Comparative study of theoretical methods for estimating pile capacity using 1-g model pile tests in cohesionless soil

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Abstract. The behavior of single pile is considered as the base of the most pile foundation design procedures. There are many different theoretical methods used to estimate the capacity of single pile embedded in cohesionless soil. In order to select the most accurate and reasonable method, 1-g model tests have been performed in this study. Different five procedures have been used to interpret the test results in order to select the suitable procedure. The statistical analysis showed that all procedures give approximate results except Chin's procedure which yields inaccurate results with respect to the average value. Then, the results of five theoretical methods have been compared with the measured pile capacity from model tests (average value). The rank index analysis was conducted based on statistical parameters and probability distributions. The results of the analysis yielded that Coyle and Casttelo method gave the most accurate and reasonable results than the other theoretical methods considered in this study (Berezantsev's method, Meyerhof's method and traditional bearing capacity equation with some modifications). Finally, the author recommended using the two tangents procedure in interpreting of the pile test results. Also, the method proposed by Coyle and Casttelo can be used to estimate the pile capacity based on soil properties with accurate results.

1. Introduction

Pile foundations have been frequently used to support structures; such as tall buildings, towers, bridges …etc, in areas where the foundation soil conditions are unsuitable for using shallow foundations. They are the most common type of deep foundation. Pile can be defined as a structural member embedded into the soil mass to transmit surface loads to lower levels. In order to be able to design an economical and safe pile foundation system, we have to analyze the interaction between pile and soil, establish modes of failure and estimate the settlement resulting from soil deformation under the applied loads [1].

The behavior of single pile is still the point of starting of most pile foundation design procedures. In order to study the behavior of a single pile, there are many different ways such as numerical method (FEM), field load tests or model (experimental) tests. In numerical methods, many impractical assumptions are made to perform the analysis. The field load test is the most confident way, but it is expensive and time consuming. Hence, the model tests is most suitable way to reproduce the field tests conditions and study the effect of different parameters on the behavior of a single pile. However, it is considered a very useful method for simulation and verification of the pile load test.

Model tests can be divided into two main groups: centrifuge tests (carried out under higher gravitational acceleration) or 1-g tests (carried out under the gravitational field). Centrifuge model
tests are unavailable or are very expansive tests. So, 1-g model is most common in studying different geotechnical problems. Therefore, 1-g model tests have been used in the present study to simulate the behavior of a single pile subjected to axial compression load.

The present study includes two main stages of work. In the first stage, six different procedures were used to interpret the results of the model tests and then compared with their average value to choose the most accurate procedure. This comparison has been conducted based on the test of hypothesis. The pile capacity of the selected procedure will be denoted as \( Q_m \). In the second stage, the results of five theoretical methods were compared with the selected procedure from the first stage. The test of hypothesis was, also, used to check the reason of the differences in their results. Finally, the rank index procedure has been carried out to determine the most suitable and accurate theoretical method to estimate the pile capacity based on the soil properties (static approach).

2. Ultimate pile capacity
As mentioned above, the ultimate pile capacity is considered as a point of starting of any pile foundation design process. In the beginning, the designer uses the soil properties and data of field tests that are carried out throughout the soil exploration program to estimate the ultimate pile capacity. Nevertheless, the pile load test is still the more accurate method to estimate pile capacity by interpretation of the test data. However, there are many methods proposed by several researchers to estimate pile capacity and to interpret the test data.

In all theoretical methods, the ultimate pile capacity is a sum of both skin (friction) resistance along pile length within the soil mass and end (bearing) resistance due to the soil below the pile tip. All methods use the same procedure which depends on soil properties to predict the skin resistance, see [2]. Also, they used the same formula to predict the end resistance which is [3]:

\[
Q_b = q'N_qA_b
\]  
(1)

These methods differ in the \( N_q' \) value. Berezantsev in 1961 and Coyle and Castello in 1981 proposed charts for \( N_q' \) based on the soil angle of internal friction (\( \phi \)) and penetration ratio (\( L_R = L/D \)) [2], but they presented different charts. Janbu in 1976 suggested a mathematical formula to compute \( N_q' \) value based on the angle of internal friction and soil state (loose or dense) which is reflected by the angle \( \phi \) [4]. Meyerhof in 1976 proposed a chart to estimate the \( N_q' \) value based on the angle of internal friction only. He stated that the computed value of end resistance should not exceed a limiting value which depends on the soil state [3]. Finally, some designers use the traditional bearing capacity equation of shallow foundation to estimate pile capacity with some modifications. These modifications include omitting the third term of the equation (\( N_f \) term) and using bearing capacity, shape and depth factors only, see [5].

