Comparison among Different Methods to Estimate Ultimate Capacity of Bored Pile

Bushra S. Albusoda\textsuperscript{1a}, Mohammed S. M\textsuperscript{1b} and Mohammad F. Abbas\textsuperscript{2c}

\textsuperscript{1}Department of Civil Engineering, University of Baghdad, Baghdad, Iraq
\textsuperscript{2}Department of Civil Engineering, University of Al-Muthanna, Al-Muthanna, Iraq
\textsuperscript{a}dr.bushra_albusoda@coeng.uobaghdad.edu.iq, \textsuperscript{b}mohammed.bridge@gmail.com, \textsuperscript{c}engmoh863@gmail.com

Abstract This study investigates the ultimate load capacity of concrete 1.5 m diameter bored pile based on three methods: field-loading test, field Standard Penetration Test results, and numerical modeling. A comparison of the ultimate load capacities from these methods was made (the measured large-scale field-loading test, the correlated SPT \textit{N} values applying Novo SPT software and numerical modeling where Plaxis3D software with Mohr-Coulomb model was utilized). The result of the pile field-loading test was more accurate than the other methods and used as a reference for comparison among their results. In general, the value of ultimate load capacity calculated from Novo SPT software and that obtained from numerical analysis were compatible in comparison with field load results.

Keywords: Pile loading, Novo SPT software, bored pile, Plaxis 3D.

1. Introduction

Concerning the doubts regarding the design and analysis of pile foundations, it has become a practice, and mostly obligatory, to conduct large-scale pile loading tests. These field-loading tests are costly, requiring much time, and for limited projects, the expenses are often tough to justify. Piles loading tests are usually executed to measure the ultimate capacity of piles of a foundation system at the project site and to estimate the quality of all piles. Pile loading also has a significant role to play as a mean in the estimation of settlements of foundations, despite the doubts expressed by many investigators that the settlement of a single pile has little or no link to that of a pile group [1]. Preferably, to allow an estimate of the distribution of base and shaft resistance during loading stages, testing of piles should use transducers. Analysis of results of such tests should consider the presence of residual stresses brought during pile construction, if it does not consider these stresses a confusing calculation of the shaft and base resistances can be made [2].

After assessment and validation in the site, the designer approves the design load that already calculated based on the site investigations report or modified accordingly for the safer design for project piles. The possible variation of piles quality having the same configuration is relatively narrow down by conducting pile integrity tests according to ASTM - D5882 for all piles [3].

To study the behavior of large pile (1.5 m) diameter, a static vertical loading and unloading tests were carried out at experimental non-working pile in Al-soodor Bridge project site according to ASTM-D1143. Both of pile loading test data and the Novo SPT software ultimate loads components were compared with Plaxis3D software analysis based on input data from site investigations report to attain more insight into the behavior of the large pile diameter subjected to vertical loading and unloading.
The Mohr-Coulomb soil model was employed for modeling the granular soil behavior and its interaction with field pile in this software.

2. Study Area
The pile load-settlement data and SPT test results of the study were obtained from Al-sodoor Bridge site in Diyala Governorate. The 1.5 m large diameter pile with 20 m length was tested using a 750-ton working load applied on it by axial compression as shown in Fig. 1. The reaction force is transferred by hydraulic jacks which conveying the field load test from a frame of steel girders loaded by an array of concrete blocks. Accurate certified calibrated instrumentations were installed onto the top of the pile test so that an accurate measurement of the test pile displacement can be obtained. Figure 2 illustrates configuration for hydraulic jacks’ group and the controls for measuring pile loading and settlement, this test was carried out according to ASTM-D1143.

![Figure 1. Pile loading test.](image1)

![Figure 2. Hydraulic jack group.](image2)

3. Pile Design Based on Soil Correlations
In general, the design of piles is based on empirical correlations specified experimentally on different soils by several researchers by conducting laboratory and field tests thus, this situation often confusing the geotechnical designers. Several site investigations boreholes may not be enough to explore the subsoil conditions of the whole pilling project. So, conducting pile loading tests are the most reliable way to confirm the integrity of as-constructed piles at the site. It is important to conduct a pile-loading test to verify the actual pile capacity [4]. In the prediction of pile load capacity from the load-settlements curve within the given criteria, it is necessary to use pile loading test data specified that the pile load tests should be supplemented by detailed site investigation to define the entire soil profile accurately [5].

