Static Load Test Imperfections Influence on Continuous Q-S Curves

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Abstract. The static load test is the most reliable method of indicating the actual pile bearing capacity. Within the pile load increments, the settlement is measured and set of points Q-s (load – settlement) is plotted. The ways of executing the pile load test and their interpretation are far from optimal and have many different approaches. Usually, the pile test does not allow evaluating the bearing capacities within the measured range and extrapolation of the results within the Q-S curves is necessary. None of the present interpretation models includes the influence of imperfections in the pile load test. The paper presents the results of calculations with the model that takes into account the occurrence of imperfections during the test execution. The analysis is based on the modified Meyer-Kowalow curve model, proposed by Meyer and Wasiluk, and on the field test obtained on many construction sites for piles in different technologies, few of them loaded up to the failure. The model considered in the paper allows extracting statistical imperfections in the collected set of points. Imperfections should be understood as mechanical changes of the pile and pile-soil interaction. All phenomena are gathered within one imperfection. The imperfections are due to changing soil and pile skin when the soil body bends according to the Kirchhoff’s principle. Calculations indicate the influence of imperfections on the pile limit load and other parameters of the Q-s curves according to the basic model that exists. Performed analysis based on approximately 65 piles defines three main groups, first with a relatively small influence of imperfections, second with changes of the limit load for the entire pile and the pile toe without the large change of pile character (ratio of skin friction and pile toe resistance) and the third with a significant change in limit loads and pile bearing capacity components ratio (skin and toe). Values measured during the pile load test can be corrected within extract imperfections. Presented model in many cases determines more critical values for designers than basic models suggest.

1. Introduction

For many years engineers try to describe the phenomenon of soil and piles cooperation under the axial force. The bearing capacity that is estimated for every pile consists of two components that are: the toe resistance and skin friction. The most reliable methods of verifying the real bearing capacity of piles are pile tests in filed, where static pile loads test is characterized as the most convergent to actual working conditions of the foundation under the load. The way of executing the pile load test and their interpretation are far from optimal and have many different approaches. In general, during the test, the pile is incrementally loaded, usually up to 150% of the designed bearing capacity of the pile [1]. As
a result of the test, the set of points is plotted (settlement $s$ for each load $Q$). Unfortunately, in practice, this range of loading does not allow to estimate the limit load of the pile. For this kind of the test to estimate values of the limit loads, it is necessary to use extrapolation methods within $Q$-$s$ curves. One of the reliable methods to interpret the static pile load test is Meyer-Kowalow (M-K) curve [2-4], it allows creating the model of the pile settlements under the higher loads that were not executed in the field. The model exists for many years and is still developing [5-9], the accompanying formulas describing the characteristics of toe bearing capacity and skin friction exist in the literature.

The paper presents the results of calculations with the model that takes into account the occurrence of imperfections during the test execution. The analysis is based on the modified Meyer-Kowalow (M-K) curve model, proposed by Meyer and Wasiluk [8, 9] and on the field tests obtained on many construction sites for piles in different technologies, few of them loaded up to the failure. In the analysis, more than 65 piles were considered. The mentioned model allows extracting statistical imperfections in the collected set of points, imperfections should be considered as mechanical changes of pile and pile-soil interaction. These imperfections are gathered as one value that should be understood as correction of set plotted during the static load test. The imperfections can have positive and negative values.

2. Analytical model

Assuming the occurrence of imperfections in the static pile load test, it is necessary to add an additional element $s_0$ (Figure 1) to the basic formula (1).

$$s_i = s_0 + C_2 \cdot \frac{N_{gr}}{\kappa_2} \left(1 - \frac{N_i}{N_{gr}^2}\right)^{\kappa_2} - 1$$

Where: $N_i$ - applied force [kN], $s_i$ - measured settlement [mm], $s_0$ - assumed imperfection [mm], $C_2$ – the inverse of the Winkler constant [mm / kN], $N_{gr}$ – limit load of the pile, which causes uncontrolled settlements [kN], $\kappa_2$ – the proportion between the resistance of the pile shaft and the base of the pile [-].

