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Limitations and risk related to static capacity testing of piles – "unfortunate case" studies

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Abstract. Static load testing of foundation piles is still considered the main capacity check technology for almost any kind of piling works (bored, displacement, driven). The rates of load, time increments or imposed displacement are the key factors for various testing methods. The load-displacement relationship, which can be transformed into a coordinate system, is always the point of departure for the analysis of the results. For axis (vertical) loading, both, applied load and measured pile head settlement are examined during the entire test. During the lateral capacity tests, the horizontal displacement and inclination of free pile head is measured. In either case, all recorded values must be thoroughly examined in order to avoid systematic errors which could flaw the results of the analysis. In this paper, the authors gather and discuss their experience from field tests in which equipment malfunctions or external circumstances had the impact on the range of load test and, thus, their results. The possible ways of test extrapolation with regard to load range are also the subject of further observations presented in this publication.

1 Introduction – the need of pile testing

Static load tests are used for direct determination of capacity, verification of static calculations or for calibration of other tests (e.g. dynamic testing) at similar soil conditions. In accordance with Eurocode 7 [1], pile foundations should preferably be designed on the basis of results from load capacity tests [2]. During these tests, increasing loads are applied stepwise specific time intervals; after each step the settlement is measured. The obtained load settlement curve is further interpreted [3]. In this technique, the load should increase until the pile reaches the limit state (i.e. the situation in which the increment in settlements is unhindered without the need of increasing the load applied), which leads to the identification of the ultimate capacity. In practice, one never reaches this moment for various reasons, like limited strength of a testing station, insufficient capacity of anchoring piles or too small a kentledge (see Fig. 1), therefore it is often impossible to achieve the loads which would actually cause the unhindered pile penetration in the plastic soil. In the end, the scope of the test does not enable one to get relevant information about the pile

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ultimate capacity and would not allow to calibrate the calculation model, even if the force applied during the test is larger than the design capacity and still, the structure safety is confirmed. Without knowing the ultimate capacity, we are not able to take advantage of the margin that would make it possible to decrease the number of piles in the foundation or to reduce their length.

Fig. 1. Static tests with anchoring pile group and kentledge (water tanks).

In designing practice, we often assume the maximum load effected in field testing as the ultimate capacity and accept that limitation due to uncertainty of extrapolation methods, as recommended by Fellenius [4]. In nowadays' trends of giving primary importance to economic factors, the fact that static tests are costly and time-consuming is especially brought to the fore, and because of that it is emphasized that they should be used to get as much information about the pile capacity as possible. This paper outlines how the number of measurements (for the range of test load effected) affects the accuracy of determining the ultimate capacity- Q_u. The review was based on data from 30 site logs of test loads applied to prefabricated driven piles. Examinations were made within supervision of Wrocław University of Science and Technology on construction and modernization of road infrastructure in 2010-2012.

2 Traditional methods of load test extrapolation

There are numerous methods of determining the ultimate capacity with extrapolating the results gained before pile reaches the state of ultimate load bearing capacity. Polish Code of Practice PN-83/B-02482 [5] makes it possible to determine Q_u from the auxiliary waveform dQ/ds. The condition $dQ/ds=0$ means unhindered increment in settlement without increase of load. The most popular extrapolation methods worldwide for foundation piles, described in detail by Fellenius [4], were tested for their accuracy (possible error of estimating Q_u). Each extrapolation method employed in these analyses may be described as fitting the results of settlement measurements in successive pile loading steps into the assumed functional form. The co-ordinate system is re-scaled (ordinates and abscissas) in order to facilitate the fitting of extrapolating function parameters; because of that, the settling-strain relation is roughly linear in the final stage of pile operation. This allows to fit the function extrapolating the test load curve with the use of the simplest linear regression in the spreadsheet. The slope of a straight line and the free term need to be fitted to estimate the ultimate capacity.

