

# Accuracy of pile capacity assessment on the basis of piling reports

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**Abstract.** Current assessment of foundation pile bearing capacity during driving may considerably improve operational reliability in terms of loads to be transferred. It also enables proper design and trial examinations by focusing attention on piles with atypical driving characteristics. The paper presents the method applicable to assess the bearing capacity of prefabricated driven piles and provides analysis of likelihood of this assessment by the example of numerous prefabricated piles documented by piling reports and results of static pile load tests to the extent allowing to determining the limit bearing capacity. The results attained could be the basis to determine respective safety factors in pile design based on driving resistance analysis.

## 1. Introduction

Nowadays, the construction sector grows up vigorously. Continuous population growth and higher levels of living standard force permanent development of road and railway infrastructure as well as residential and commercial buildings. Due to diminishing offer of attractive lands for development, investors locate the building projects “wherever possible”, often on lands which were earlier recognized as unfit for such purposes. Repeatedly, such lands feature very poor ground conditions where construction of even small structures, like single-family houses, call into question direct founding. In case of large facilities there is no question that the foundation must be of indirect type, e.g. pile foundations. Thanks to them, a large bearing capacity and reduced settlement could be achieved. Various piling technologies are now available on the market. Driven piles are among most popular and also the oldest solution [1]. Formerly, they were made out of wood, now the reinforced concrete is the most often material used for prefabricated piles. Main advantages of this technology include high productivity of pile operations, suitability in almost all soil conditions and high control and quality of piling work. The last advantage is extremely important for regulations and standards in force. When work is run below ground level, soil conditions are really known in the spots of ground investigations only. Conditions in other areas can be just estimated to some probability basing on those found in adjacent boreholes. The more boreholes were made the lower probability of erroneous estimations.

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Bearing in mind that the soil is a random medium, capacity of piles need to be verified on a current basis. There are many methods enabling to assess the bearing capacity listed by Fellenius [2] and recently Sobala [3]. The most popular include: static pile load test [4] with critical discussion [5], estimation based on subgrade investigation [6] and Cone Penetration Test [7, 8], dynamic pile load test and capacity estimation based on driving report (dynamic formulae) [9]. Most of these methods generate additional costs, hence testing are made to the number required by current regulations only to reduce these costs. As an example, according to the standard PN-83/B-02482, two load tests are required for the first 100 piles and one test for each next 100 piles started. The number of tests poses some risk related to improper pile execution as just about 2% of all piles are covered by tests in practice.

In practice, it is impossible to make more tests due to high cost of it and its duration. Reliability of piling can be considerably improved by current control of pile capacity by means of limit capacity estimation basing on driving logs. Limitation of this method results stems from the fact that such estimation is valid for axial capacity only, i.e. when pile direction is consistent with future load. Thanks to this method, it is possible to estimate bearing capacity of all piles without generation of additional costs, and to point out potentially dangerous spots where piles may not be of required capacity. The paper presents various methods evaluating capacity of driver prefabricated piles; then, a reliability assessment of the method based on piling recording by comparing the results with those from static pile load tests.

## **2. Methods used to assess the bearing capacity of prefabricated driven piles**

### **2.1 Static load test**

Static load test is the fundamental trial of pile bearing capacity. It creates a reference point for other methods enabling to determine the maximum limit load of pile. Static load test is most often made using the reverse beam method using neighboring piles as the anchoring piles, using kentledge, or bi-directional test [10]. Local standards detail interpretation procedures and number of static tests to be made. According to Polish standard, the maximum force during the test should amount to at least 150% of the design compressive capacity. Pile load should increase in steps; their number should be not less than 10. Transition to the next step should be made when settlement stabilization is attained. When the required force may not be achieved in static test, extrapolation methods are used. Applying these methods carries the risk of large errors in assess the bearing capacity [5].



