Estimation of the Large Diameter Bored Pile Ultimate Capacity Using Different Design Methods: Assessment Study

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Abstract. In this paper, in situ measurements of two well-instrumented loading tests performed on large diameter bored piles (LDBP) have been utilized to assess the reliability of the predicted ultimate pile capacity using three settlement-based and capacity-based methods. The first test was conducted on a short LDBP with a 1.3m and 9.50 length. This LDBP was constructed in stiff clay soil and loaded till the achievement of the failure. While the second in-situ loading test was performed on a long LDBP with a 1.00 m diameter and 34.00 m length. This LDBP was constructed in multi-layered soil and examined under three axially loading and unloading cycles to obtain the ultimate load settlement relationship. Although this LDBP was loaded with an applied load of three times its working capacity, but no apparent failure was reached at the end of the loading test. Thus, two different methods are adopted to interpret the test data and determine the ultimate pile capacity. The obtained ultimate capacities of the two tests were utilized in an assessment study. The comparative analysis results showed a significant difference between the ultimate capacity obtained using three different methods and field measurements. Out of the three utilized methods in this study, the two settlement-based methods underestimated the LDBP ultimate capacity of the two LDBP cases; conversely, the third capacity-based method overestimated the ultimate capacity of the two LDBP cases.

Keywords: Large-diameter bored piles, Assessment Study, International codes, Pile Ultimate capacity.

1. Introduction

Recently, significant growth has been experienced in the construction of high-rises buildings, offshore ports, wind power mills, storage silos, and many other types of heavily loaded structures. In those cases, large-diameter bored piles (LDBP) are qualified to be the most powerful of deep foundation elements that can successfully be implemented in various subsurface conditions. They are employed most frequently to support heavy loads and minimize settlement (O’Neill and Reese 1999 [1]; and Al-Atrash et al. 2021 [2]). With that in mind, several international foundation design standards and geotechnical codes recommend the full-scale in-situ pile loading test methodology to determine a reliable LDBP’s ultimate capacity (ECP 202/4 2005 [3], DIN 4014 1990 [4], SBC 303 2007 [5], and AASHTO LRFD 2005 [6]). However, loading this class of pile till reaching an obvious failure is practically seldom. In most cases, a substantial pile settlement is usually essential for achieving the full mobilization of the base and shaft resistances. In addition to the considerable test load and costly configuration of the reaction systems with high capacity that are mandatorily required for the achievement of enormous settlements at the failure state (Meyerhof 1986 [7]; O’Neill and Reese 1999 [1]; and Mullins et al. 2000 [8]). Therefore, practically, the aspired failure load may not always be achieved. In most cases, this is why the measured pile load-settlement curves for the LDBP usually do not show an apparent failure point. Therefore, several failure criteria have been developed for interpreting the pile failure load using the field data of the loading test. Hansen 1963 [9] criteria, Chin 1970 [10] extrapolation approaches are examples of diverse failure methods developed for that purpose.
Figure 1 presents the calculated ultimate capacities (Wael 2012 [11]) for three LDBPs with equal diameters and lengths. Those three LDBPs were implemented and insitu-tested in the same multi-layered soil. The first pile was tested under a load of 200% of its working load, while the second and third piles were tested under 150% of their working loads; thus, three different load settlement curves were obtained for the three piles. Chin 1970 [10], Hansen 1963 [9], Decourt 1999 [12], Ahmed and Pise 1997 [13] approaches have been used to determine the three LDBP ultimate capacities using measured pile load-settlement curves of the three in-situ pile loading tests.

