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THE ANALYSIS OF ESTIMATION THE PILE BEARING CAPACITY ON THE CPTU

1. Introduction

The development of new CPTU subsoil testing techniques has not only contributed to the precise recognition of geotechnical parameters, but also to the creation of methods for estimating piles bearing capacity. The characteristic values of soil resistance under an impacted cone (q_c) and soil friction resistance on the shaft of the probe's sleeve (f_s) are directly applied to calculation algorithms. Unit resistance to the base of the pile and the pile's shaft are successively determined. This approach helps accelerate the process of pile design and it allows for the omission of interpretation of the CPTU tests.

Several methods for estimating compressive pile bearing capacity on the basis of static probe CPTU findings are presented in this paper. These methods have been divided into four groups based on their usefulness in the design process for particular pile construction techniques. All of the calculations refer to the universal method of Eurocode 7.

The methods that fulfill the estimation of characteristic pile bearing capacity on the basis of subsoil CPTU tests rely on the same assumption and use the same formula (1):

$$R_{ck} = R_{b,k} + R_{s,k} = A_b \cdot q_{b,k} + \sum_{i=1}^{n} A_s \cdot q_{s,k,j} \tag{1}$$

The characteristic compressive resistance of the ground against a pile (1) is the sum of the characteristic values of the base resistance and of shaft resistance with respect to the base area under the pile (A_b) and the area of the shaft (A_b). Their values are established on the basis of the characteristic values of the base resistance pressure ($q_{b,k}$) in accordance with (2) and the characteristic values of shaft friction in the subsequent strata ($q_{s,k,j}$) in accordance with (3).

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$$q_{b,k} = \psi_1 \cdot \bar{q}_c \tag{2}$$

$$q_{s,k,j} = \frac{\bar{q}_{sci}}{\psi_2} \qquad q_{s,k,j} = \frac{\bar{f}_{si}}{\psi_3} \tag{3}$$

Base and shaft resistance factors ψ_1, ψ_2, ψ_3 are chosen according to the calculation method used for determining the pile bearing capacity. Their values depend on the technology of the pile manufacture, soil type and condition and also on the method of averaging the values $\bar{q}_c$, $\bar{q}_{csi}$, $\bar{f}_{si}$.

The average unitary soil resistance under the probe's cone ($\bar{q}_c$) in the pile's base area is determined in accordance with (4), however the average unitary soil resistance under the probe's cone ($\bar{q}_{csi}$) is based on qc measurement from equation (5), and the average unitary soil resistance to the probe's shaft friction ($\bar{f}_{si}$) is based on fs measurement according to (6).

$$\bar{q}_c = \frac{1}{l_1 + l_2} \int_{h-l_1}^{h+l_2} q_c(h)dh \tag{4}$$

$$\bar{q}_{csi} = \frac{1}{\Delta h} \int_{h_{i-1}}^{h_i} q_c(h)dh \tag{5}$$

$$\bar{f}_{si} = \frac{1}{\Delta h} \int_{h_{i-1}}^{h_i} f_s(h)dh \tag{6}$$

Notation of formula (4, 5, 6) are consistent with Figure 1.

Analytical calculations were performed on the actual soil conditions on site at the planned foundation of a structure. Figure 2 shows the measurement of cone resistance (q_c), sleeve friction (f_s), penetration pore pressure (u_2) and the designated geological profile according to standard PN-B-04 452 classification [3] which were recorded while testing with a static probe.

Hard-plastic cohesive soil in the form of clays and silty clays occured to the depth of about 5 m. Loose condensed hydrated and highly condensed soil in the form of medium sand and gravely sand performered below.

2. Methods of estimation of pile bearing capacity

A division of methods for an estimation of the pile capacity has been created by dividing piles into four main groups characterized by different manufacture technology, and

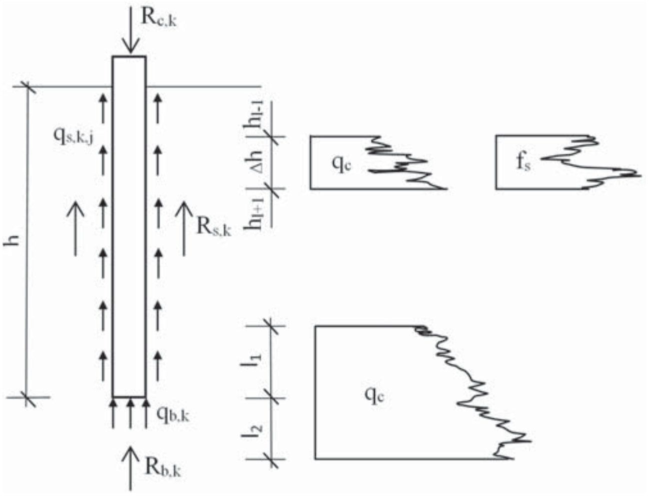

Fig. 1. The notation used for the calculation of the bearing capacity of a single pile is on the basis of the CPTU tests