**Fig. 1.** Static Load Test (SLT) testing appliance anchored to adjacent piles

## 2.2 Soil investigations

A very common way of estimating pile capacity is to use soil geotechnical investigations. These methods are divided into indirect and direct ones. According to the first group, pile capacity is determined on the basis of geotechnical profile knowledge including the degree of plasticity or degree of compaction. Basing on these data, determination is made for unit resistances under pile base and frictional unit resistances on pile shaft and when these variables are substituted into the formula (1), the capacity can be estimated.

$$R_{c,k} = A_b q_{b,k} + \sum_{i=1}^n A_{s,i} q_{s,k,i} \quad (1)$$

$R_{c,k}$  – characteristic pile capacity,  $A_b$  – pile base area,  $q_{b,k}$  – unit resistances under base,  $A_{s,i}$  – surface of pile shaft in the  $i$ -th layer,  $q_{s,k,i}$  – unit resistance on pile shaft in  $i$ -th layer

The second group includes methods which enable direct implementation of investigation results to algorithms and estimate the pile capacity in this way. Determination of capacity directly from field measurements ensures a large convergence with the results of static load tests. Examples of such method are procedures basing on soil investigations with CPTU probe [11]. Readout data from probe penetration measurements in situ allow to determine unit resistances under pile base and on pile shaft, which then can be used in the aforementioned formula (1). In principle, the most popular methods based on CPTU records differ each other in the range of averaging the resistances and in empirical coefficients depending on piling technology and soil conditions [12].

## 2.3 Dynamic load test

These are in situ direct tests carried out on trial piles. The pile subjects to dynamic load by a blow of hammer on the pile head [13]. The hammer weight exceeds pile capacity by at least 2% (in case of driven prefabricated piles, it may be the same hammer used to drive the pile in) An exemplary test is shown on Figure 2. During the blow, a stress wave propagates in the pile. Acceleration and deformation, which are generated during the blow, are the basis for determining the load-settlement relation and for estimating the limit capacity of the pile. The results may be post-processed by means of the simple CASE or more sophisticated CAP-WAP analysis (Case Pile Wave Analysis Program), where the model of pile and the surrounding soil enables for determining of pile shaft capacity along its length. Assessing capacity piles based on numerical analyses are rare [14-16].



**Fig. 2.** Dynamic load testing

## 2.4 Piling reports

Pile capacity assessment can be based on pile recording. During hammering process, the pile set is being measured [17]. The pile set is the displacement of pile top in soil caused by one hammer blow. For the sake of practical problem related to accurate estimation of pile head after one hammer blow, usually the measure of set is assumed as the number of blows necessary to sink the pile by 0.2 m.

The number of blows is continuously monitored and analyzed over the whole pile length. These data may be then used, among others, to assess the pile capacity on the basis of dynamic formulae. One of fundamental dynamic formulae to estimate the limit capacity is so called Danish formula. It was elaborated by Andreas Knudsen in 1955. This formula is used in Polish standard PN-83/B-02482. The current Polish standard PN-EN 1997-1 allows also using it as a dynamic formula. It is recommended for use in non-cohesive and stratified soils with prevailing loose soil. The expression provides so credible results that it is used, in some countries, as the fundamental method to determine the capacity of piles driven into loose soils. The formula (2) for the maximum pile capacity is given below.

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

(2)

where:  
 $R_{FD}$  – pile limit capacity acc. to Danish formula [kN],  $s_0$  – pile elastic shortening [m],  $s$  – set on the final segment of pile sinking (length for counted blows divided by the number of blows) [m],  $G$  – hammer weight [kN],  $\eta$  – hammer efficiency [-],  $h$  – vertical height of hammer drop [m]

3. Credibility of the method based on piling records

In order to examine the usefulness of dynamic formulae based on pile driving logs, they should be correlated with reference values, i.e. the results of static trial loads. The comparison results are provided below.