As shown in Figure 1, differences in the estimated ultimate pile capacity from the different methods ranged from 20% to 50%. The largest ultimate capacity for the first pile was determined using Hansen method 1963 [9]. However, in the second and third pile cases, the largest ultimate capacities were obtained using Decourt 1999 [12] method. Also, Chin 1970 [10] method results were greater than those obtained from Hansen method 1963 [9], which is dissimilar to the first pile case results. None of these methods were consistent or superior to others in the three cases. This disagreement was expected because most of these methods were developed using the results of dissimilar cases of pile loading tests with a large diversity of pile proportions and soil geological conditions. Consequently, variable degrees of uncertainty may be associated with these criteria, and hence seldom will any two give the same failure load (Al-Atroush et al. 2020 [14], Ezzat et al. 2019 [15]). Nevertheless, most of those approaches are broadly accepted by several international design standards (e.g., ECP202/4 2005 [3]) to estimate the LDBP’s ultimate capacity in case of the failure of reaching an apparent failure point at the end of the in-situ loading tests.

Many interesting developments have been contributed towards a definition of a nominal failure load for LDBP in cohesionless and cohesive soils using specific settlement based criteria, e.g., 5% of the pile diameter (O’Neill and Reese 1999 [1]), and 10% of the pile diameter (Weltman 1980 [16]). In case of unfeasibility to execute pile loading test during the design phase, international codes (e.g., ECP202/4 2005 [3], DIN 4014 1990 [4] and AASHTO 2005 [6]) provide prediction methods to estimate the LDBP’s ultimate capacity. Most of these approaches depend on the specific settlement-based criteria to forecast the pile ultimate bearing resistance at a certain settlement rate. Also, the pile ultimate friction resistance could be estimated according to standard penetration test (SPT) results.

El Gendy et al. 2014 [17] calculated the ultimate capacities of 38 LDBPs with different geometries in multi-layered soils, using ECP202/4 2005 [3], German standard (DIN 4014 1990 [4]), AASHTO 2005 [6], and modified Chin 1970 [10] methods. A summary of the results is shown in Figure 2. It can be seen that there is an obvious difference between the determined ultimate capacities using different codes. Compared to DIN 4014 1990 [4] and AASHTO 2005 [6] codes calculations. It was perceived that the determined ultimate capacities using the ECP202/4 2005 [2] are mostly more conservative.
In this paper, field measurements of two full-scale well-instrumented large-diameter bored pile loading tests are used to investigate the feasibility of determining the LDBP’s ultimate capacity through the loading tests. In addition, two interpretation approaches are used to predict the ultimate—capacity of the long LDBP. Lastly, the calculated ultimate pile capacity using the in-situ loading test is used to assess the reliability of three different methodologies.

2. LDBP Case Studies: Full-Scale Loading Tests

Two well-instrumented large-diameter bored piles loading tests are utilized in this assessment study. The first test was performed on a short LDBP at the Alzey Bridge Project (Germany) by Sommer and Hambach (1974) [18] (Figure 3). This loading test was carried out to assess the Alzey Bridge foundation system optimization feasibility, and the LDBP was loaded until the complete failure. On the other side, the second test was performed on a long LDBP in the Damietta Port New Grain Silos project 2018 (Eid et al. 2018 [19]). As shown in Figure 4, it was decided to establish metallic silos (cone Type) with storage capacities of 70,000 tons, consisting of 10 storage cells, each of them with a diameter of 25 m. LDBP foundations were recommended because of the large loads acting on these silos due to their high capacities. According to the Egyptian code of deep foundation (ECP202/4 2005 [3]), two non-working piles were installed to be tested under the load of 9000 kN (Three times of design load) in order to determine ultimate pile capacity. One of those two piles was chosen to be instrumented in order to investigate the pile load transfer mechanism.
As shown in Figure 5, apparent failure was achieved by the end of the first loading test (Figure 5.a). This test was performed on a short large-diameter bored pile at the Alzey Bridge Project (Germany). In contrast, failure was not achieved by the end of the second load test (Figure 5.b); nevertheless, this long pile was tested under a load of about three times its working capacity failure was not achieved by the end of the second load test, as shown in Figure 5. The in-situ test measurements of the load settlement relationship, pile side friction, and base resistances under every loading increment are also shown in the exact Figure.