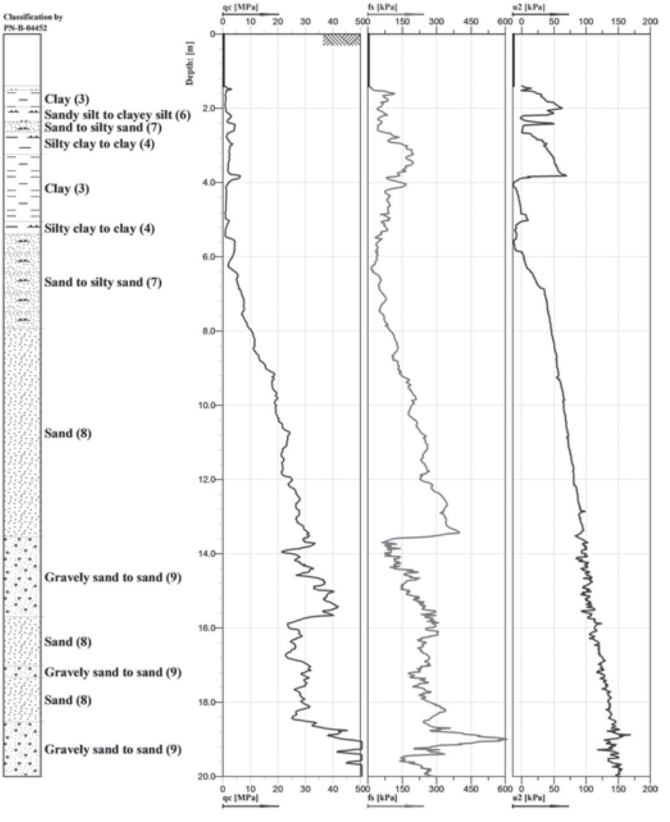

Fig. 2. Profile of static CPTU probing with interpretation

consequently with their different ways of working in the soil. This division is essential in order to choose the appropriate calculation criteria imposed by specific design methods (Table 1). This procedure allows one to choose the appropriate load factors ψ_1, ψ_2, ψ_3 depending on the type of technology.

TABLE 1
Division of piles according to manufacturing technology and methods of calculating pile bearing capacity

<table>
<tr><th></th><th>Division of piles according to manufacturing technology</th><th>Pile bearing capacity calculation methods</th></tr>
<tr><td rowspan="3">Displacement piles</td><td>Driven or vibrated piles:
— Prefabricated reinforced concrete plies,
— Steel piles</td><td>Eurokod 7 Method
Philipponant, Kłos Method
Wiłun Method
Gianeselle, Bustamante Method
Energopol Method</td></tr>
<tr><td>Piles made in soil:
— Vibro-Fundex, Vibrex, Fundex Piles,
— Frank Piles</td><td>Eurokod 7 Method
Philipponant, Kłos Method
Wiłun Method
Gianeselle, Bustamante Method
Energopol Method</td></tr>
<tr><td>Piles made without shield pipe:
— Omega I CG Omega Piles,
— SDP Bauer BG Piles,
— de Wall Piles,
— Tubex Piles</td><td rowspan="2">Eurokod 7 Method
Philipponant, Kłos Method
Wiłun Method
Gianeselle, Bustamante Method
Energopol Method</td></tr>
<tr><td>Patial displacement piles</td><td>— CFA Piles:
• Starsol,
• PCS Lambda,
• Soilex</td></tr>
<tr><td>Drilled piles</td><td>Drilled large diameter piles:
— Piles drilled without shield pipe,
— Piles drilled in concrete suspension,
— Piles drilled in a shield pipe vibrated-in,
— Piles drilled in a shield pipe,
— Piles drilled with an injection under the base and on the shaft</td><td>Eurokod 7 Method
Adamczyk Method
Energopol Method
Gwizdała Method
Philipponant, Kłos Method
Wiłun Method
Gianeselle, Bustamante Method</td></tr>
</table>

2.1. Adamczyk Method [1, 6]

The Adamczyk method is effective in designing large-diameter piles constructed mainly in non-cohesive soils. Since they are large-diameter piles constructed in a shield pipe with its subsequent extraction, or more seldom, without a shield pipe, looseness of the soil at the shaft surface results. As a result, the load transfer of this kind of pile by the shaft is not taken into account when determining the bearing capacity of the element and it is assumed that the load is carried entirely by the base of the foundation. This method is rarely selected due to its limited use, but it gives a relatively high value in terms of the load capacity of the foundation, in comparison to alternative methods.