On the other hand, there are several procedures stated in the literatures to estimate ultimate pile capacity based on the pile load test data. Five methods are used in the present study. These methods are denoted as follows: Davisson's method (IM-1), Chin-Kondner’s method (IM-2), Brinch Hansen's 80% method (IM-3), Decourt's method (IM-4) and two tangents method (IM-5) as explained by [6] and [7].

Theoretical methods and interpretation procedures will be denoted as TMs and IMs groups, respectively, throughout this study.

3. Experimental work
In order to simulate the behavior of a single pile subjected to an axial compression load, model piles using 1-g tests have been used. The following sub-sections explain the details of materials used in the modeling process and testing procedure.
3.1. Soil used
The soil used throughout this work was brought from a site at the middle region of Iraq. Physical (grain size analysis and specific gravity) and chemical tests were conducted for the soil used. Figure 1 shows the gradation curve of the soil which consists of about 98.7% sand and 1.3% silt and clay. The results of chemical and physical tests are demonstrated in Table 1.

According to the unified soil classification system (USCS), the soil is classified as SP soil (poorly graded sand).

![Gradation curve of the used soil](image)

**Figure 1.** Gradation curve of the used soil

3.2. Modeling of pile
As mentioned earlier in this section, a 1-g model was used to conduct the model pile test. The steel box (container) was made of steel plates with (75×75×75) cm inner dimensions. The plate thickness was 4 mm. Plate 1 illustrates the used container.

Closed-ended pipe sections were used to simulate the model piles. The model section was 30 mm outer diameter and 1.5 mm wall thickness.

The axial load was applied to the model pile using the loading system shown in Plate 1 which was manufactured by Shijhait (2013) [8] and modified by Al-Gharrawi (2016) [9].

| Chemical properties          | 0.73 % | 0.56 % | 1.35 % |
|------------------------------|--------|--------|--------|
| Total soluble content, T.T.S |        |        |        |
| Sulfate content, SO₃        |        |        |        |
| Gypsum content              |        |        |        |

| Physical properties | 0.33 | 0.63 | 0.95 | 2.88 | 1.27 | 18.5 kN/m³ | 15.2 kN/m³ |
|---------------------|------|------|------|------|------|------------|------------|
| D₁₀                 |      |      |      |      |      |            |            |
| D₃₀                 |      |      |      |      |      |            |            |
| D₆₀                 |      |      |      |      |      |            |            |
| C_u                 |      |      |      |      |      |            |            |
| C_c                 |      |      |      |      |      |            |            |
| γ_d(max)            |      |      |      |      |      |            |            |
| γ_d(min)            |      |      |      |      |      |            |            |

3.3. Test procedure
The following steps were used to prepare soil bed and test the model pile:

1. Preparation of the soil bed: the sandy deposit was prepared using the sand raining technique. The falling height of the sand was selected to achieve the required soil state based on the pre-constructed relationship as shown in Figure 2. Three soil states were selected which are loose, medium and dense with falling height of 20, 40 and 60 cm, respectively.

2. Installation of model pile: the model pile was derived in the soil bed to the required depth using a manufactured simulated hammer [8].

3. Loading: the axial compression load was applied to the model pile using the loading system mentioned previously. The settlement of the model pile head corresponding to each load increment was recorded using two fixed digital dial gauges.

