Static Load Tests, Short Series Interpretation

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Abstract

Static load test is the most commonly used for estimation the bearing capacity of piles. From the test we obtain the series a values: load-settlement, \( Q - s \) curve. In practice it is extremely difficult to reach the critical load of the pile when the settlement turns out of control. The existing methods that allows to calculate bearing capacity give the value which is very often 1/10 of the critical load. The question appears is it possible based upon short series of load i.e. \( 0 \div 0.4 \) critical load, to predict the critical value of the load, with accuracy which is sufficient for practical calculation. The paper presents a method how to calculate the critical load based upon short series of load in the static load tests.

Key words: soil mechanics; static load tests; piles.

1. INTRODUCTION

Static load test is a widely used method for estimation of bearing capacity of a simple pile [1,2,3,4,5,8,9,10,11]. For a sequent load, the settlement is a measured so the result of the test is given as a set of values: settlement-load \( \{s_i; N_i\} \). In the existing literature there exists a number of methods and equations which can be used for calculation of bearing capacity of a single pile. The methods do not analyse the critical value of the load, that one for which the settlement turns out of control. So the allowable load which is assumed in engineering practice is 1/6\( \div \)1/9 of the critical load. On the other hand, the small assumed allowable load is the reason of very small settlement of the pile which has nothing to do with the allowable settlement of the foundation. That was the reason of undertaking the following research trying to answer, if it is possible to estimate the critical load of a single pile based upon short series of load, i.e. \( 0 \div 0.4 \) of the critical load.

Normally it is extremely difficult to reach the critical load during static load tests, in order achieve the settlement which turns out of control. If we know the critical load, we can assume then the allowable load putting safety factor or we can assume allowable settlement and from this condition we can calculate the load which implies this settlement.

2. MATHEMATICAL DESCRIPTION OF THE SETLEMENT OF A SINGLE PILE

In literature there exists a number of the proposal how to draw the curve: settlement – load. But if we use them for further mathematical analysis i.e. differentiation, integration, boundary values they fail.

So that was the reason that for mathematical description a nonlinear model was taken developed by the author [6,7,]. The applied curve has following advantages:

- one curve for the whole range of load from zero to the critical load,
- one curve for the whole range of settlement,
- the curve has two asymptotes, one vertical for critical load, and one skew asymptote for load equal to zero (very small load), and it refers to linear Boussinesq theory,
The numerical calculations for the available static load tests sets \( \{s_i; N_i\} \) indicate that the curve fits very well the measured data. The proposed curve is of the shape:

\[
s = C \cdot N_{gr} \cdot \left(1 - \frac{N}{N_{cr}}\right)^{-\kappa} - 1
\]

(1)

where: \( s \) – is settlement [mm]; \( C \) – is a constant value representing the aggregated soil reaction modulus \( \left[ \frac{mm}{kN} \right] \) (Winkler elastic constant); \( N \) – is load applied to the pile head [kN]; \( N_{gr} \) – is critical load [kN]; \( \kappa \) – dimensionless constant.

An example of the graph of the curve (1) is given in Fig. 1.

![Graph of the curve](image)

Fig. 1. The graph of the curves \( s = s(N; \kappa) \)

From Fig. (1) it comes that for \( N \to 0 \) it gives:

\[
s = C \cdot N
\]

(2)

that denotes the skew asymptote. For \( N \to N_{gr} \) we have \( s \to \infty \) and it denotes the vertical asymptote. Formally the solution that we are looking for relay upon fitting three parameters of the curve: \( C \), \( \kappa \), and \( N_{gr} \), to follow the measured values \( \{s_i; N_i\} \) obtained during the static load test. From the aforementioned three parameters it seems to be easy to calculate the value \( C \), taking points from the beginning of the curve.

Two others parameters: \( \kappa \) and \( N_{gr} \) should be estimated using least square method. So we have:

\[
\delta^2 = \sum \left[ s_i - s(N_i; N_{gr}; \kappa) \right]^2 = \text{min}
\]

(3)

Numerical calculations based upon available sets \( \{s_i; N_i\} \) indicates that the resulting values: \( \kappa \) and \( N_{gr} \) are very sensitive for the errors of the measured values \( s_i \) and \( N_i \). One of the way to obey, it is to search for an additional relation:

\[
N_{gr} = N_{gr}(\kappa)
\]

(4)
3. **ESTIMATION OF THE RELATION** \( N_{gr} = N_{gr} (\kappa) \)

From the basic eq.(1) we can derive the function \( N_{gr} = N_{gr} (\kappa) \) using linear regression only for \( \kappa = 1 \) and \( \kappa = 2 \) so we have:

- **for** \( \kappa = 1 \)

\[
N_{gr} (1) = \frac{\sum (N_i^2)}{\sum (N_i \cdot Y_{ii})} \quad \text{where}
\]

\[
Y_{ii} = 1 - \frac{C \cdot N_i}{s_i}
\]

- **for** \( \kappa = 2 \)

\[
N_{gr} (2) = \frac{\sum (N_i^2)}{\sum (N_i \cdot Y_{2ii})} \quad \text{where}
\]

\[
Y_{2ii} = \frac{4 \left( \frac{s_i}{C \cdot N_i} - 1 \right)}{4 \cdot \frac{s_i}{CN_i} - 1 + \sqrt{8 \cdot \frac{s_i}{CN_i} + 1}}
\]

For other \( \kappa \) values for rough estimation we can use linear relation:

\[
N_{gr} (\kappa) = N_{gr} (1) \cdot \left[ 2 - \frac{N_{gr} (2)}{N_{gr} (1)} + \kappa \cdot \left( \frac{N_{gr} (2)}{N_{gr} (1)} - 1 \right) \right]
\]

More accurate relation \( N_{gr} (\kappa) \) we can obtain by expanding function (1) in Maclaurin series. If we put:

\[
X = \frac{N}{N_{gr}}
\]

\[
B = \frac{s}{C \cdot N}
\]

then, for \( 0 < X < 0.4 \) it allows following approximation:

* \( N_{gr} = \frac{N}{6} \cdot F_0 \) \quad \text{where}

\[
F_0 = \frac{2B + 1}{B - 1} (\kappa + 1) + 2 \quad \text{or}
\]

** \( N_{gr} = \frac{N}{6} \cdot \left( \frac{\kappa + 2}{Y} \right) \) \quad \text{where}

\[
Y = \sqrt{\left[ F_0 + 2(\kappa + 2) \right]^2 - 4(\kappa + 2) - \left[ F_0 - 2(\kappa + 2) \right]} / 2 \cdot (2F_0 - 1)
\] (15)

\[
N_{gr} = \frac{N}{6} \left[ F_0 - \frac{\kappa + 2}{F_0 + 2(\kappa + 2)} \right]
\] or (16)

Examples of comparison the results \( N_{gr} / N \) for different values \( B \) are given in Table 1.

<table>
<thead>
<tr>
<th>Nr</th>
<th>Eq</th>
<th>( B=2 )</th>
<th>( B=1.5 )</th>
<th>( B=1.3 )</th>
<th>( B=1.1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.83</td>
<td>2.06</td>
<td>1.66</td>
<td>4.33</td>
<td>3.00</td>
</tr>
<tr>
<td>2</td>
<td>2.80</td>
<td>1.97</td>
<td>1.13</td>
<td>4.31</td>
<td>2.98</td>
</tr>
<tr>
<td>3</td>
<td>2.80</td>
<td>1.97</td>
<td>1.13</td>
<td>4.31</td>
<td>2.98</td>
</tr>
</tbody>
</table>

Taking Eqs. (12, 13, 14, 15, 16) it is possible to formulate a general function \( N_{gr}(\kappa) \) numerically. And then to use it for statistical calculations. Deeper investigation of the numerical methods is not a matter of the present paper. Furthermore the author focus on a practical method which can be used in engineering activity dealing with static load tests.

4. SIMPLIFIED METHOD OF ESTIMATION \( N_{gr} \)

The simplified method is based upon replacing original function (1) by approximate function of type

\[
\ln B = C_1 + C_2 \cdot \ln X
\] (17)

and noting that

\[
B = \left( \frac{(1-X)^{-\kappa} - 1}{\kappa \cdot X} \right)
\] (18)

We can estimate constant values: \( C_1 \) and \( C_2 \) as functions of \( \kappa \). It gives:

\[
C_1(\kappa) = 0.4062 + 0.5980 \cdot \kappa
\] and (19)

\[
C_2(\kappa) = 0.1665 + 0.2684 \cdot \kappa
\] (20)

The level of this approximation is very high, correlation coefficient is of order 0.98. Practical application of the procedure is as follows. The calculation of \( N_{gr} \) takes two stages (Fig.2). We assume that we have set of values \( \{ s_i; N_i \} \).
For the subset – area 1, we calculate constant $C$ using approximation:

$$s = A_0 \cdot N \cdot A_i^N$$

(21)

If we rearrange this equation into:

$$Y = \frac{S}{N} = A_0 \cdot A_i^N$$

(22)

We can apply linear regression using least square method. It can be seen that this approximation gives:

$$C = A_0$$

(23)

For the subset area 2 we use another approximation:

$$s = D_0 \cdot N^{D_1}$$

(24)