Of key importance are the last points on settlement-strain curve, which represent elastic/plastic operation of pile prior to reaching the ultimate capacity. The method presented in Fig. 2 proposed by De Beer [6] to evaluate the pile capacity may be helpful as the criterion of selecting the range of point fitting. The settlement-loading relation is given in logarithmic scale; hence it is roughly linear in intervals. The operating ranges of pile are presented in Figure 2. The intersection point of curves drawn on the diagram represents approximate value of load above of which the pile operates in plastic range. It should be emphasized that the concept of De Beer [6] was not aimed at determining the value of Q_u but merely the load above which permanent pile displacement occurred. Similar nature (however for another system of co-ordinates) had the interpretation of test loads according to Polish Code of Practice [5]. In fact, the ultimate capacity can be determined by means of points on the straight line representing the plastic range of pile operation. The more points are recorded in this range, the higher precision of ultimate capacity estimation is guaranteed. If the number of measurements is too small, errors occur and make the extrapolation method useless. Errors generated by a selected method are compared and the effect of the number of measurements in elastic/plastic range and in plastic range of pile operation on extrapolation accuracy is verified.

3 Decourt's, Brinch-Hansen's 80% and Chin-Kondner's method

According to Decourt's method [7], the settlement-loading relation (s–Q) is transformed into the coordinate system: Q - abscissa and Q/s - ordinates (Fig. 3). For the last points of the performed test at which the settlement reached stabilization the following linear dependence is found (by way of approximation): $Q/s = A \cdot Q + B$.

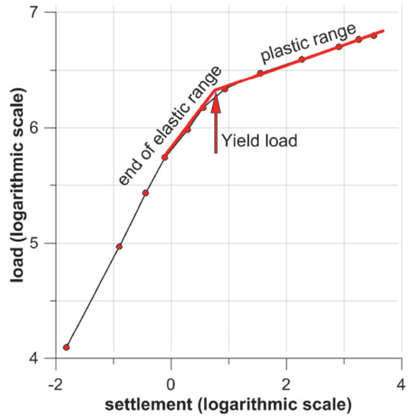

Fig. 2. De Beer double logarithmic method [6].

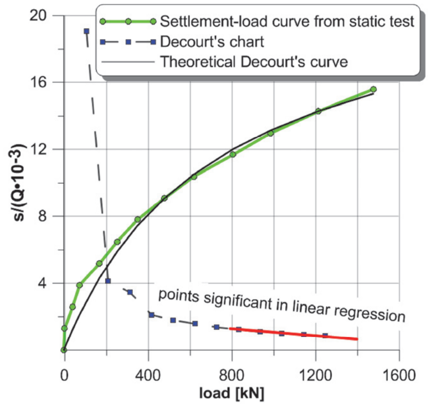

Fig. 3. Decourt's method [7].

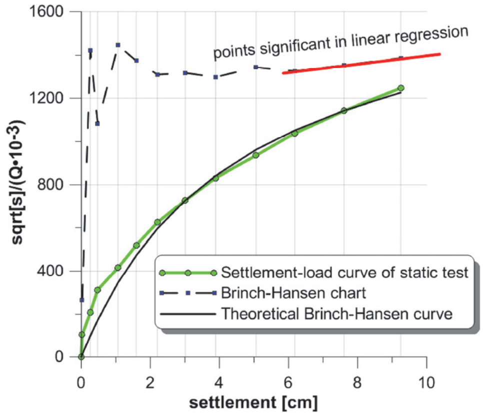

Fig. 4. Brinch-Hansen 80% method [8].

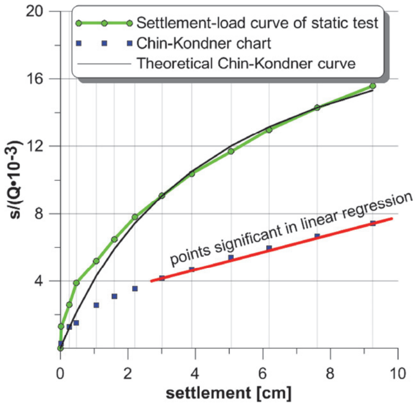

Fig. 5. Chin-Kondner method [9].

