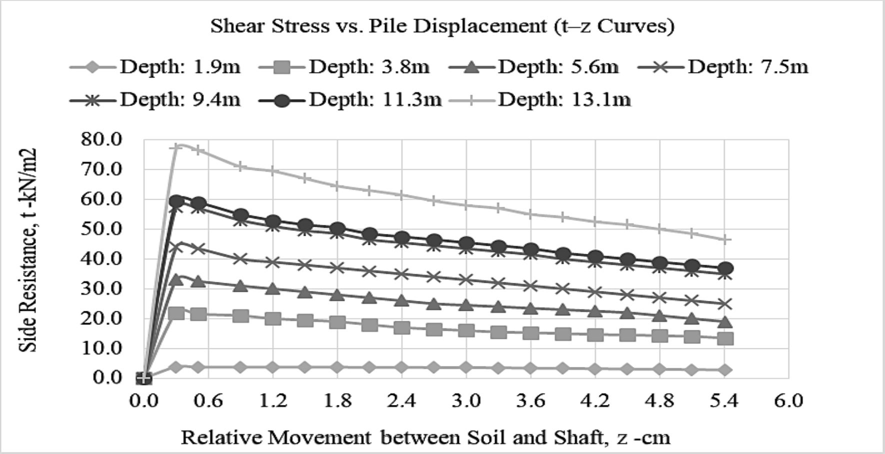


Figure 3. Relationship between Shear Stress and Displacement (t-z curves) at the Soil-Pile Interface along the Length.

4.2 Vertical Load-Settlement (Q-S) Curves for Bored Pile in Silty Clayey Soils

The load-settlement curves (Q-S curves) of a cast in-situ pile in silty clay soils under vertical loading is shown in Figure 4. The steeper portion at the beginning of the load-settlement curve indicates less pile settlement at a given load. The total vertical/total bearing capacity of the boring pile was 903.10 kN with a small settlement of 0.78 cm (or 7.8 mm). After that a large settlement was observed without increasing the load capacity. The reduction in final capacity may be due to surface friction between the soil and the pile. A portion of the pile was absorbed by soil skin friction, resulting in a downward force, which increases the load on the shaft pile, reduces the bearing capacity of the pile, and finally shear failure is pronounced in soil mass.

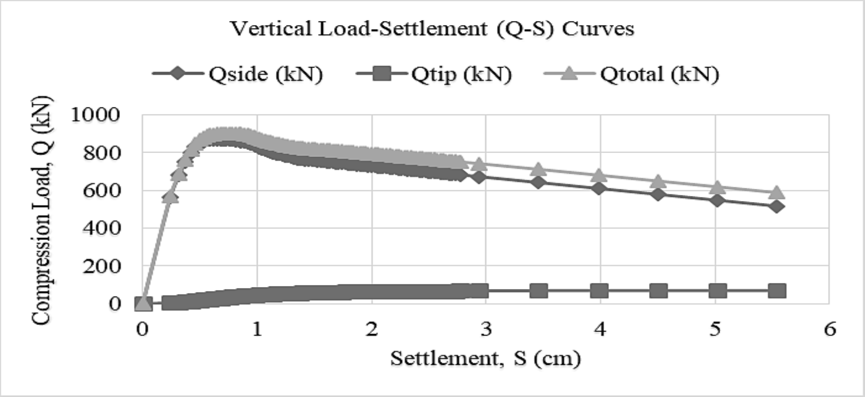


Figure 4. Load-Settlement (Q-S) Curves for BCIS Pile in Silty Clay Soils.

4.3 Variation of Allowable Capacity with Pile Length

Figure 5 illustrates the variation of allowable downward capacity (Qd) and uplift capacity (Qu) with pile length (L). The analysis results revealed that the allowable capacity (Qd and Qu) increased linearly with the increased depth of pile. The allowable uplift capacity of bored pile was found to be 315.5 kN, whereas, the allowable downward capacity was found to be 364.48 kN when the length of pile was 15 m, embedded in silty clay soils.