Using MIDAS GTS NX, two finite element models were established to simulate the behavior of the well-instrumented LDBPs, which were installed in a homogeneous stiff clay soil, and multi-layered soil for the first and second case studies, respectively. The Modified Mohr-Coulomb constitutive soil model has been utilized to define the isotropic drained conditions for sandy soil layers and the undrained conditions for clayey layers in the two cases. Extensive laboratory and in-situ soil tests have been performed through the site investigation process, results of this exploration have been used to determine the engineering properties of each soil layer. Numerical results were compared with the measurements of the in-situ loading test, and excellent agreement was obtained in the two cases, as shown in Figure 7. Details of the first case numerical analysis are given by Eid et al. 2018 [20], and for the second case are given by Ezzat et al. 2019 [15].
Figure 6. The numerical model established to simulate the response of the LDBP of the Alzey bridge case history (After Al-Atroush et al. 2020 [14])

Figure 7. Comparison between field and numerical results of pile load transfer mechanisms (After Eid et al. 2018 [20])

For the first case (Alzey Bridge), the complete failure was achieved in both field and numerical results. However, the maximum applied load in the long LDBP test (Damitta case) was three times the working load, and no apparent failure was reached. That’s why the LDBP’s ultimate capacity of this test has been estimated using the modified chin method 1970 [10] and numerical analysis, as presented by Eid et al. 2018 [20]. The numerical model was used to predict the failure load for the pile, and the maximum value obtained is 10500 kN. Figure 8 shows the pile load-settlement, bearing, and friction capacities results that are obtained at the end of this analysis. A large increase in pile settlement was observed at the 10500 kN load (55.42 mm). This was more than twice the pile settlement value at the end of the test under the load 9000 kN. Fundamental to note that pile friction resistance tends to slightly decrease after a load of 9750 kN. Also, an obvious increase in pile bearing resistance was noted at the ultimate load of 10500 kN.
Figure 8. The obtained numerical results at the failure state, the relation between LDBP settlement and ultimate bearing, friction, and total capacities (After Eid et al. 2018 [20])

3. Methodology

Failure load (ultimate capacity) is defined according to DIN 4014, 1990 [4] through the load-settlement curve of static load tests by the creep settlement under constant load. According to ECP202/4 2005 [3], if field loading test results do not show apparent failure results, the ultimate load can be estimated as the average values that are obtained from modified Chin 1970 [10] and Hansen 1963 [9] methods. These two methods were used to extrapolate the pile failure load using in-situ test measurements. As shown in Figures 9 (a) and (b), the ultimate pile load of 10904 kN and 9215 kN was the determined capacities using modified Chin 1970 [10] and Hansen 1963 [9] methods, respectively for the second case study. Therefore, according to ECP202/4 2005 [3], the ultimate pile load will be 10059 kN which is the average of these two results. Figure 9 (a) and (b) pinpointed a difference of about 18% between the calculated ultimate load using modified Chin 1970 [10] and Hansen 1963 [9] methods.

Figure 9. [a] Relation between pile settlement and settlement/applied load ratio (Modified Chin method 1970 [10]). [b] Relation between pile settlement and applied load (Hansen 1963 [9] method).

Three different methodologies were used to estimate the ultimate capacity of the two LDBP cases utilized in this study. ECP 202/4 2005 [3], DIN 4014 1990 [4], and Meyerhof, 1951 [21] classical method are the used to determine the ultimate capacity of both Alzey and Damitta cases, the obtained results of ultimate bearing and friction resistances will be compared with the in-situ measurements of the two loading tests to assess the reliability of the three methodologies.