4. Analysis Method and Material Properties

4.1. Pile Ultimate Load Capacity Analysis Using Static Load Test
To ensure the geotechnical and the structural reliability of the pile also to predict settlement of other piles, the pile load test is frequently carried out. This field loading was performed using a reaction method. The test procedure involves applying an axial compression load on the top of the experimental large (1.5 m) diameter pile test (with 20 m length from the ground surface level) by four hydraulic jacks on the top of the test pile as shown in Fig. 1. The static pile load test caused a mobilization along the soil-pile interface where this mobilization generally occurs well before the ultimate structural capacity of the pile is reached. Once the test is complete, the working pile is returned to an unload condition and the rebound of the pile can be measured.

According to ASTM-D1143, the non-working pile test was loaded to twice its design-working load that already estimated based upon the soil investigation report for site pilling and then unload leaving
the load off until the pile rebound substantially ceases. Figure 3 illustrates pile test settlement and rebound vs. loading and unloading while Figs. 4 and 5 illustrate the time versus load and (settlement and rebound) respectively.

**Figure 3.** Relation between pile settlement and rebound vs. loading and unloading.

**Figure 4.** Loading and unloading of pile test with time.

**Figure 5.** Settlement and rebound of pile test with time.
4.2. Ultimate Load Capacity Analysis from Field SPT N Values

It is known that, the prediction of the piles ultimate load capacity as being the region of highest uncertainty in the design of foundation. For predicting piles ultimate load capacity, several approaches and methods have been proposed to conquer their uncertainties. Some simplified postulations or empirical approaches concerning soil stratigraphy, soil-pile structure interaction, and distribution of soil resistance along the pile were included in these approaches. So, they do not provide quantitative values that are directly useful in foundation design [6]. In recent years, as a supplement of the static and dynamic load capacity analysis is the determination of piles load capacity from field loading data that has been used by geotechnical engineers. This is due to the fast progress of field-testing devices, a better appreciation of the soil’s behavior, and the subsequent comprehension of insufficiencies of traditional laboratory tests and some of their restrictions [7].

The Standard Penetration Test is yet the most generally used field test to characterize soil materials and for the determination of pile capacity, which is one of the earliest purposes of this field test. Nevertheless, some limits and disadvantages are involved with the SPT regarding the clarification and repeatability of test data. These problems are due to the uncertainty of the energy provided by different SPT hammers to the anvil system and regarding the field test procedures (the borehole diameter, the rod length, the split spoon sampler type, the blow rate, and the anvil type) [8]. The direct pile capacity evaluations are conducted by applying SPT N values with some modification factors to empirical correlations. Yet, there is a great deal of suspicion about averaging and filtering data that deals with pile ultimate capacity, the failure area in the vicinity of pile tip, utilizing a total stress method, and the piles capacity of narrow base penetration in compacted layers [9]. Depending on many theories, the indirect SPT approaches utilizing friction and undrained shear strength parameters predicted from measured data. In the indirect approaches, only soil parameters are attained from Standard Penetration Test and the procedure of the pile bearing capacity calculation is matching the static method, and thus contains a similar basis of faults [10].

In foundation design codes as well as in the literature there are several prescribed SPT-based design methods, most of them being empirical. The field tests are faster and cheaper than those carried out in the laboratory and do not necessitate any sampling. SPT test is suitable to estimate the resistance and density of granular media and is largely practiced within the scope of foundation projects. It should be however mentioned that the diversity of empirical interpretations of SPT and the dependence of this field test on the test procedure and the device features are the source of uncertainties and discrepancies between methods aimed to evaluate bearing capacity and settlement of foundations. These uncertainties in geotechnical pile design, notably within the scope of big sized projects, often lead to carry out static pile loading tests to experimentally determine pile load capacity and settlements as well. Although the SPT-based pile design literature is wealthy, one needs to be aware of local geotechnical conditions from which several empirical formulas were derived. Caution is then necessary when using any SPT-based method. Several studies on pile test databases were undertaken to empirically derive methods of pile design [11] or to assess existing methods [12].

