Static Load Test interpretation methods of pile base capacity approximation for design of wind turbine deep foundation

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Abstract: The bearing capacity of a pile is mainly assessed from a static load test, which is widely considered as the most reliable method of pile testing. The test provides important information about pile behaviour in a subsoil, but often for more precise data it should be performed on additionally instrumented piles. With specially prepared pipe piles static load tests can be performed with a load applied only to a pile base. The results of this test allow on an evaluation only of pile base bearing capacity, although it often requires an application of some of the methods dedicated to analyse the static load test results. In paper some of the methods for evaluation bearing capacity of a pile from a static load test are introduced. Evaluation of pile base bearing capacity by different methods was compared using results of static load tests with a load applied only to the pile base. A discussion of results and future recommendations were also presented.

1. Introduction

Design of wind turbine towers is an important issue in civil engineering last years [1]. Rapid development of wind farms can also be observed in Poland, especially in the north part of the country, near the Baltic Sea coast [2]. The most important and expensive part of the power plant is wind turbine and tower construction [3-5]. Various technical solutions are being examined for land and offshore constructions [6,7]; however, due to heterogeneity of soil conditions, the properly designed foundation is responsible for the safety of whole power plant [8,9]. Due to determined construction localization (usually near the sea coast, where the complicated soil conditions can appear), proper geological survey quality is often required [10,11]. Its results can be then used for numerical studies [9] and design of shallow foundations [11], soil improvement technologies [9] or deep foundation on piles [10]. For complicated constructions and uncertain soil conditions a pile foundation as the most reliable solution is often chosen. Control procedures in course of work conduct are usually related to their dynamic impact on the neighborhood [12-14].

Bearing capacity of piles can be determined from the static load test [15-17]. Nevertheless, sometimes more specific information of the pile is required, such as the ultimate bearing capacity of the pile base or shaft. This often requires conducting a test on additionally instrumented piles [18]. Evaluating only the pile base bearing capacity is also possible with instrumented pipe piles. The load can be applied strictly to pile base with additional steel pipe inside the tested pile. Performing tests on that device allows on observing behavior under load only of the pile base. In both static loads test: standard with anchoring piles (figure 1) and in the self-balanced variant (figure 2), while the pile is
loaded by means of a hydraulic jack, only its head displacements are measured. Anyway, most of the extrapolation methods of load-displacement analysis bring some risk of over or underestimation of its capacity [17,19,20].

2. Materials and methods of non-failed load test analysis
There are many procedures how the analysis the test results should be conducted [21-26], the most often method used in Poland is the procedure proposed in the local standard PN-83/B-02482 (Foundations. Bearing capacity of pile and pile foundations [in Polish]). Results of the test are presented on a load-displacement curve, also named $Q-s$ curve. Furthermore, basing on test results, the ultimate pile bearing capacity $Q_u$ can be assessed. There are many methods allowing to obtain $Q_u$ value, despite some inaccuracies in test results.

![Figure 1](image1.png)

**Figure 1.** Pile base Static Load Test: reaction system and control of displacements.

![Figure 2](image2.png)

**Figure 2.** Static load test in self-balanced appliance: reaction system and control of displacements.

The ultimate bearing capacity is defined as a load applied to pile, after which pile starts to plunge. There are however many cases when is not easy to determine that load from the $Q-s$ curve. In many cases ultimate bearing capacity is described as a load applied to pile, for which displacement of pile
head is equal value of 10% of its diameter [21] This simplified assumption does not include however the pile technology, soil conditions, elastic shortening of a pile and many other factors [16,20]. Ultimate bearing capacity can be also evaluated with some of the different methods which are dedicated to assess that value from Q-s curve [22-27].

2.1. Chin method [22]
In Chin method results of the static load test are approximated by a hyperbolic curve described by an equation (1):

\[ Q = \frac{s}{C_1 \cdot s + C_2}, \tag{1} \]

where \( C_1 \) and \( C_2 \) are two constants. Equation (2) describes an asymptote of a hyperbole which is considered as a bearing capacity of a pile:

\[ Q_u = \frac{1}{C_1}, \tag{2} \]

2.2. The Brinch-Hansen method - 80% [23]
In Brinch-Hansen method shape of the Q-s curve is the parabolic and it is described by the formula (3). The bearing capacity is established when for the coordinate point \( \{s, Q(s)\} \) and the point \( \{0.25s, 0.8Q(0.25s)\} \) both lies on Q-s curve. From equations (4) and (6) boundary displacement \( \{s_b\} \) and the bearing capacity \( \{Q_u\} \) can be determined, respectively.

\[ Q = \frac{s \cdot C_3 + C_4}{s}, \tag{3} \]
\[ s_b = \frac{C_4}{C_3}, \tag{4} \]
\[ Q_u = \frac{1}{2 \sqrt{C_3 \cdot C_4}}, \tag{5} \]

where \( C_3 \) and \( C_4 \) are constants for the Brinch-Hansen method. Brinch-Hansen 90% method is other variation of this method.