According to Brinch-Hansen, in a so-called 80% method [8], the ultimate capacity Q_u is understood as such loading for which the settlement s_u exceeded four times the value s measured after 80% of the load Q_u has been applied. The settlement-loading relation (s–Q) is then transformed into the coordinate system: s - abscissa and $\sqrt{s}/Q$ - ordinates (Fig. 4). For the last points of the performed test at which the settlement reached stabilization the following linear dependence is found (by way of approximation): $\sqrt{s}/Q = A\cdot s + B$.

According to Chin-Kondner method [9], the settlement-loading relation (s–Q) is transformed into the coordinate system: s - abscissa and s/Q - ordinates (Fig. 5). For the last points of the performed test at which the settlement reached stabilization, the following linear dependence is found (by way of approximation): $s/Q = A\cdot s + B$.

The ultimate capacity and settlement-load relation the for all the methods can be then derived from formulae juxtaposed in Table 1.

Table 1. The ultimate capacity and settlement-load relation the for all the methods.

method	Decourt's	Brinch-Hansen 80%	Chin-Kondner
ultimate capacity	$Q_u = -B/A$	$Q_u = \dfrac{1}{2\sqrt{A\cdot B}}$	$Q_u = 1/A$.
settlement-load relation	$Q = \dfrac{B\cdot s}{1 - A\cdot s}$	$Q = \dfrac{\sqrt{s}}{A\cdot s + B}$	$Q = \dfrac{s}{A\cdot s + B}$

where: A – slope of regression straight line;
B – intersection point between regression straight line and 0Y axis.

4 Example of evaluation of ultimate capacity inaccuracy

It must be noticed that all the extrapolation methods are strongly dependent on the range of the performed test in relation to the computed ultimate capacity. In this study, the authors chose the Chin-Kondner method for its simplicity; similar calculations, however, for Decourt's and Brinch-Hansen 80% criteria gave very similar results.

A series of calculations were performed to check to what an extent we can be mistaken when the test range reaches a certain percentage of ultimate capacity. For load-settlement charts from failed load tests – an estimation of (known) capacity was done on the basis of insufficient data. In some of the cases the result was quite satisfactory. In other cases (see Fig 6) extrapolation led to serious under- or overestimation of ultimate capacity Q_u.

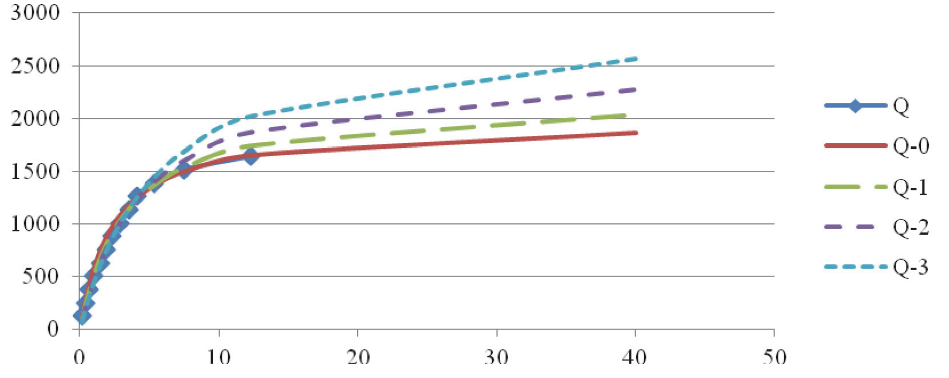

Fig. 6. Chin-Kondner extrapolation for reduced test information (very risky).