![Plate 1. Loading frame and steel container [9]](image)

![Figure 2. Relationship between dry unit weight and the soil falling height](image)

It should be stated that the shear test (shear box test) was conducted for the used soil in each soil state (loose, medium and dense). Table 2 illustrates the results of these tests.
Table 2. Results of shear test.

| Soil compactness | RD % | $\gamma$ (kN/m$^3$) | $\phi$ |
|------------------|------|---------------------|------|
| Loose            | 25   | 15.5                | 31°  |
| Medium           | 50   | 16.1                | 36°  |
| Dense            | 75   | 17.5                | 40°  |

3.4. Test program
The behavior of pile is affected by many factors such as soil type, soil properties, pile material and pile geometry (length and diameter). In the present study, two parameters have been considered. These parameters are penetration ratio ($L_R = L/D$) and soil state (loose, medium and dense). Table 3 summarizes all models which were tested through the present work. However, total of eight tests were conducted in this study.

Table 3. Characteristics of the soil and model tests.

| Model pile | Soil state |
|------------|------------|
| D (mm)     | $L_R$       |
| 30         | 10         | Loose$^a$     |
| 30         | 12         | Medium        |
| 30         | 15         | Dense         |

$^a$ For this soil state only 12 and 15 penetration ratio were used.

4. Discussion and statistical analysis of tests data
In this section the tests results will be presented with the model piles capacity estimated using both IMs and TMs groups. Then, the model piles capacities will be analyzed statistically.

The results of the model tests are presented as load-settlement curves. Figure 3 shows the obtained results of the model tests using 1-g experimental tests.

It can be noted that the model pile capacity increases with increasing the penetration ratio ($L_R$) for the same soil state. This increase, theoretically, is due to the increasing of the pile surface area within the soil and the overburden pressure above the pile tip.

Figure 4 illustrates the load-settlement curves of the model pile tests for different state of the soil at the same penetration ratio ($L_R = 15$). It can be seen that the model pile capacity increases with increasing of soil relative density (changing the soil state from loose to dense state). This is attributed to the increasing of the soil unit weight in addition to its strength. Also, it can be stated that there is no significant effect of changing soil state from loose to medium state on the model pile capacity. It may be due to the type of soil used in the experimental tests (poorly graded soil-SP).
4.1. Prediction of pile capacity based on interpretation procedures

This stage of the study aims to assign the measured pile capacity ($Q_m$). Hence, the test of hypothesis is performed on six groups of results where each group represents certain procedure. Each group will be checked with a reference group which represents the average values of all groups. Before performing this study, it should be assessed whether all groups come from normal populations or not. Two normality tests have been used in the present study to achieve this purpose. These tests are Jarque-Bera and W/S tests. Jarque-Bera test depends on the skewness and kurtosis of the distribution while W/S test depends on the range and standard deviation of the distribution. Table 4 shows the results of the normality tests at significant level of 5%. It can be concluded that all interpretation procedures’ results are not significantly different than normal distribution. Therefore, the hypothesis test can be performed on these groups.

**Figure 3.** Load-settlement curves of model pile tests for different soil state and penetration ratio
Table 4. Results of normality tests for six interpretation procedures of model pile tests.

| Statistical parameters | IM-1       | IM-2       | IM-3       | IM-4       | IM-5       | Average    |
|------------------------|------------|------------|------------|------------|------------|------------|
| X                      | 571.25     | 1081       | 797.7      | 794.5      | 592.5      | 606.25     |
| s                      | 156.5      | 683        | 256.6      | 301.4      | 184.5      | 200.2      |
| sk                     | 0.328      | 1.337      | 0.494      | 0.674      | 0.496      | 0.572      |
| ku                     | -1.727     | 0.447      | -1.900     | -1.084     | -1.496     | -1.520     |
| Range                  | 435        | 2064       | 580        | 853        | 520        | 528.2      |

Jarque-Bera test

|                | statistic  | conclusion |
|----------------|------------|------------|
| IM-1           | 1.138      | Normal     |
| IM-2           | 2.448      | Normal     |
| IM-3           | 1.147      | Normal     |
| IM-4           | 0.997      | Normal     |
| IM-5           | 1.075      | Normal     |
| Average        | 1.206      | Normal     |