For the long LDBP (Damitta Case), the obtained ultimate LDBP capacity using Meodifed chin and Hansen methods will be used to assess the calculated ultimate-capacity of the same LDBP case using three adopted approaches. However, for the short LDBP (Alzey Case), the obtained failure load from the loading test will be used to assess three different international design standards proposed methods. This assessment will be beneficial to evaluate the reliability of the current design methods of the mentioned codes.
4. Results and Discussion
The Egyptian code of practice (ECP202/4 2005 [3]) recommends determining the ultimate load capacity of LDBP from the pile loading test at the design stage. In case of impossibility to perform a pile load test, the code suggests using an empirical settlement-based method to predict the pile capacity. In this method, ultimate unit skin friction for each soil layer is estimated using values of SPT, and then the pile side capacity is calculated based on pile dimensions. The skin friction could be considered fully mobilized at a settlement value of 1% of the pile diameter. The ultimate base resistance is assumed to be fully mobilized at either pile settlement of 15 cm for granular soils or 10% of the pile diameter. The Egyptian code 2005 provides a correlation between the value of the base bearing pressure at failure and the failure settlement; thus, the ultimate bearing resistance can be determined. A bi-linear relation between total load and settlement can then be constructed, and the total ultimate capacity could be considered to occur at a settlement value of 10% of the pile diameter.

![Figure 10](image1.png)

**Figure 10.** Comparison between obtained ultimate capacity using in situ loading test measurements and those calculated using ECP 202/4 2005 [3], and numerical analysis (Ezzat et al. 2019 [15]) methods.

![Figure 11](image2.png)

**Figure 11.** Comparison between obtained ultimate capacity using in situ loading test measurements and those calculated using ECP 202/4 2005 [3], and numerical analysis (Eid et al. 2018 [20]) methods.

Similarly, DIN 4014 1990 [4] also recommends determining the LDBP’s ultimate capacity through the full-scale in situ loading tests. However, in the impossibility of conducting a loading test, DIN 4014 1990 [4] forecast the skin friction capacity utilizing the static cone penetrometer test (CPT) measurements for cohesionless soil and the undrained shear strength of cohesive soil. Standard penetration test results SPT results could also be used in case of unavailability of penetrometer test results. Thus, The ultimate skin friction could be obtained using the conversion factors \( q_s/N_{30} \), where \( N_{30} \) is the SPT number of blow counts, and \( q_s \) is the cone penetration resistance. On the other hand, based on the base diameter, the ultimate base resistance could be found utilizing the soil properties at the base level \( C_u \) and \( q_s \), and the forecasted settlement rate (Settlement-Based method). Figures 12 and 13 compare the calculated LDBP’s ultimate capacity using the DIN Settlement-Based approach with the obtained ultimate capacities using the interpretation of in situ measurements and the numerical results of the two cases.
Figure 12. Comparison between obtained ultimate capacity using in situ loading test measurements and those calculated using DIN 4014 1990 [4], and numerical analysis (Ezzat et al. 2019 [15]) methods.

Figure 13. Comparison between obtained ultimate capacity using in situ loading test measurements and those calculated using DIN 4014 1990 [4], and numerical analysis (Eid et al. 2018 [20]) methods.

On the other side, Meyerhof’s capacity-based classic formula is endorsed in several international design standards for estimating the ultimate pile capacity. Meyerhof, 1951 [21] developed his theory of bearing capacity of foundations based on the plastic theory by extending the previous analysis for surface footings to shallow and deep foundations in a uniform, cohesive material with internal friction (c-Ø soil). In 1976, Meyerhof utilized the empirical data obtained from field observations alongside some theoretical considerations in developing his classic formula for the bearing capacity of a pile in a soil possessing both cohesion and friction. As presented in Equation 1, the foundation's physical characteristics and the soil’s mechanical properties were represented in this formula through bearing capacity factors (Nc, Nq, and Ng). Figure 14 compares the obtained ultimate capacities using the Meyerhof [21], and the field measurements of two tests.

\[
P_{\text{ult}} = A_s \left( c_s + K_s \frac{L}{2} \tan \delta \right) + A_b \left( cN_c + \gamma L N_q + \gamma \frac{D}{2} N_g \right)
\]

Where, \(c_s\): soil adhesion per unit area; \(\delta\): friction angle of the soil on the shaft. \(K_s\): the earth pressure coefficient. \(L/2\): critical depth. \(N_c, N_q, \text { and } N_g\): factors of bearing capacity depend on \(\delta\) and the embedment depth ratio L/B.
Figure 14. Comparison between field measurements of Alzey and Damietta Case studies and the calculated friction, bearing, and total ultimate resistance using Meyerhof formula.

