Soil parameters’ numerical back analysis for comparison of driven pile’s capacity assessment methods

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Abstract. The paper shows several methods of driven piles capacity assessment. The piling work consisted of driving around 10 000 prefabricated concrete piles for the indirect foundation of National Stadium’s located in Warsaw city center. A total number of 68 investigated piles was divided into three groups, depending on their length, because longer piles tend to be weaker, what is shown in the paper. Results of dynamic load test, CASE and CAPWAP limit capacity and piling reports provided by AARSLEFF company stood the basis for further analysis in this work. The given results of dynamic test were taken as the most reliable data to compare with other methods, as they gave surprisingly close values, while being nondependent. Large amount of displacement piles happened to impact existing soils’ mechanical properties. The difference in maximum resistance force was estimated, by carrying out a numerical back analysis with GEO5 software. The computation shows significant growth of internal friction angle, and compaction index which led to three times higher limit pile capacity. The extra compaction effect during pile driving should be considered, during the design process, both as positive for soil stiffness, and potential impediment for the contractor.

1. Introduction
The National Stadium in Warsaw was built in 2011 in order to fulfill the infrastructure need, as Poland got granted the right to host the 2012 UEFA European Football Championship.

The founders of the stadium were happy to find a spacious spot near the city center, nonetheless, they needed to overcome several obstacles such as geotechnical conditions. Geological research stated that sandy soils, eligible in the matter of foundation, are settled underneath a layer of anthropogenic soils, containing rubble. AARSLEFF company came up with a solution – driven piles, that are the oldest and most commonly used method for indirect foundations. It is used so often, mostly due to relatively low price, and good piling quality control [1-5]. Availability of several methods of capacity assessment also stands in favor. In everyday practice, still the most popular seem to be methods using soil parameters[6-8] and pile’s geometry. More accurate are methods based on piling reports [9], dynamic [10,11] and static load tests [4], however, they increase the general cost and take relatively long time to be performed in accordance with theoretical standards. The impact hammer records number of blows, required for 20cm driving, that fits a simple Danish formula, to estimate the limit capacity quickly, and low cost.

In order to transfer the load to the ground, rectangular prefabricated reinforced concrete piles were driven deep enough to reach sand soils, that were at level of 5 to 20m below the terrain.
2. Pile capacity assessment methods

2.1 Piling reports

Pile driving process is strictly monitored throughout the whole worktime. The machine records pile set while blowing the hammer, however, results for single blows could be inaccurate. This is why, most often the software is set to count number of blows for 20cm displacement. The whole gathered data for full pile length is analyzed and can be later used during future realizations to estimate pile capacity in similar soil conditions.

The amount of blows for the last 20cm of driving can be easily used to assess pile limit capacity with Danish dynamic formula. For vertical piles the formula is given below.

\[ R_{FD} = \frac{\eta \cdot h \cdot G}{s + 0.5 \cdot s_0} \]  

\[ s_0 = \sqrt{\frac{2 \cdot \eta \cdot h \cdot G \cdot l_p}{A \cdot E}} \]  

\( R_{FD} \) – limit pile capacity [kN], \( s_0 \) – elastic pile shortening [m], \( s \) – length of the final pile sinking divided by the number of blows [m], \( G \) – hammer weight [kN], \( \eta \) – hammer efficiency [-], \( h \) – hammer drop height [m]

It is recommended for piles driven into non-cohesive, prevailing loose soils. The main factors are number of blows and pile length. As Rainer’s study [9] shows, the bigger amount of blows, the bigger relative error in capacity you should suspect.

2.2 Dynamic load test

Dynamic tests are performed by dropping weight (e.g. driver hammer) on a pile head to generate elastic wave [10,11] which is monitored with installed sensors. The needed equipment is handy and easy to set up. This is why the method is used so often, especially for prefabricated piles. In order to get capacity results, it is necessary to process the data. In the case of this work, AARSLEFF company used CASE and CAPWAP methods and provided the data.

CAPWAP (Case Pile Wave Analysis Program) was developed by Professor George G. Goble, Dr. Frank Rausche, Garland Likins in Cleveland, who formed Pile Dynamic, Inc., a firm devoted to deep foundations quality assurance instruments. [10] It divides the piles into a number of mass points and springs. In this way there are three times as many unknown soil parameters as pile elements. Regarding the soil parameters, first assumption is made, and motion of the pile is assumed, using the measured pile top acceleration as a boundary value. Then, pile elements movement and soil resistance is computed, both as a function of time. If the measured and computed values do not agree with each other, the assumed soil parameters should be changed. Once a proper model is finished, CAPWAP can estimate the total bearing capacity, and resistance distribution at the toe and all over the pile shaft. The general idea is to simulate a static load test using force and velocity data obtained with Pile Driving Analyzer.

CASE method models the soil resistance as a sum of dynamic and static component. Damping force is pile toe velocity (calculated using top velocity at the time of impact) multiplied by damping constant (soil dependent). While having total resistance computed, static force is obtained by subtracting damping force.
3. Danish formula, CASE and CAPWAP results.
Having piling reports provided it was possible to estimate pile capacity using Danish formula, and then compare the results. First of all, CASE and CAPWAP results were compared, and shown in the diagram below. The dotted line corresponds to a situation when results from both methods are equal.