![Figure 1. Graphical presentation of imperfection s0 in M-K curve](image-url)
For calculation of certain pile bearing capacity components (skin friction and pile toe resistance) and plot of the curves for each following formulas were used:

\[
N_2(s) = N_{gr2} \left[1 - \left(1 + \frac{\kappa_2 \cdot s}{C_2 \cdot N_{gr2}}\right)^{-\frac{1}{\kappa_2}}\right]
\]  
(2)

\[
N_1(s) = N_{gr1} \left[1 - \left(1 + \frac{\kappa_1 \cdot s}{C_1 \cdot N_{gr1}}\right)^{-\frac{1}{\kappa_1}}\right]
\]  
(3)

\[
T(s) = N_2(s) - N_1(s)
\]  
(4)

Where: \( C_1 \) – the inverse of the Winkler constant [mm / kN] for pile toe, \( N_{gr1} \) – maximum load in the head, which causes uncontrolled settlements [kN], \( \kappa_1 \) – the proportion between the resistance of the pile shaft and the base of the pile [-] for pile toe curve,

For estimation of limit loads and other unknown of the model, it is necessary to apply the formulas based on previous research performed by Żarkiewicz and Meyer [4,10]. To describe the characteristics of pile toes resistance following formulas from the literature were used:

\[
N_{gr1} = \frac{N_{gr2}}{(1 + \kappa_2)^{4/3}}
\]  
(5)

\[
\kappa_1 = \ln(1 + \kappa_2)
\]  
(6)

\[
C_1 = C_2 (1 + \kappa_2)^2
\]  
(7)

The solution is based on a statistical analysis of the basic set, with three points as conditional equations, i.e \( s_i, s_{i+1}, s_{i+2} \) on the curve. Then, it is possible to determine the curve parameters after eliminating the measurement inaccuracy \( s_0 \) as follows. To do this, subtract adjacent points from each set and then divide by themselves the difference of these points.

\[
s_{i+1} - s_i = C \cdot N_{gr} \left(1 - \frac{N_{i+1}}{N_{gr}}\right)^{-\kappa} \left(1 - \frac{N_i}{N_{gr}}\right)^{-\kappa} \]  
\[ \frac{s_{i+2} - s_{i+1}}{s_{i+1} - s_i} = C \cdot N_{gr} \left(1 - \frac{N_{i+2}}{N_{gr}}\right)^{-\kappa} \left(1 - \frac{N_{i+1}}{N_{gr}}\right)^{-\kappa} \]  
(8)

(9)

Based on the measured settlement values and the corresponding forces, it is possible to determine the function:
\[ Y_{\text{measured}} = \frac{S_{i+1} - S_i}{s_{i+2} - s_{i+1}} \]  
\[ Y_{\text{calculated}} = \left( 1 - \frac{N_{i+1}^{\text{gr}}}{N_{i+1}^{N}} \right)^{-\kappa} - \left( 1 - \frac{N_i^{\text{gr}}}{N_i^{N}} \right)^{-\kappa} \]

For the calculation of the assumed imperfection formula (…) was used:

\[ \sum s_{i+1} = n \cdot s_0 + \frac{C \cdot N_{i+1}^{\text{gr}}}{\kappa} \cdot \sum \left( 1 - \frac{N_{i+1}^{\text{gr}}}{N_{i+1}^N} \right)^{-\kappa} \]

On Figure 2, two types of static load test are presented. First one is typical tests executed often on construction sites with the curve of settlement similar to the straight line, without possibility to interpret the limit load of the pile. The second one is an example of a test executed up to the failure of the pile (as failure should be understood the settlement within an uncontrolled manner). In that kind of test, it is not necessary to extrapolate the results to estimate the limit load of the pile because it has been already reached and can be read from the graph. Graphical interpretation of the curve shows the clear path of settlement within the load.

![Figure 2](image_url)

**Figure 2.** Results of static pile load tests a) typical results of the test (a small range of settlements) with extrapolation, b) results of test executed up to the failure with an interpretation of measured values

For the purpose of the analysis were available 5 static pile load tests loaded up to the failure. All 5 piles were executed with the same technology. Bored in shaft piles with diameter from 1 to 1.5 meters. To verify the model used in the analysis the sets of points Q-s from 5 piles were reduced to the form of the typical test without a big range of settlements. Since the settlement paths and limit loads are known, the verification of these values within shorter sets is possible. The analysis showed accurate convergence of results obtained in the field and reached during the analysis. A detailed description is available in [9, 11].
3. Results and discussions

The analysis is based on approximately 65 static load tests of piles. Each result of static load tests was calculated with M-K curve and modified M-K curve. For both models, the values of bearing capacity components using formulas (2-6) were estimated. For the modified procedure, the assumed imperfections were designated within the formula (12).