2.2. Gwizdała Method [1]

This method, like the previous one, is recommended for use with large diameter elements. A numerical analysis of the bearing capacity can only be carried out when the pile is based on low-density soil like sand or gravel. In contrast to the Adamczyk method, it is recommended that not only the bearing capacity carried by the base of the foundation be considered, but also the bearing capacity of the pile shaft.

2.3. Energopol Method [1, 6]

This method assumes the presence of two characteristic groups of piles, for which numerical analysis is carried out using different selected safety factors ψ_1 and ψ_2. The first group comprises of piles with a diameter or diagonal cross-section of up to 0,60 m. The second group includes large diameter piles with diameters in the range 0,60–1,20 m. This method does not specify the piles' manufacture technology and allows for carrying out calculations on soils such as sand and clay. However, there are no contraindications to using this method with gravel and gravel sand, and in the case of mixed soil the values of both factors can be interpolated.

2.4. Gianeselle, Bustamante Method [1, 6]

This method has a wide range of possibilities. The factors are chosen individually depending on the soil and pile manufacturing technology. The average resistance of the cone static probe is determined in three stages.

1) The preliminary correction of q_c obtained from CPTU tests, which means that the curve $q_c(z)$ (where z — is the depth of the measurement), should be close to the minimum values of q_c.
2) The determination of the average value of q_c on the basis of the adjusted values of q_c in the segment (z – 1,5·D; z + 1,5·D) (where D is the pile diameter).
3) The determination of the average cone resistance under the CPTU probe in the area of the pile's base.

It is one of the safest methods of design, because it is characterized by suitably large parameters of ψ_1 and ψ_2, and imposes the maximum values allowable for unitary shaft resistance, in the calculation. Higher values are rejected.

2.5. Wiłun Method [6]

The Wiłun method for estimating single pile bearing capacity on the basis of an *in-situ* probe CPT can be used for all types of piles and soil. In this case, great precision is given to determining the factors of capacity, which makes it very time consuming. To determine the factors, a number of computational models and charts are used.

2.6. Philipponant, Kłos Method [2]

This method requires that before calculating the bearing capacity, preliminary calculation must be performed according to particular formulas. Firstly, all the values that are significantly higher than from the average course of the graph q_c must be eliminated from the graph q_c, and the qualification of these jumps depends exclusively on the engineer's interpretation. It is very possible that this procedure aims to eliminate the local inclusion of insignificant influences on the pile's bearing capacity. This amendment eliminates local jumps of the q_c plot and causes the estimated value of the bearing capacity have a higher safety stock. ψ_1 and ψ_2 factors are selected from the relevant tables depending on soil type and the pile manufacture technology.

2.7. Eurokod 7 Method [4]

This is a method described in detail according to the new European standards, (Eurocode 7). These standards currently also apply in Poland and we are obliged to follow them. Certainly we can say that this method is the most detailed; it requires thorough analysis of resistance charts q_c and f_s and their partial transformations. All the other design methods mentioned above are based on an algorithm presented in Eurocode 7, however, they are its simplification and approximation. They don't investigate as thoroughly into the analysis of the strength of the pile foundation and they do not perform as many transformations and calculations. The biggest advantage of this method is that we work according to reliable standard recommendations.

3. The results of the estimation of the pressed pile bearing capacity

Calculations were carried out in two different ways for all groups of piles with different manufacture technologies for the actual geotechnical conditions (Fig. 2).

In the first method, different diameters and lengths for the pile were assumed and a single pile bearing capacity was determined. The diameter was increased adapting to changing technology. In the second method, a certain capacity for the pile was assumed, and the length of the pile with which it was achieved was determined.

3.1. Driven or vibrated-in piles

Five methods were used for estimating the bearing capacity of a pile with a diameter of 02 m and 0.4 m. Four of them were adapted to the manufacture technology of driven and vibrated-in piles, and one universal. The capacities were defined with the assumption of three defined pile foundation depths: 7.00 m, 11.00 m and 14.00 m (Fig. 3). For the depth of 7 m very similar results were obtained regardless of the design method. The deeper the depth of the foundation was assumed to be, the greater the dispersion of capacity values obtained.