W/S test

|                | statistic  | conclusion |
|----------------|------------|------------|
| IM-1           | 2.780      | Normal     |
| IM-2           | 3.022      | Normal     |
| IM-3           | 2.260      | Normal     |
| IM-4           | 2.830      | Normal     |
| IM-5           | 2.818      | Normal     |
| Average        | 2.639      | Normal     |

The statistical test contains the following two hypotheses [10]:

Null hypothesis: \( H_0: \mu_i = \mu_{av} \) \hspace{1cm} (2)

Alternative hypothesis: \( H_1: \mu_i \neq \mu_{av} \) \hspace{1cm} (3)

Table 5 demonstrates the results of the hypothesis test. It can be concluded that all procedures have the same mean of the pile capacities when compared with their average. In other word, we have 95% confidence that there is no difference between the mean of the interpretation procedures and the average value. Table 5, also, contains the values of coefficient of variation (COV), coefficient of determination (R\(^2\)) and Theil’s inequality coefficient (U). The low value of COV, high value of R\(^2\) (close to one) and low value of U (close to zero) mean that the procedure results match with the average values. It can be stated that all interpretation procedures considered in this study reveal good agreement with the average values except the procedure proposed by Chin. Chin’s procedure reveals the highest values of COV and U which are 63% and 0.36, respectively, and the lowest value of R\(^2\) which is 0.691. Therefore, the measured value of pile capacity (Q\(_m\)) will be the average of the five
procedures. These measured values will be considered in the second stage of the present work. At the end of this stage, it can be recommended that the use of two tangents procedure, which is a simple and direct method, yields reasonable capacities for the piles embedded in cohesionless soil.

4.2. Assessment of pile capacity from theoretical methods

This stage of the study is aimed towards choosing the accurate and reasonable method of estimating pile capacity based on the results of 1-g model pile tests. A unique method for computing capacity due to shaft resistance is used while five different theoretical methods are considered for capacity due to end resistance. These methods are denoted as follows: Berezantsev’s method (TM-1), Coyle and Castelto method (TM-2), Janbu’s method (TM-3), Meyerhof’s method (TM-4) and traditional bearing capacity equation with some modifications (TM-5). The rank index analysis is the tool used in the present work to assign the accurate method. In rank study, the rank index (RI) is computed for each theoretical method. The accurate and efficient method is the method which has the lowest value of RI.

The value of RI comprises of three components \([11]\) and \([12]\), as shown below:

\[
RI = R_1 + R_2 + R_3 = \sum_{i=1}^{3} R_i \tag{4}
\]

where \(R_1\) is the rank of methods based on modeling efficiency (COD). The value of COD is used to test the competence of measured and predicted values of pile capacity. The value of COD is computed as:

\[
COD = 1 - \frac{\sum_{i=1}^{n} \left( \frac{Q_{th}}{Q_{m}} \right)_{i} - \left( \frac{Q_{th}}{Q_{m}} \right)}{\sum_{i=1}^{n} \left( \frac{Q_{th}}{Q_{m}} \right)} \tag{5}
\]

The value of \(R_2\) is the rank of method depending on the mean \((\bar{Q})\) and standard deviation \((s)\) of \((Q_{th}/Q_{m})\). The lower scatter of the method corresponds to the closer \((\bar{Q})\) to one and the closer \((s)\) to zero. In this study the coefficient of variation (COV) for \((Q_{th}/Q_{m})\) is considered. The lower scattering of method is corresponding to the closer COV to zero.

The value of \(R_3\) is the rank of method based on cumulative probability approach. To compute the cumulative probability of \(i^{th}\) data element, order the ratios of \((Q_{th}/Q_m)\) in ascending order and use the following:

\[
P = \frac{i}{n+1} * 100 \tag{6}
\]

where: \((i)\) is the rank of the element and \((n)\) is the total element in the group.

