Comparison of various approaches to pipe-pile capacity control for offshore wind turbines

Michal Baca

Wrocław University of Science and Technology, Wyb. Wyspianskiego 27, 50-370 Wrocław, Poland

E-mail: michal.baca@pwr.edu.pl

Abstract. Tubular pipe piles have a wide application in geotechnical engineering, for example as foundation structures in rivers, lakes and for offshore structures. For assessment of pipe pile bearing capacity the static load test is often used due to its commonly consideration as the most reliable method of pile testing. Nevertheless, because of high costs of the test and difficulties with appropriate construction of kentledge system, the application of static load test is often limited. The great supplement to obtain information on pile’s capacity are tests conducted on model piles in small laboratory scale. In this paper, results of static load test conducted on small scale tubular model pipe pipes installed in non-cohesive homogenous soil are introduced. The installation process, pile testing procedure and equipment applied for continuous load and model pile head displacement measurement are presented. The results of tests are shown in load-displacement charts. For load-displacement curve construction and pile bearing capacity estimation from static load test several different method are introduced with their application to performed tests and discussion of the results. Finally, future research plans are proposed.

1. Introduction – the scope of the study

Electricity in Poland is mainly generated by hard coal and lignite power plants. Due to restrictions on environmental protection, European Union countries are obliged to use renewable energy sources, including wind farms. In 2013, the share of wind farms in the total electricity demand in Poland was small. The forecasts of the Polish Wind Energy Association predicted in 2013 a six-fold increase in the power obtained from wind turbines. This meant construction in the years 2013-2020. about 3,000 new wind farms.

Wind farms are designed in areas where the frequency of winds at a given speed allows achieving satisfactory turbine energy performance. Zones favorable for the operation of this type of facilities can be found mainly in the northern part of Poland [1, 2], near the Baltic Sea coast. Based on observations and measurements, you can approximately determine the dominant wind directions in given zones and the speed at which they blow. However, these values are not precise enough to be based on them when performing static-strength calculations. As most of favourable locations for wind turbines are found near the sea coast, some social problems (related to annoying noise) are risen by people in neighbouring villages. Offshore construction profit of beneficially higher speed of wind and does not demand special agreements with neighbours.

Proper design of the foundation for a wind turbine is not a trivial issue, especially due to the lack of national guidelines for the design of these structures. In addition, national practice does not abound in too many similar implementations (growth in recent years is promising, which can be optimistic) for the possibility of comparing or drawing up a Polish standard. Fortunately, turbine manufacturers
provide a complete set of design recommendations and guidelines (most often German and Danish companies with a large number of projects and extensive experience). Design procedure starts from the tower construction [3,4]. The costs of laying the foundation for a wind power plant range from 5% to 24% of expenditure, which is not a relatively large value. Considering the fact that this is the part responsible for the safety of the entire structure, the costs associated with a possible disaster will be immeasurably greater. That is why geological survey quality is of primary importance [5]. Data acquired from field testing form the basis for numerical studies [6] and design of shallow foundations [7], soil improvement technologies [8] or deep foundation on piles [9].

2. Basic aspects of pile capacity control

Static load tests (figure 1) are widely considered to be the most reliable method of pile bearing capacity assessment. In the test, a load is applied to the pile through a hydraulic jack. During the test, displacements of the pile head are measured depending on the applied load.

Many research procedures describe how such a test should be conducted. Some of them are described in [10-12]. In Poland, the procedure from the standard [13] has been used for many years. In this method, a load is applied gradually up to the bearing capacity of up to 1.5Nt, where Nt is the design bearing capacity of the pile according to design code [13]. The next load step is applied after stabilization of pile settlements in a previous step.

An important problem is the proper interpretation of test results. The results of the research are used to construct a curve describing the settlements of the pile depending on the loads, which is named the load-displacement or Q-s curve. Based on this curve, the load capacity of the pile from a test can be determined. However, if the ultimate capacity Qu of the pile was not reached in the test, an extrapolation of the obtained results can be required with regard to their inaccuracies [12].

![Figure 1. Full scale static load test on pipe piles](image)

3. Determination of pile bearing capacity

The pile bearing capacity is defined as the lowest load applied to a pile, above which an uncontrolled settlement increase occurs under a pile [14]. Nevertheless, in many cases there are difficulties with the exact determination of this point on the load-displacement curve. To solve that problem the bearing capacity is often assumed to be a load applied to the pile, for which the settlement is 10% of the diameter value. This approach is also proposed in Eurocode 7 [15]. This assumption, however, does not take into account soil conditions, a pile technology or an elastic shortening of the pile and other problems [16-19]. Over the years, many methods have been developed allowing on the assessment of the pile bearing capacity [20-25]. The selection of the appropriate method depends both on the researcher's experience and the ability to refer to a specific database of previous experiences. For example, Fellenius [19] recommends the Brinch-Hansen 80% [20], Chin [21], Butler and Hoy
methods. In this paper, the first two methods, as well as more modern Decourt method [22] and the Polish more extended method proposed by Meyer [23-25] are presented. One should notice that a reliable quality (integrity) control of piles should be performed prior to capacity testing of foundation piles in order to avoid misleading results [26].