3.1 Trial description

In dynamic formulae, such as the Danish formula, the final value attained is the pile limit capacity. For the comparison the values with real data is possible, it is necessary, while making analysis, to consider those static tests only wherein the limit capacity was attained. The number of piles qualified for comparison was 29. These piles were made in 2009-2010. All prefabricates were made of class B50 concrete and their cross-section was a square of 0.4 m side length. Pile lengths were from 9 to 22 m. They were located over areas with predominating non-cohesive soils. The angle from vertical is 0° for all piles. While driving, the hammers of the weight 60 kN, 70 kN and 84 kN were used. The hammers were dropped from the heights of 0.2 to 0.8 m.

Table 1. Breakdown by pile length of samples and by hammer drop height

Pile length [m]	Number of piles	Hammer drop height[m]	Number of piles
9.0-11.9	13	0.2	1
12.0-14.9	7	0.4	4
15.0-17.9	5	0.6	9
18.0-22.0	4	0.8	15

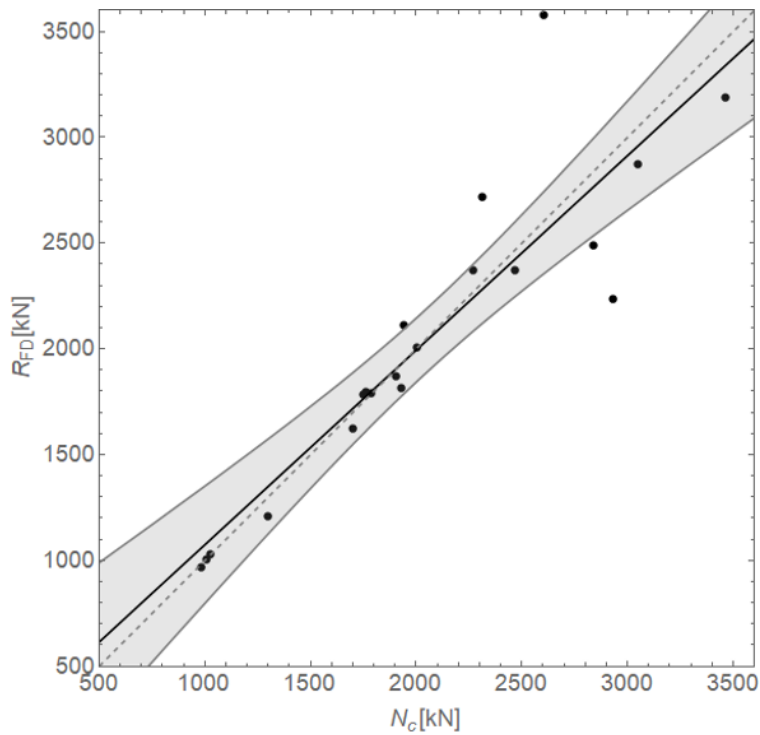
3.2 Presentation of the results

The analysis was carried out by comparing the value of limit capacity from static test load according to the result interpretation rules of the standard PN-83B/02482 and the limit capacity from the dynamic formula (Danish formula). The diagram below illustrates the relation between static test and Danish formula.

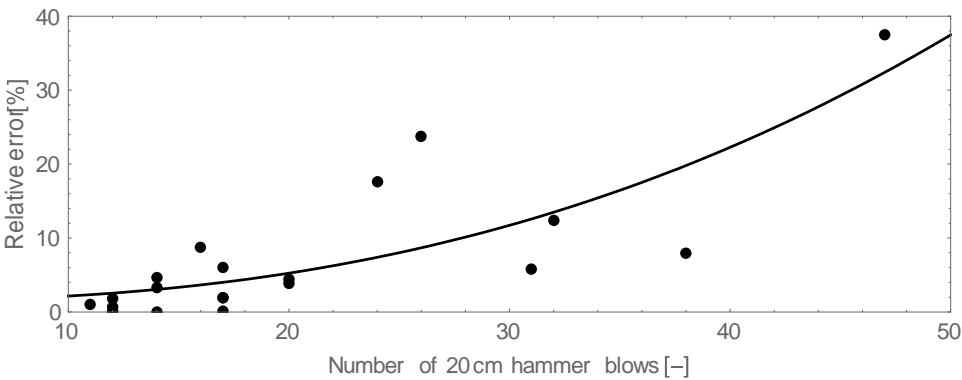
The dotted line is inclined at an angle of  $45^0$  and de notes the situations when capacity results from two different sources are equal. Black dots mean real values for particular piles. A straight line (3) is inscribed into these points:

$$R_{FD} = 0.92 \cdot N_g + 155 \tag{3}$$

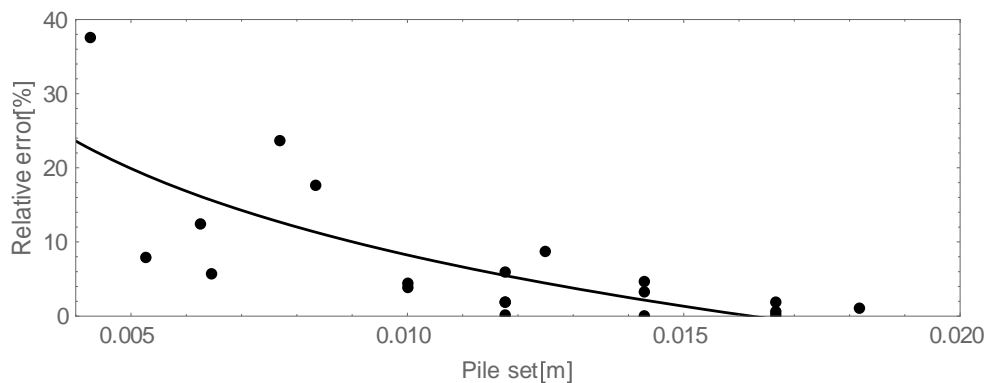
The shaded area correspond to the 95% confidence interval for forecasting the limit capacity according to dynamic formulae basing on the limit capacity valued from static test loads.