From the cumulative probability distribution, the values of \((Q_{th}/Q_m)\) corresponding to 50% and 90% cumulative probability are obtained. The value of average error is estimated as follows:

Table 5. Hypothesis test, coefficient of determination and Theil’s inequality coefficient for interpretation procedures of model pile tests.

|                     | IM-1 | IM-2 | IM-3 | IM-4 | IM-5 | Average |
|---------------------|------|------|------|------|------|---------|
| \(t\) – value       | 0.390| -1.887| -1.514| -1.472| 0.143| -       |
| \(t\) – limits      | Upper| 2.160| 2.306| 2.262| 2.179| 2.160   |
|                      | Lower| -2.160| -2.306| -2.262| -2.179| -1.60   |
| Conclusion about \(H_0\) | Accept| Accept| Accept| Accept| Accept| -       |
| COV                  | 27 % | 63 % | 32 % | 38 % | 31 % | 33 %    |
| \(R^2\)             | 0.978| 0.691| 0.997| 0.958| 0.975| 1       |
| \(U\)               | 0.05 | 0.36 | 0.18 | 0.15 | 0.02 | 0       |
The method of lowest values of \( (P_{90} - P_{50}) \) and \( E_{av} \) is considered the best method. Also, the value of \( P_{50} \) should be closer to unity.

Table 6 contains the values of COD, COV, \( P_{50} \), \( P_{90} \) and \( E_{av} \) for the theoretical methods used to estimate end resistance and in turn the pile capacity. Figure 5 illustrates the cumulative probability distributions for the theoretical methods. It can be concluded from the cumulative probability distributions that all methods give underestimated pile capacity except the method suggested by Meyerhof which yields, in general, overestimated capacity of piles.

| Method | COD | R1 | COV | R2 | \( P_{50} \) | \( P_{90} \) | \( E_{av} \) | R3 | R1 |
|--------|-----|----|-----|----|------------|------------|----------|----|----|
| TM-1   | 0.055 | 1  | 0.38 | 5  | 0.72       | 0.90       | -0.28    | 1  | 7  |
| TM-2   | -0.922 | 2  | 0.23 | 2  | 0.55       | 0.66       | -0.45    | 2  | 6  |
| TM-3   | -3.906 | 4  | 0.36 | 4  | 0.30       | 0.37       | -0.70    | 5  | 13 |
| TM-4   | -4.983 | 5  | 0.32 | 3  | 1.54       | 1.70       | 0.54     | 4  | 12 |
| TM-5   | -1.924 | 3  | 0.20 | 1  | 0.48       | 0.52       | -0.52    | 3  | 7  |

From the results of analysis shown in Table 6, the highest accuracy level is corresponding to Coyle and Castello method. The lowest level of accuracy is corresponding to Janbu’s method and Meyerhof’s method. Berezantsev and the traditional bearing capacity methods are ranked as methods with good accuracy. Coyle and Castello method can be used to estimate the pile capacity of single pile embedded in cohesionless soil with accurate and reasonable results when it is compared with the pile capacity from the load test.

**Figure 5.** Cumulative probability for different theoretical methods
5. Conclusions
The accuracy of five different theoretical methods (Berezantsev's method, Coyle and Castello method, Janbu's method, Meyerhof's method and traditional bearing capacity equation with some modifications method) is investigated throughout this study based on the rank index. In order to predict the pile capacity, eight model pile load tests were performed by 1-g model. The average of five different procedures for interpreting the model test was used as the measured pile capacity. The following outcomes can be pointed out:

1. From the statistical analysis of the interpretation procedures, the results of Chin's method can be considered as inaccurate as compared with the other procedures. Davisson, Hansen 80%, Decourt and two tangents methods gave approximately close results.

2. Results of all procedures proposed to interpret the load-settlement behavior of pile are from normal populations and there are no significant differences between their results and the average value.

3. It is recommended to use the two-tangents procedure for interpreting the pile test result because it is a simple and direct method. Also, it gives good results as compared with the average capacities obtained from interpretation procedures.

4. From the rank index analysis, the method proposed by Coyle and Castello gave the most accurate and reasonable results than the other theoretical methods considered in this study (Berezantsev's method, Janbu's method, Meyerhof's method and traditional bearing capacity equation with some modifications).

5. Berezantsev's method and the traditional bearing capacity equation with some modifications can be used to estimate the pile capacity with reasonable results. Also, they are considered as relatively simple methods when they are compared with Coyle and Castello method.

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