2.3. The Decourt method [24]
In Decourt method results are approximated, with hyperbole from equation (6) and the bearing capacity is determined from equation (7).

\[ Q = \frac{C_6 \cdot s}{1 - C_5 \cdot s}, \tag{6} \]
\[ Q_u = \frac{C_6}{C_5}, \tag{7} \]

where \( C_5 \) and \( C_6 \) are constants for the Decourt method. The main advantage of this method is an simple curve construction in the transformed axis Q/s-Q system [24].

2.4. Meyer method [25-27]
The Q-s curve in Meyer method is described by equation (8):

\[ s = C \cdot \frac{Q^\kappa - 1}{Q_u}, \tag{8} \]

where: \( s \) – settlement [mm], \( N \) – load applied to the pile [kN], \( C \) – parameter describing soil reaction modulus [mm/kN], \( Q_u \) – ultimate capacity of a pile [kN], \( \kappa \) – dimensionless constant [-].
In this method appears a constant $\kappa$ which describes shape of Q-s curve. From a linear range of a curve the C parameter can be determined. Parameters $Q_u$ and $\kappa$ can be determined using the least squares method. In [25-27] more accurate information about the method can be found.

3. Results of the analysis

The methods used for bearing capacity evaluation were compared using the results of static load tests of the pile base. Tests were performed on model pipe pile installed in test box filled with medium dense sand (figure 3). The model piles were 0.045 m diameter and driven into the soil by a dynamic probing light to 0.8 m. During the test, the load was applied by means of a screw jack only to the pile base through the perch. More details of the test procedure were presented in references [27, 28].

![Figure 3. Static test load of model pipe pile base.](image)

Basing on the results of the pile static load test of model pile base the application of different methods of evaluation of ultimate bearing capacity was compared. Evaluated values for each method are presented in table 1.

| Method       | Chin | Brinch-Hansen | Decourt | Meyer |
|--------------|------|---------------|---------|-------|
| Capacity [kN]| 2.05 | 1.80          | 2.45    | 2.24  |

4. Discussion of the results

The results of the static load test of a pile base, shapes of the load-displacement curves and evaluated ultimate base capacities for each method are presented in figure 4. Results of the static load test are presented as points; curve approximations are presented as continuous lines and evaluated pile capacities as dashed lines. There are some differences in the shape of the curves and evaluated pile base bearing capacity for every method. The results prove findings from reference [17] about limitations and risk related to static capacity testing of piles. It is important to notice that the extrapolation of the testing results seems to be doubtful due to some differences in estimated values of ultimate capacity.

There are some differences in the shape of the load-displacement curve in each method and in evaluated bearing capacity. What is more, the results of evaluated capacities differ from load corresponding to the settlement equal of 10% of the diameter, i.e. the value assumed by Eurocode 7. The closest value to this load is obtained from the Brinch-Hansen method. The Chin, Brinch-Hansen and Decourt methods are quite similar in their assumptions.
The Meyer method is different and quite new in comparison to other methods, but results evaluated from that method are quite similar to them. Some aspects of the Meyer method still need to be refined (e.g. finding a relationship between the κ coefficient and the piling installation method) [26, 27].

The main advantage of the Chin and Brinch-Hansen methods is their wide application through many years and their verification by many researchers.

An appropriate method for evaluation of the bearing capacity should be chosen basing on the researcher's previous experience in analysing a larger number of tests. It is also recommended to utilize a few methods for pile capacity evaluation and connect them with proper safety factor.

![Figure 4](image-url) Results of evaluations of pile base bearing capacity from static load test.

5. Conclusions
In paper four methods of the pile ultimate bearing capacity evaluation from the results of the static load test were introduced. Basing on the static load test of the pile base performed on small-scale model pipe pile, its base ultimate bearing capacity was assessed with those methods. Results of evaluation showed some differences depending on utilized methods, which was also confirmed by other researchers [16,17]. Nevertheless, results have shown the application of the method created for pile bearing capacity evaluation also for evaluation of the ultimate bearing capacity of the pile base. Achieved results form the bases for subsequent numerical studies [28].

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References
[1] Quilligan A, O’Connor A and Pakrashi V 2012 Fragility analysis of steel and concrete wind turbine towers. *Engineering Structures* 36 270-282
[2] Łodo A and Michałek J 2014 Wieże z betonu wirowanego pod małe turbozespoły wiatrowe [Spun concrete supporting towers for small wind turbines] *Materiały Budowlane* 6 50-51 [In Polish]
[3] Łodo A and Michalek J 1998 Application of precast spun concrete units to power engineering constructions. Prace Naukowe Instytutu Budownictwa Politechniki Wroclawskiej 70 163-164

[4] Łodo A and Michalek J 2002 Chosen design and realization problems concerning telecommunication towers of spun concrete Concrete and concrete structures. Proc. of the 3rd int. conf., Zilina, Slovakia, April 24-25., Zilina : University of Zilina 211-218.