![Figure 1. Relation between CAPWAP and CASE methods](image)

As the figure shows for most cases, the results fit the line, what suggests, that they are rather accurate. However it takes much more time to obtain them, than to use Danish formula. For most cases, the basic dynamic equation stands a basis for pile capacity investigations, and the more accurate, sophisticated methods are used for single results which are not certain in the matter of future load. As the relative error between CASE and CAPWAP capacity is within 7%, it is possible to state, that they give accurate outcomes. CASE results were taken as a representative of both methods for further analysis.
As the figure shows, Danish formula gives significantly different results. Mean value of relative error is 32%. It should be taken into account as an additional safety factor. Nonetheless, the longer the pile, the lower the difference. Exponential trend line (without dots) was computed (3):

$$y = 81.142e^{-0.081x}$$  \hspace{1cm} (3)

Next aim was to define relationship between pile capacity from Danish formula and the number of blows necessary to sink them for the last 20cm. The whole population of 68 piles was divided into 3 groups depending on their length.

| Pile length [m] | $R_{FD10}$ | $R_{FD15}$ | $R_{FD20}$ |
|----------------|------------|------------|------------|
| Number of piles | 18         | 34         | 16         |
The lines for $R_{FD10}$ and $R_{FD15}$ on figure 3 are nearly parallel, which suggests it is a close interpretation of the relationship shown. $R_{FD20}$ don’t show the same equation. It is believed, it is so because all of the piles were blown with similar number of blows (were driven in same soil conditions) and the evaluation might be inaccurate. The general tendency suggests – the longer the pile, the lower the limit resistance, what was also noted in other investigations.

4. Soil parameters numerical back analysis.

Further investigation led to numerical model in GEO5 Pile module. Geological research came up with soils parameters shown below:

| Soil symbol | Depth [m] | $y$ [kN/m$^3$] | $\phi$ [$^\circ$] | $c'$ [kPa] | $\nu$ [-] | $E_{oed}$ [MPa] | $l_D$ [-] | $l_L$ [-] |
|-------------|----------|----------------|-----------------|-------------|----------|-----------------|---------|---------|
| saSi        | 0-4.9    | 20.11          | 15.0            | 24          | 0.29     | 17.0            | -       | 0.37    |
| CSA         | 4.9-9.8  | 19.62          | 33.5            | -           | 0.25     | 90.0            | 0.6     | -       |
| MSa         | >9.8     | 20.11          | 34.5            | -           | 0.25     | 110.0           | 0.7     | -       |

Numerical model assumed several theoretical methods:
- Vertical bearing capacity – NAVFAC DM 7.2
- Settlement analysis – linear load – settlement curve (Poulos)
- Methodology EN 1997 standard

The computation was processed with GEO5 Pile module and were focused on vertical force limit capacity. All safety factors were set for 1.0 value to provide data comparable with previous methods.

As the picture below shows, the limit pile capacity computed with basic soil parameters provided by geologists give 3-4 times lower results than dynamic load tests (2700kN – 3500kN for most cases). It is so because it doesn’t take the extra compaction during piling work into account, which contributed to a significant growth of the existing coarse river sand (of high uniformity coefficient).
Computing of axial capacity NAVFAC
DM 7.2

Analysis of a single pile

The worse design load case (Force no 1)
Coefficient of critical depth $k_{dc}=1.00$

Pile shaft capacity $R_s=213.99$ kN
Pile base capacity $R_b=763.10$ kN
Total pile capacity $R_c=977.09$ kN
Vertical design load $V_d=977.00$ kN
$R_c=977.09$ kN $> 977.00$ kN $= V_d$

Figure 4. GEO5 result with parameters from geotechnical research before piling

Next step was a back analysis leading to estimation of the parameters giving more accurate results, to find out how big the impact of piling work was. Several iterations were computed, changing only the coarse sand’s parameters (shaft capacity contribution is relatively low and was neglected).

Computing of axial capacity for ULS
Design

Analysis of a single pile

The worse design load case (Force no 1)

Pile shaft capacity $R_s=409.04$ kN
Pile base capacity $R_b=3154.21$ kN
Total pile capacity $R_c=3563.25$ kN
Vertical design load $V_d=3563.00$ kN
$R_c=3563.25$ kN $> 3563.00$ kN $= V_d$

Figure 5. GEO5 result with parameters from the last step of back analysis

Table 3. Soils’ parameters from numerical back analysis

| Soil symbol | Depth [m] | $\gamma$ [kN/m$^3$] | $\phi$ [$^\circ$] | $c'$ [kPa] | $\nu$ [-] | $E_{oed}$ [MPa] | $I_D$ [-] | $I_L$ [-] |
|-------------|----------|----------------------|------------------|------------|--------|----------------|--------|--------|
| saSi        | 0.40     | 20.11                | 14.0             | 24.0       | 0.29   | 17.0          | -      | 0.37   |
| CSa         | 4.9-9.8  | 20.11                | 42.5             | -          | 0.25   | 145.0         | 1.0    | -      |
| MSa         | >9.8     | 20.11                | 34.5             | -          | 0.25   | 110.0         | 0.7    | -      |

As it is shown, a limit capacity, comparable to dynamic load test, were achieved with 42.5° and 145 MPa Young Modulus. Such high values are not spotted in natural conditions and could be even hard to achieve in laboratory tests. It is possible to state, that the piling works have contributed to 60% relative growth of Young Modulus growth and 9° higher internal friction angle, and resulted in approximately
3.5 times higher capacity. To ensure the exact increment values it would be recommended to follow the investigation with CPTU probing [13].

5. Final remarks
Following the aforementioned results we may conclude that:

- CASE and CAPWAP methods give comparable results with rather low relative error
- Danish formula can be used in practice as a first evaluation of pile capacity as it gives results in the matter of minutes
- The longer the pile, the more accurate Danish formula results
- Pile capacity basing on piling reports might be approximated with linear functions of number of hammer blows
- Driven piles can improve sandy soils’ (of high uniformity coefficient) mechanical properties by even several dozen percent what results in roughly 3 times higher limit capacity

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