4.3. Ultimate Load Capacity Analysis from Novo SPT Software

Novo SPT version 2.79.2014 is a software that deals with the analysis of Standard Penetration Test data and connecting between soil properties and the number of blows depended on more than 310 formulae. These formulae were quoted from more than 70 academic researches and papers are implemented in Novo SPT program along with powerful features for organizing the correlations such as statistical charts, reports, import, export data, and more. The SPT raw data are corrected/normalized for field procedures (Energy level, Borehole diameter, Samper type and Rod length) to obtain $N_{o}$ and applying overburden correction resulting ($N_{b}$/o) values (based on several types of research chosen by the user) where this parameter is widely used in engineering analysis including soil liquefaction among other correlations.

This software has a wide ability of calculating soil (Static and Dynamic) parameters and representing them graphically with borehole depth based on several researchers selected by the program's user [13]. The soil parameters that can be calculated by this program are: Overburden Correction factor ($C_{o}$), (E),...
(Ø), (Dₚ), Undrained Shear Strength (Sᵤ), Shear Wave Velocity (Vₛ), (G), Liquefaction Potential (CCR), Allowable Bearing Capacity (qₚall), Settlement (S) for a shallow foundation, Pile Bearing Capacity, CBR and other soil parameters, each equation is derived for specific soil type and may have limitation for use. Table 1 summarizes the calculated load resistance components for (1.5 m) diameter pile based on field SPT N values by utilizing Novo SPT software.

Table 1. Pile-load capacity values by utilizing Novo SPT software.

| Method | fₛ(Ton) | qₚ(Ton) | Comments |
|--------|---------|---------|----------|
| GEO, 1996 and Yau, 2000 | 515 | - | For bored pile |
| Hassan and O’Neill, 1994 | 1805 | - | For drilled piles |
| Meyerhof, 1976 | 313 | 809 | For small displacement piles (bored) |
| Quiros and Reese, 1977 | 780 | - | For drilled piles |
| Reese and O’Neill, 1988 | 1805 | 556 | For drilled piles |
| Reese and Wright, 1977 | 1393 | 592 | For drilled piles |
| Yves Robert, 1997 | 940 | 776 | For bored pile in granular soils |

4.4. Ultimate Load Capacity Analysis by Plaxis3D Software

Numerical analysis is increasingly accepted in geotechnical problems consideration where finite element evaluations are progressively employed in foundations design. In this study, many methods for evaluating the ultimate load of piles from field SPT data were used and matched with large-scale field loading test results. In this part, the Plaxis3D, which is a software, based on a three-dimensional finite element program specially developed for the analysis of foundations. This software described the behavior of the model by graphical procedures and some input parameters, which permit the user to generated models automatically, so induced good output facilities and detailed evaluation procedures.

To interpret the behavior of 1.5 m diameter single pile with 20 m length with the input parameters listed in Table 2, a model is made (with a 5 × 5 m) working area using Mohr-Coulomb model (which is an elastic perfectly-plastic model) where the model is isotropic and does not account for soils stress-dependency where soils tend to stiffen with increased pressure [14]. It is recommended using this model as an initial estimation of soil because of a relatively fairly accurate and fast for analysis. To generate the model of the pile in the program by employing a solid member from the standard option list and it is placed inside the interface layer at the center coordinates of the mesh. The generated mesh and the load-settlement curve of the system (for pile: L = 20 m, D = 1.5 m) by this software are shown in Figs. 6 and 7 respectively. Figure 8 illustrates the pile skin resistance-settlement curve. The borehole log for the study site is shown in Figure 9.

Table 2. Material input properties from site used for Mohr-Coulomb Model.

| Property | Values | Information Reference |
|----------|--------|-----------------------|
| γₛsat (kN/m³) | 20 | Project site investigation report |
| Drainage type | Undrained | Quick loading |
| E (MPa) | 58 | AASHTO, 1996 |
| ν | 0.49 | Undrained loading |
| Cohesion Cu (kPa) | 40, 50, 80 | Site investigation report for depths 0-8, 8-10, 15-20 m respectively |
| Friction angle (Ø°) | 36, 46 | Site investigation report for depths 6-15, 19-20 m respectively |
| Dilatancy angle (ψ°) | 6, 16 | Plaxis-3D Material Manual |
| γₛ (kN/m³) | 24 | Pile materials |
| Poisson's ratio (µ) | 0.2 | Pile materials |
| Modulus of Elasticity (MPa) | 200 | Pile materials |
Figure 6. Generated mesh of the system (for pile: L=20m, D=1.5m) as executed by Plaxis-3D.