[5] Bukala J, Damaziai K, Karimi H R, Malachowski J and Robbersmyr K G 2019 Evolutionary computing methodology for small wind turbine supporting structures International Journal of Advanced Manufacturing Technology 100(9-12) 2741-2752

[6] Dymarski C, Dymarski P and Zywicki J 2015 Design and Strength Calculations of the Tripod Support Structure for Offshore Power Plant Polish Maritime Research 22(1), 36-46

[7] Dymarski C, Dymarski P and Zywicki J 2017 Technology Concept of TLP Platform Towing and Installation in Waters with Depth of 60 m Polish Maritime Research 24(s1) 59-66

[8] Midor K and Zasadzień M 2017 Practical use of methodological foundations in designing wind power plants – case study Int. Multidisciplinary Sci. GeoConf. Surveying Geology and Mining Ecology Management, SGEM 17(43) 733-740

[9] Topolnicki M and Soltyś G 2012 Novel application of wet deep soil mixing for foundation of modern wind turbines Grounting and Deep Mixing 2012 533–542

[10] Król M 2013 Problemy związane z posadowieniem elektrowni wiatrowych [Issues associated with the construction of wind farms] Geoinżynieria Drogi Mosty Tunele 3 44-46 [In Polish]

[11] Rybak J 2015 Posadowienia elektrowni wiatrowych: wyzwania w projektowaniu i wykonawstwie [Wind farm foundations: design and construction challenges] Geoinżynieria Drogi Mosty Tunele 1 40-46 [In Polish]

[12] Wyjadłowski M 2017 Methodology of dynamic monitoring of structures in the vicinity of hydrotechnical works - selected case studies Stud. Geotech. Mech. 39(4) 121-129

[13] Lohnunova O and Wyjadłowski M 2018 Modification of vibratory driving technology for sustainable construction works MATEC Web of Conf. 151 03063

[14] Wojtowicz A, Michalek J and Ubyssz A 2019 Range of dynamic impact of geotechnical works on reinforced concrete structures” E3S Web Conf. 97 03026

[15] Rybak J, Sobala D and Tkaczyński G 2008 Static and dynamic testing of driven piles in Poland The application of stress-wave theory to piles: science, technology and practice : proc. of the 8th int. conf., Lisbon, Portugal, 8-10 September 615-618

[16] Sobala D and Tkaczyński G 2017 Interesting developments in testing methods applied to foundation piles IOP Conf. Ser.: Mat. Sci. Eng. 245 (2) 022074

[17] Rybak J and Król M 2018 Limitations and risk related to static capacity testing of piles – “unfortunate case” studies“ MATEC Web Conf. 146 02006

[18] Fleming K, Weltman A, Randolph M and Elson K 2008 Piling Engineering, Third Edition (CRC Press)

[19] Wrana B 2015 Pile load capacity–calculation methods Studia Geotechnica et Mechanica 37 (4) 83-93

[20] Rybak J 2017 Some remarks on foundation pile testing procedures IOP Conf. Ser.: Mat. Sci. Eng. 245 (2) 022092

[21] Fellenius B H 2001 What capacity value to choose from the results of static load test Deep Foundation Institute, Fulcrum Winter 2001, 19 – 22 and Fall 2001 23–26

[22] Chin F K 1970 Estimation of the ultimate load of piles not carried to failure Proc. 2nd Southeast Asian Conf. on Soil Eng. 81-90

[23] Brinch Hansen J 1963 Discussion: Hyperbolic stress-strain response. Cohesive soils, ASCE J. SMSFD 89 (4) 241-242

[24] Decourt L 1999 Behaviour of foundations under working load conditions. Proceedings of the Pan-American Conference on Soil Mechanics and Geotechnical Engineering, Foz Dolguassu, Brazil, August 1999. 4 453-488

[25] Meyer Z 2014 Static load test. Short series interpretation. Studia Geotechnica et Mechanica 36
(2) 45-49

[26] Meyer Z and Zarkiewicz K 2018 Skin and toe resistance mobilisation of pile during laboratory static load test. *Studia Geotechnica et Mechanica* **40** (1) 1-5

[27] Siemaszko P and Meyer Z 2019 Static load test curve analysis based on soil field investigations. *Bulletin of the Polish Academy of Sciences: Technical Sciences* **67** (2) 329-337

[28] Brząkała W and Baca M 2017 Numerical modeling of pile installation influence on surrounding soil. *17th Int. Multidisciplinary Sci. GeoConf., SGEM 2017, 29 June-5 July, Albena, Bulgaria* **17** (12) 619-626