Constants: $D$ and $D_1$ come again from linear regression: And as a result we have:

$$B = \frac{s}{CN} = \frac{D_0}{C} N^{D_1 - 1}$$

(25)

and further the equation (17) takes form:

$$B = e^{C_i(\kappa)} \left( \frac{N}{N_{gr}} \right) C_2(\kappa)$$

(26)

It implies

$$C_2(\kappa) = D_1 - 1$$

(27)

and

$$N_{gr} = \left( \frac{C}{D_0} \right)^{\frac{1}{D_1 - 1}} e^{C_i(\kappa)}$$

(28)

Finally the solution takes form

$$N_{gr} = \text{const} \left( \frac{C}{D_0} \right)^{\frac{1}{D_1 - 1}}$$

(29)
where

\[\text{const} = 10.9841 - 1.0567 \cdot D_i\]  

and

\[\kappa = 4.924 \cdot (D_i - 1.1595)\]  

5. EXAMPLES OF CALCULATIONS

To present the practical usage of the proposed method of simplified estimation of critical load \(N_{gr}\), four sets of data coming from field static load test were chosen.

The test were made in the surrounding of the town Szczecin, so the ground is formed by glacial sands from Odra river valley. The piles were prefabricated concrete elements of size 0.4x0.4x12.0m. The results of the evaluation are given in Table 2. The analysis of the Eqs. (29) to (34) indicates that for the rough estimation of the critical load simple formulae can be used:

\[N = 9 \cdot \left( \frac{C}{D_0} \right)^{1/3}\]  

The graph of the results of estimation as shown in Table 2 i given in Fig. 3.

![Graphs of the obtained correlation for the evaluated piles from [7]. (Solid line calculated, dot lines – measured)](image)

**Table 2**

<table>
<thead>
<tr>
<th>Nr</th>
<th>(C\left[\frac{mm}{kN}\right])</th>
<th>(D_0)</th>
<th>(D_1)</th>
<th>(\kappa)</th>
<th>(N_{gr}) [kN]</th>
<th>(N_{gr}^*) [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.002097</td>
<td>0.000300</td>
<td>1.690</td>
<td>1.83</td>
<td>4240</td>
<td>4290</td>
</tr>
<tr>
<td>2</td>
<td>0.001244</td>
<td>0.00017727</td>
<td>1.338</td>
<td>0.52</td>
<td>2860</td>
<td>3100</td>
</tr>
<tr>
<td>3</td>
<td>0.002606</td>
<td>0.0000006590</td>
<td>2.277</td>
<td>4.00</td>
<td>5880</td>
<td>5400</td>
</tr>
<tr>
<td>4</td>
<td>0.001476</td>
<td>0.0000002941</td>
<td>2.700</td>
<td>5.62</td>
<td>4800</td>
<td></td>
</tr>
</tbody>
</table>
Knowing the parameter of Eq. (1) i.e. $C$, $\kappa$ and $N_{gr}$ we can now calculate the allowable load for the pile $N_{al}$ based upon allowed settlement $s_{al}$. So we have:

$$s_{al} = \frac{C \cdot N_{gr}}{\kappa} \left(1 - \frac{N_{al}}{N_{gr}}\right)^{-\kappa} - 1$$  \hspace{1cm} (33)$$

where $N_{al}$ - allowable load [kN]; $s_{al}$ - allowed settlement of the pile [mm]. And next:

$$N_{al} = N_{gr} \cdot \left[1 - \left(\kappa \cdot \frac{s_{al}}{C \cdot N_{gr}} + 1\right)^{\frac{1}{\kappa}}\right]$$  \hspace{1cm} (34)$$

and furthermore, we have then safety factor $SF$:

$$SF = \frac{N_{gr}}{N_{al}}$$  \hspace{1cm} (35)$$

As an example if we take values of the pile 1 from Table 2, it gives for $s_{al} = 3cm$, $N_{al} = 2800kN$. And so, $SF = 1.51$.

6. CONCLUSIONS

1. Nonlinear model of the load-settlement for static load test results was investigated. It comes that the method can be used for interpretation off static load test results in case of short series.

2. As the basic method of estimation of the curve (1) parameters: $C$, $\kappa$ and $N_{gr}$, remains the least square method applied according to the formulae (3).

3. For practical calculations a simplified method can be used. The method comes from replacing the original Eq.(1) by approximate formulae (17). Using this formulae it makes the calculation simple when $N_{gr}$ is seen.

4. The problem which remains to be investigated is the meaning of the parameter $\kappa$ in the basic curve (1). It seems to be that it has a physical representation because it corresponds to the ratio of the skin forces to the tow forces of the pile. Another problem is the correlation of the parameters: $C$ and $\kappa$ to the parameters of soil forming the ground.

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