Figure 7. Load-Settlement curve (for pile: L = 20 m, D = 1.5 m) as executed by Plaxis-3D.
Figure 8. Skin resistance-Displacement curve (for pile: L = 20 m, D = 1.5 m) as executed by Plaxis-3D

Figure 9. Borehole log for the study site.

5. Discussion of Results
Concerning pile ultimate load capacity values based on correlation with SPT N values, it is clear that these correlations were originally derived empirically based on different soil properties from soil property of the study site, which reflect the wide range of these bearing capacity values. Excluding high load capacity values from N values, there is a fair agreement with other value from field load test as well as with load capacity value obtained from Plaxis3D software analysis.

Evaluating the ultimate load capacities of piles is an importing approach in geotechnical engineering. Find a suitable method for predicting carrying load capacity of the pile is the trend of the investigators to peruse additional researches on this subject. In recent years, conducting field-testing such as SPT,
which can be used to predict the ultimate load capacity of the pile, because of its low cost, its simplicity, and being able to give a numerical parameter, that may be related to crude but straightforward design rule. The analysis of pile ultimate load capacity by finite element method using Plaxis3D software and comparing it with field loading methods, tried to find a reasonable prediction for its load capacity. The results indicate that, in this site, the field load capacity measured value (750 Ton) was fair close to the one obtained by the finite element method (FEM) (about 1000 Ton) based on input data from site investigation report, which is also close to pile load capacity components calculated based on SPT N values by utilizing Novo SPT software (1,071 Ton).

6. Conclusion

- Many factors are affecting SPT and produce a wide scattering in N values within test site where density, structure, water table, or lateral stress within the test medium will lead to a high range in calculated pile load capacities.
- The considerable difference in SPT apparatus and field procedures, a significant variability of measured penetration resistance can occur.
- The Mohr-Coulomb model gave a good prediction of the ultimate pile load as compared with empirical correlations based on field SPT N values.
- Conducting a pile load test is an essential matter in geotechnical foundation engineering concerning heterogeneity of site soil properties, being several boreholes for site investigation cannot give clear insight of soil substrata.
- It is a suitable and fast approach for simulation of soil behavior by using little input parameters of the Mohr-Coulomb model for analyzing geotechnical problems.

Reference

[1] H.G. Poulos, Pile testing and settlement prediction, Conference Paper in Geotechnical Special Publication, March 2012.
[2] A. Eslami and B.H. Fellenius, Pile capacity by direct CPT and CPTu methods applied to 102 case histories, Canadian Geotechnical Journal, 34 1997 886-904.
[3] N.T. Singh, Verification of pile load capacity using static pile load test, Conference Paper in Geotechnical Special Publication, December 2016.
[4] T. Matsumoto, K. Matsuzawa, and P. Kittiyodom, A role of pile load test–Pile load test as element test for design of foundation system, In Proc. 8th Inter. Conference on the Application of Stress Wave Theory to Pile: Science, Technology, and Practice, 2008 39-58.
[5] H.G. Poulos, Pile behavior-theory and application, Geotechnique 39 1989 365-415.
[6] A. Eslami and B.H. Fellenius, CPT and CPTu data for soil profile interpretation: review of methods and a proposed new approach, Iranian Journal of Science and Technology, Transaction, 28(B1) 2004 69-86.
[7] T. Lunne, P.K. Robertson, and J.J.M. Powell, Cone Penetration Test in Geotechnical Practice, Blackie Academic & Professional (1997).
[8] N.V. Nayak, Foundation Design Manual, Dhanpat Rai & Sons pub (1985).
[9] H.G. Poulos and E.H. Davis, Pile Foundation Analysis and Design, JohnWiley, New York (1980).
[10] B.H. Fellenius, D.E. Harris, and D.A. Anderson, Static loading test on a 45 m long pipe pile in Sandpoint, Idaho, Canadian Geotechnical Journal, 41(4) 2004 613-628.
[11] Robert, Y., 1997. A few comments on pile design. Can. Geotech. J. Vol.34. pp.: 560-567.
[12] M. Bustamante, R. Frank, and S. Christoulas, Evaluation de quelques méthodes de calcul des pieux forés, Revue française de géotechnique, (54) 1991 39-52.
[13] NovoSPT User's Manual, Design and Programming by Alireza Afkhami, 4188 Hoskins Road North Vancouver, BC Canada [Online]. Available at http://www.novotechsoftware.com.
[14] Plaxis-3D, Plaxis Material Manual, Version 1, 2013.