3.1. Chin method [21]
The method is an application for the piles the more general method for soils proposed by Kondner. In the Chin method, the hyperbolic shape of the Q-s chart has been proposed, described by the equation (1):
\[
Q = \frac{s}{s \cdot C_1 + C_2},
\]
where \( C_1 \) and \( C_2 \) are two constants. Bearing capacity is the asymptote of hyperbole, determined from the equation (2):
\[
Q_u = \frac{1}{C_1}.
\]

3.2. The Brinch-Hansen method - 80% [20]
In this method, the parabolic shape of the Q-s curve is proposed, described by the formula (3). The bearing capacity is considered as the coordinate point \( \{ s, Q(s) \} \) for which the point \( \{ 0.25s, 0.8Q(0.25s) \} \) also lies on this curve. The boundary displacement \( \{ s_b \} \) and the bearing capacity \( \{ Q_u \} \) can be determined from equations (4) and (6).
\[
Q = \frac{s \sqrt{s}}{s \cdot C_3 + C_4},
\]
\[
s_b = \frac{C_1}{C_3},
\]
\[
Q_u = \frac{1}{2 \sqrt{C_3 \cdot C_4}}.
\]

3.3. The Decourt method [22]
Decourt proposed a method similar to the Chin and Brinch-Hansen proposition. The relationship between load and settlement and bearing capacity is determined from the equations (6) and (7).
\[
Q = \frac{C_6 \cdot s}{1 - C_5 \cdot s},
\]
\[
Q_u = \frac{C_6}{C_5},
\]
where \( C_3 \) and \( C_6 \) are constants for the Decourt method. This method provides comparable results to the Chin method. Its advantage is an easy curve construction process in the Q/s-Q transformed axis system [22].

3.4. Meyer method [23-25]
The dependence between settlement and the applied load is presented in equation (8):
\[
s = C \cdot Q_u \frac{(1 - \frac{N}{Q_u})^{-\kappa}}{\kappa} \cdot 1,
\]
where: \( s \)-settlement [mm], \( C \)-parameter describing soil reaction modulus [mm/kN], \( N \)-load applied to the pile [kN], \( Q_u \)-ultimate capacity of a pile [kN], \( \kappa \)-dimensionless constant [\(-\)].
The most important difference between this method and the previous methods is a constant $\kappa$, which is responsible for the appropriate modelling of the shape of the $Q$-s curve. The proposed curve has a vertical asymptote $Q \rightarrow Q_u$. As in the other methods, using the results of the test static loads $\{s, N\}$, the curve parameters - $C$, $\kappa$ and $Q_u$ are determined. The $C$ parameter is determined from the linear range of the curve, while to determine the $Q_u$ and $\kappa$ parameters the least squares method should be used. The accurate procedure for determining the curve is described in [23].

4. Static load test example
To compare the described methods, the example of a static load test is introduced. The test was conducted on a model pipe pile installed in a test stand filled with medium dense sand (Figure 2). The model piles were 0.045 m diameter and driven into the soil by a dynamic probing light to 0.8 m. More details of the test procedure were presented in references [27, 28].

Figure 2. Full scale static test load on pipe piles

5. Evaluation of results and discussion
To compare application the presented methods load-displacement curves and bearing capacities were determined based on the results of the model piles static load test. The estimated values of bearing capacity of a pile are presented in Table 1.

| Method          | Chin | Brinch-Hansen | Decourt | Meyer |
|-----------------|------|---------------|---------|-------|
| Capacity [kN]   | 5.64 | 4.92          | 5.62    | 7.85  |

The graphic interpretation of the evaluated curves for each method and bearing capacities $Q_{gr}$ are presented in Figure 3. Results of the static load test are presented as points; curve approximations are presented as continuous line and estimated pile capacities as dashed lines. It is important to notice that all curves are very similar along the known range of test. The extrapolation of the testing results seems to be doubtful due to high differences in estimated values of ultimate capacity. The results prove findings from reference [12] about limitations and risk related to static capacity testing of piles.

6. Summary and conclusions
Methods for estimating the pile bearing capacity of a pile and plotting a load-displacement curve based on the results of static load test were introduced in the paper. The application of four different methods was presented for the results of a single static load test of a model pipe pile. The performed calculation showed large differences between the results of bearing capacity estimation depending on the utilized method. These differences are also confirmed by other researchers [14, 28].
Figure 3. Results of evaluations of pile bearing capacity from static load test

The shape of the load-displacement curve is similar in each method, some difference occurs in comparison with the estimated capacities. The bearing capacity evaluated by utilized methods differs from load corresponding to the settlement equal to 10% of the diameter, i.e. the value assumed by Eurocode 7 [18]. The closest value to this load is obtained from the Brinch-Hansen method. Values obtained from the Chin and Decourt method are similar due to a similarity in their assumptions. The highest value of bearing capacity, very different from other methods, was received in Meyer proposition, but this method is relatively young and some aspects of it still need to be refined (e.g. finding a relationship between the κ coefficient and the piling installation method) [24].

The choice of the appropriate method to estimate the bearing capacity should be based on the researcher's previous experience and requires experience in analysing a larger number of tests. This is an advantage of the Chin and Brinch-Hansen methods, which have already been used for many years and have been verified by many researchers. It is also recommended not to utilise one method, but several different methods at the same time. What is more, the estimation of the bearing capacity should still correspond with the selection of the appropriate safety factor.

The obtained results are part of bigger research program which includes also full scale pipe pile static load tests and numerical simulations of performed tests in finite element method.

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