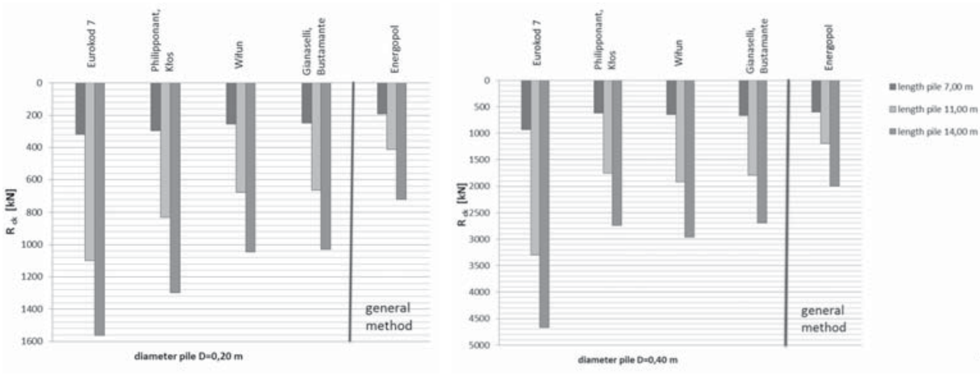

Fig. 3. Estimation of driven and vibrated-in pile's bearing capacity

Assuming a pile bearing capacity of 1000 kN, a pile length needed to provide this capacity was calculated (Fig. 4). For piles with a diameter of 0.2 m a large spread for the pile length was obtained. The solution for piles with a diameter of 0.4 m is much more stable.

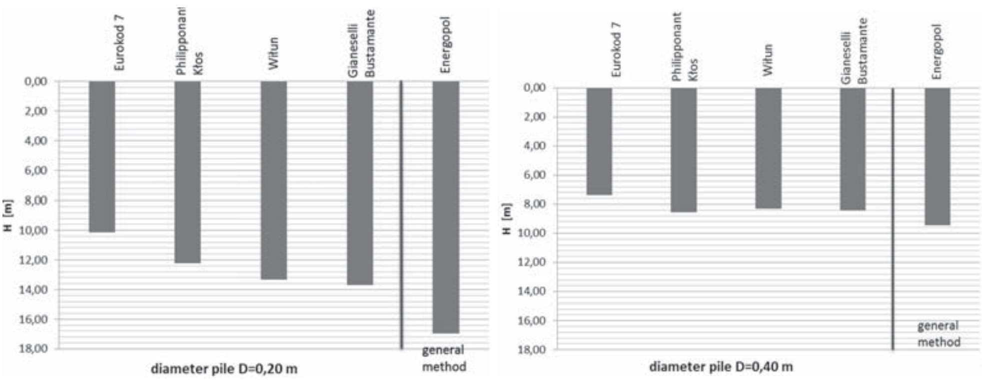

Fig. 4. Estimation of driven or vibrated-in pile length

The analysis showed that the Energopol method gave the lowest estimation in both, determining the capacity and also determining the length of a pile at a constant capacity. The greatest bearing capacity, which is the shortest length of the pile to obtain a specified bearing capacity comes from the standard Eurocode 7 method.

3.2. Piles constructed in soil with the removal of a shield pip

Five methods were used for estimating the bearing capacity of a pile with a diameter of 0,4 m, while for the pile with a diameter of 0,6 m six methods were used. Four were adapted to the manufacture technology of piles constructed in soil with the removal of a shield pipe. The capacities were defined on the assumption of three defined pile foundation depths: 7.00 m, 11.00 m and 14.00 m (Fig.5). For piles 7 m the greatest bearing capacity was determined by the Wiłun method, and the smallest by the Gianeselle, Bustamante method. For the remaining lengths, the highest values of capacity were obtained using the Eurocode 7 method, and the lowest with the general Energopol method, regardless of the pile diameter.

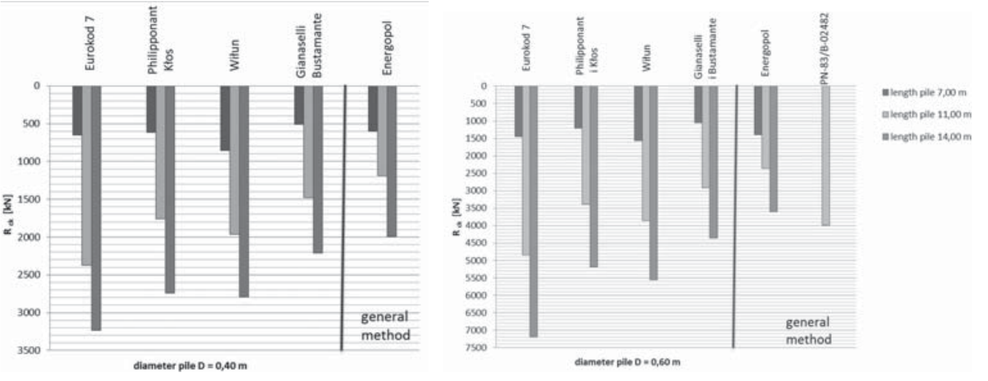

Fig. 5. The estimation of bearing capacity of piles constructed
in soil with the removal of a shield pipe