For the first case, the ultimate capacity of the instrumented pile was calculated using ECP202/4 2005 [3], DIN 4014 1990 [4], and Meyerhof, 1951 [21] criteria utilizing the stiff clay soil properties determined from laboratory and field tests Sommer and Hambach (1974) [18]. The obtained ultimate capacities are compared with those obtained from field measurements and the numerical analysis, as shown in Figures 10, 12, and 14. For the second case, the ultimate capacity of the instrumented pile was calculated using ECP202/4 2005 [3], DIN 4014 1990 [4], and Meyerhof, 1951 [21] criteria utilizing the multi-layered soil properties determined from laboratory and field tests (Eid et al. 2018 [19]). The obtained ultimate capacities are compared with those obtained from numerical analysis, and the average load estimated from Chin 1970 [10] and Hansen 1963 [9] methods, as shown in Figures 11, 13 and 14.

Based on the comparative analysis performed, it was found that the Egyptian code's calculated ultimate LDBP capacity was apparently more conservative than DIN 4014 and Meyerhof, 1951 [21] results. The pile capacity obtained using ECP202/4 2005 [3] criteria for the second case study was 48% and 83% obtained from the Meyerhof, 1951 and DIN 4014, respectively. It also was about 60% of the average value estimated from modified Chin 1970 [10] and Hansen 1963 [9] methods.

On the other side, the ultimate load obtained using Meyerhof, 1951 [21] method was higher than those obtained using other ECP and DIN codes criteria; it was also about 13 % of the ultimate load obtained from the pile loading test (the average value estimated from modified Chin 1970 [10] and Hansen 1963 [9] methods). It is clear that the proposed settlement-based methods using ECP and DIN codes criteria underestimate the LDBP’s ultimate capacity of the two LDBP cases. However, Meyerhof capacity-based method has overestimated the ultimate capacity of the two LDBP cases. As shown in figure 14, the calculated ultimate capacity using the Meyerhof formula is greater than the field measurements with the interest of about 17 % and 13% for Alzey bridge and Damietta Port Silo case studies, respectively. The main reason for this difference is the high acquired bearing resistance using the Meyerhof equation; for instance, it represents 60% greater than field measurements of the Alzey bridge case study. Nevertheless, the calculated pile friction resistance using the Meyerhof formula for the same case is less than the field measurement with an interest of 12%.

5. Conclusions
This study has presented a comparative analysis of the estimation of LDBP ultimate capacity using several approaches, including three methods. Based on the comparative analysis results, the following conclusions can be drawn.
No doubt, full-scale pile loading test is still the most efficient and essential method to obtain the ultimate capacity of the LDBP. However, the complexity in achieving an obvious failure point at the end of loading tests for such a class of piles.

The calculated ultimate load using modified Chin (1970) was higher than the ultimate load calculated using Hansen (1963), with a difference of about 18%. Noteworthy, pile ultimate load calculated from numerical analysis (10500 kN) is nearly equal to the average load estimated from Chin 1970 and Hansen 1963 methods.

The obtained ultimate capacities using ECP 202/4, and DIN 4014, were respectively about 60% and 70% of the obtained ultimate capacity using in situ loading test measurements. Which is means that the two codes proposed settlement-based methods underestimate the ultimate LDBP capacity. Conversely, Meyerhof's capacity-based method overestimated the two LDBP cases' ultimate capacity.

6. References
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