Results can be interpreted according to many criteria; in the paper analysis, it is focused on the influence of modified procedure on extrapolated Q-S curves plot, regarding the basic procedure. Reached results have formed three groups. Group I with no influence on the limit load of the pile and certain parameters of the curve – no changes in bearing capacity components (skin and toe). In group II, the modified procedure present slightly different values than the basic formula, there are no significant changes in the ratio of toe resistance and skin friction. Group III is characterised within the change in bearing capacity distribution, the ratio between toe resistance and skin friction is changing significantly.

In Tables 1 and 2, the parameters of basic and modified approximation are shown (8-11), values for toe resistance were reached within (5-7).

| Tech. | Length [m] | Diameter [m] | $N_{gr}^2$ [kN] | $\kappa_2$ [-] | $C_2$ [MN/mm] | $N_{gr}^1$ [kN] | $\kappa_1$ [-] | $C_1$ [MN/mm] |
|-------|------------|-------------|----------------|---------------|----------------|----------------|---------------|----------------|
| Vibro | 10,5       | 0,51/0,56*  | 7063           | 1,78          | 0,0017         | 1808           | 1,02          | 0,01312       |
| Bored | 23,5       | 1,0         | 4777           | 0,39          | 0,0007         | 3067           | 0,33          | 0,00136       |
| Vibro | 10,0       | 0,41/0,46*  | 6097           | 4,68          | 0,00139        | 602            | 1,74          | 0,04486       |

* - pile base diameter

In the paper, Figures 3 to 5 present the examples of each group, described above with usage of formulas (2-4).
Figure 3. Results of Q-s set extrapolation within 1) basic M-K curve and 2) modified M-K curve – results for the group I
Figure 4. Results of Q-s set extrapolation within 1) basic M-K curve and 2) modified M-K curve – results for the group II
Figure 5. Results of Q-s set extrapolation within 1) basic M-K curve and 2) modified M-K curve – results for group III
From over 65 piles the groups were created approximately by 20 piles each. The distribution is rather equal, there is no correlation between the technology and assumed imperfections. In each group, the calculated values of imperfections have negative and positive values. Certain values of imperfections do not indicate big numbers, all of them below ±2 mm. However, it should be considered within the results of static load tests.

Most of the tests as mentioned above are executed within the range of relatively small settlements; usually according to the available results and literature, these values are 1 to 4 % of pile diameter. The evaluation of the imperfections analysis should be based on the ratio between the maximal settlement of the pile during the static load test and the value of estimated imperfection. After that calculation in analysed groups, the value of imperfection reaches up to the value of 10% of maximal settlement in the last step of the load test. This number is more relevant for engineers and the way of executing the static load test should be reconsidered. Within the fact that modified procedure gives different bearing capacity distribution on the pile, both procedures are suggested for static pile load test interpretation.

Procedure for executing the static pile load test should be based more on required settlements, not only on the design force with a safety margin. Within that kind of approach over designing should be decreased. Resources saved on foundation optimization should be saved for more advanced soil investigation and bigger amount of static pile load test. These steps lead to higher quality research and finally lower costs spent on construction.

4. Conclusions

The presented calculation model allows to determine the measurement imperfections from a set of \( \{ s_i; N_i \} \) values, which is manifested by phenomena like: adaptation of the soil to the pile (initiation of cooperation between the pile and the ground requires the soil to "fit" to the pile), deformation of the loading structure ensuring vertical force and its impact on the pile cooperation with the ground. The determined imperfections enable the correction of the data set determined from these static pile load test \( \{ s_i - s_0, N_i \} \). Static load tests realized up to the failure allowed to verify both models basic M-K curve and modified M-K curve.

The modified procedure with an assumed imperfection of static load test presented in the paper indicates influence on parameters of M-K curve. Moreover, the results of most relevant parameters i.e. limit load of the pile \( N_{gr} \) for the most part of analysed cases decreased relative to the basic model. Considering the imperfections in the analysis affects the changes in the pile load distribution (skin friction and pile toe resistance).

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