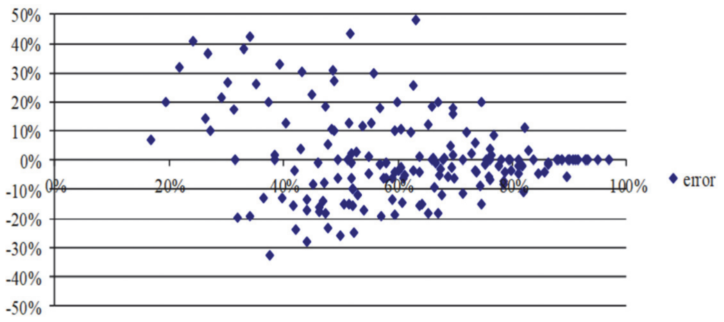

Fig. 7. Error in ultimate capacity estimation for Chin-Kondner method.

The error shown in Fig. 7 is the distance between the ultimate capacity estimated on the basis of only some part of the obtained data (i.e. the values preceding the limit state) and the actual limit state values measured during the test. In most of the cases the result is positive, which points to an overestimation of capacity (as in Fig 6).

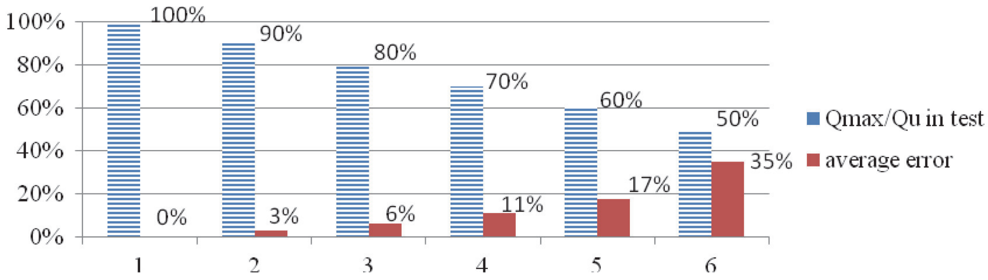

Fig. 8. Average error in ultimate capacity estimation for short series.

It can be noticed (Figure 8) that if the range of test does not exceed 70% of Q_u, then the average absolute error reaches almost 20%. Such result will be unacceptable for design.

5 Summary and conclusions

The authors evaluated each method described in this paper with respect to its accuracy of estimating the ultimate capacity. The review of 30 site logs of pile static testing proves that the Brinch-Hansen 80% method is the most accurate of all extrapolation methods. If we want to be able to apply it, however, we need a relatively large number of load steps. When used for extrapolating the points from the elastic range of pile operation (i.e. after the limit capacity has been reached), the method turns out overtly futile. Calculations made by way of steps proposed by Chin-Kondner and Decourt show that the estimated capacities differ significantly from those determined in static tests. However, the features of applied approximating functions make it possible to use them for loads performed in a narrower range. If former authors' works [10] it was already proved that the loss in accuracy in determining the capacity is the consequence of the having the advantage of possible extrapolation for points from elastic/plastic interval of pile operation. Fellenius [4] expressed doubts about the sense of using the Chin-Kondner and Decourt method, labelling them as insufficiently conservative. It must be underlined that same doubts must be emphasised when dealing with numerical modelling of pile behaviour under test [11], especially in the last stages of static load test [12].

Table 2. Method comparison – derived errors.

	Brinch-Hansen 80%		Chin-Kondner		Decourt	
Points used	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
2	24.86%	9.76%	50.71%	10.67%	45.13%	10.48%
3	16.84%	10.12%	42.93%	9.99%	37.42%	11.43%
4	11.09%	9.47%	36.20%	8.03%	31.18%	10.39%
5	10.18%	7.04%	29.09%	7.78%	25.24%	8.66%
6	6.46%	4.75%	20.83%	7.14%	18.93%	8.24%
7	4.43%	2.92%	9.59%	4.73%	14.60%	7.84%

It is also an essential information that measurements from the first steps of pile loading have no effect on the result. Attempts to extrapolate the ultimate capacity from the initial measuring points are completely useless, as the result would not be even slightly similar to real value. Theoretical curves fit well in plastic range, while large discrepancies are observed in the range of pile operation. Results of three methods of estimating the ultimate capacity are presented in Table 2 on the basis of data from 30 site logs of static tests.

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