**Fig. 3.** Relationship between limit capacity from static test and that estimated from dynamic formula

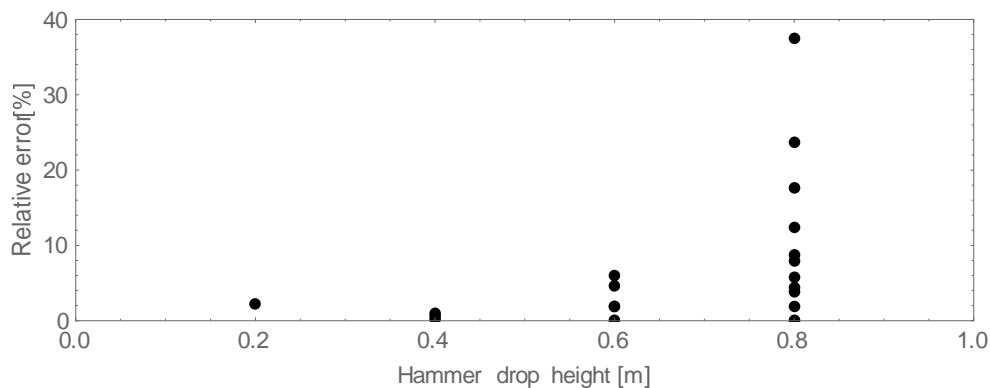


**Fig. 4.** Relation between the number of 20 cm hammer blows and relative error

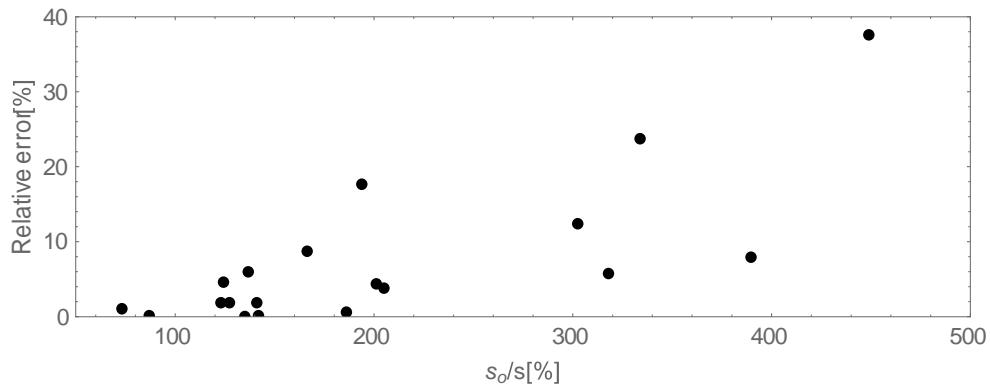


**Fig. 5.** Relation between pile set and relative error

The above diagram shows the relationships between the number of hammer blows for the last 20 cm of pile driving, the pile set and the relative error. The relative error is defined as the quotient of absolute value of the difference between the two methods and the limit capacity given by static load test expressed as a percentage. Exponential functions were inscribed into these relationships which provide the best approximation of the real values.



**Fig. 6.** Relationship between hammer drop height and relative error



**Fig. 7.** Relationship between the ratio of elastic strain and permanent set and relative error

Figure 6 present relationship between hammer drop height and relative error. On this chart it is visible that when the drop height increase, the dispersion of relative error also increase Figure 7 shows the relationship between the ratio of elastic and permanent set and relative error. As a permanent deformation is considered pile set. The elastic deformation is associated only with the elastic shortening of the pile. As we can see on the chart above, if relationship is smaller than 150%, the relative error is relatively small at an acceptable level.

### 3.3 Conclusions of displayed results

It stems from the above analysis that results of estimation of limit capacity on the basis of driving records are very similar to those from static load tests. It is pointed out by, among others, the directional coefficient of the straight line in the formula (3), which is close to one, i.e. the situation when both capacities are equal. In addition, application of linear regression model ensures in this case good matching the model as the determination coefficient equals to 0.83. While analyzing Figure 1, it can be concluded that the values are most similar to each other when the limit capacity from static tests is less than 2500 kN. It is worth noting that the estimation error definitely increases along with the higher number of hammer blow (Figure 2). The pile set directly stems from the number of blows, which also have an effect on the relation between relative error and pile set. The lower is pile set, the estimation is of higher uncertainty. Both these relationships are described by exponential function. This situation may result from difficulties with measurements during pile driving. Precise determination of small sets causes high uncertainty and dispersion of capacity results. Additionally, a large number of blows per measurement length, the ratio of pile elastic strains to permanent sets rises decidedly, which can also be a source of error increase for lower pile sets. The relationship between these strains and the error is as shown in Figure 5. The pile is not enough overloaded, which also raises the risk of improper measurement. Hence, in case of dynamic tests, an appropriate pile overload is demanded to eliminate these effects. Figure 4 illustrates the relation between drop height and relative error. In general, pile driving procedure is started from the drop height as small as possible. If operator finds that the driving in process is too slow (sets are too low), he increases the hammer drop heights causing rise of dynamic forces applied to the pile, which in turn leads to accelerated pile sinking. These were the causes why errors, which arise in case of lower drop heights, have less dispersion – operator has always a leeway and may raise the sets by increasing the heights.

## 4. Summary and final remarks

Reliability is the one of most important features which should characteristic of contemporary construction, including also pile foundations. The lower probability of failure, the building is safer. Comprehensive approach to the scope of testing the pile bearing capacity should include both static and dynamic tests. While the trial test could not be eliminated due to respective regulations and because they constitute references for remaining tests, the additional dynamic testing may be limited in case of prefabricated driven piles. They can be replaced with limit capacity estimation based on driving records. For such approach, static test load should be considered as the reference point for the method calibration as shown in the computational example above. Owing to this procedure, a pile can subject to capacity estimation which reduced a risk of improper execution of piling works. The formula (3), describing the relationship between limit capacity from static tests and that from dynamic formulae, refers to specific facility and particular soil conditions.

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