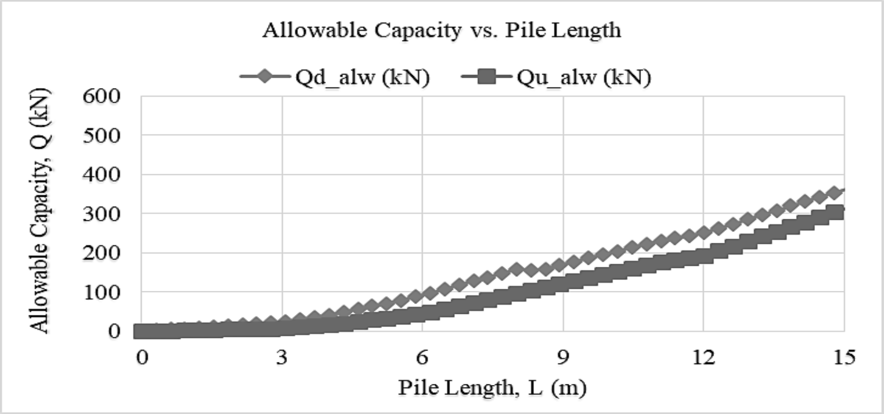


Figure 5. Variation of Allowable Capacity with Pile Length.

4.4 Variation of Skin Friction (Side Resistances & Adhesion) between Soil and Pile

The friction curve of the pile surface is formulated and shown in Figure 6. The friction to the pile increased gradually as the pile depth increased. This is due to the fact that in the process of load transfer, the friction resistance at the pile gradually begins to work as the depth increases and reaches the maximum level until the pile top load is mainly borne by the pile tip resistance. Since the soil profile under study was soft silty clay, the frictional resistance of the soil surrounding the pile was dominated over the tip resistance and thus increased gradually. In addition, pile-soil adhesion plays an important role in increasing the side resistance of piles in clay in terms of total stress.

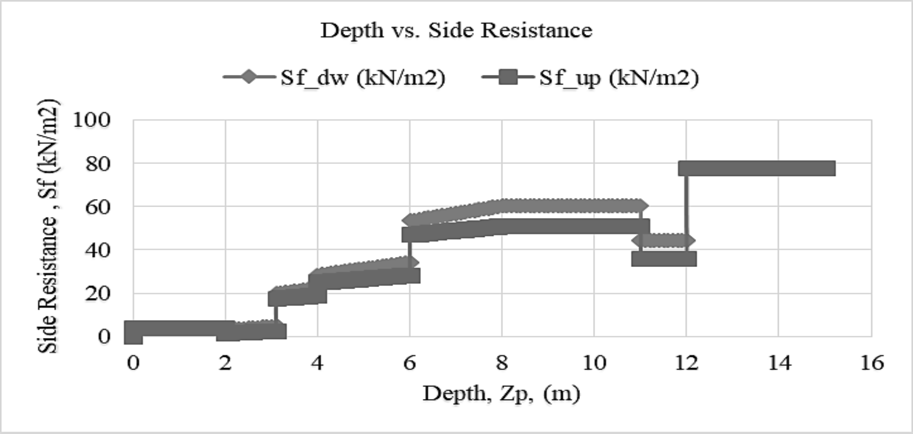


Figure 6. Variation of Side Resistances (Uplift and Downward) between Soil and Pile.

5 Conclusions

Based on the results presented in this study, the major findings can be summarized as follows-

- Based on load-settlement curve, the total ultimate capacity of bored pile was found to be 903.10 kN, with a little settlement of 7.8 mm, beyond which a large settlement was observed without increasing of ultimate capacity.
- The allowable uplift and downward capacity of bored pile was 315.5 kN and 364.48 kN respectively for fully embedded length of pile.
- The frictional resistance offered by the soil surrounding the pile was found to be dominated over the tip resistance and consequently increased gradually with the depth.
- The maximum pile displacement (Zm) to fully mobilized shear strength was found to be 3.0-5.0 mm from the simplified "t-z" curves derived from numerical analysis.
- The proposed numerical analysis is a simple, time and cost-effective solution for efficiently understanding soil-pile interface properties and helping to optimize pile design and construction.

6 Recommendations

Geotechnical and structural engineers can use the simple and time-saving AllPile 6.5.0V software to numerically analyze the soil-pile interface properties of all types of pile foundations using only soil-layered bore log data as an alternative to time consuming and costly empirical and CPT based methods.

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