For a pile diameter of 0.6 m and length of 11 m a pile bearing capacity was additionally estimated with the classical method of withdrawn standards PN-83/B02482. This value is comparable to that obtained with the Wiłun method, and it constitutes only 55% of the capacity obtained using standardized Eurocode 7 method. Assuming a pile bearing capacity of 2000 kN the wide spread necessary to render a pile's length was obtained with a diameter of 0.4 m, while for piles with a diameter of 0.6 m similar lengths were obtained (Fig. 6).

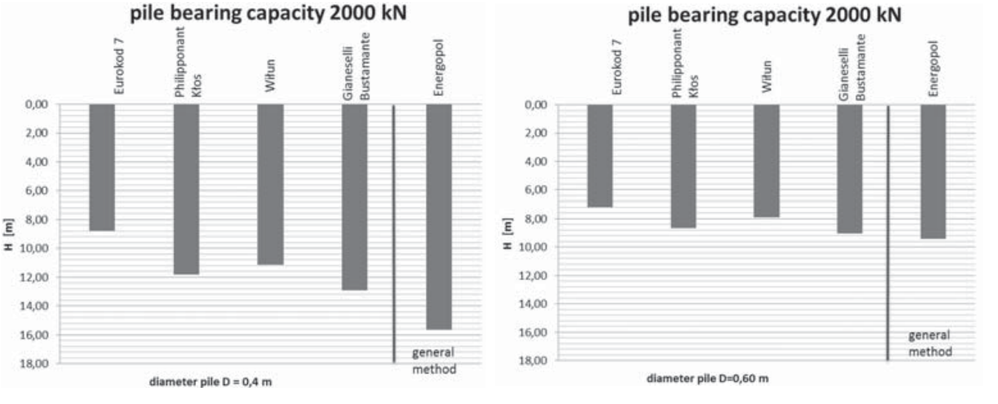

Fig. 6. The estimation of the length of piles constructed in soil with the removal of a shield pipe

3.3. Piles constructed in soil without a shield pipe

Five methods were used for estimating the bearing capacity of piles with a diameter of 0.6 and 0.8 m. Four methods are adapted to the manufacture the technology of piles constructed in soil without a shield pipe. The capacities were defined on the assumption of three defined pile foundation depths: 7.00 m, 11.00 m and 14.00 m (Fig.7). For piles of 7 m the largest bearing capacity was determined using the Wiłun method, and the smallest with the Energopol method. For the remaining lengths and the diameter of 0.6 m, the highest values for bearing capacity were obtained by the Wiłun method, and the lowest with the general Energopol method. Different solutions were observed for piles with a diameter of 0.8 m, where the highest results came with the Eurocode 7 method, and the lowest ones from the Gianeselle, Bustamante method.

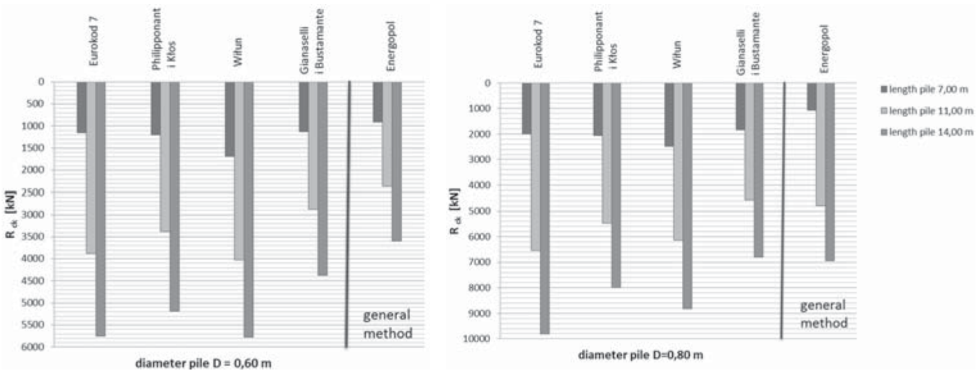

Fig. 7. The estimation of bearing capacity of piles constructed in soil without a shield pipe

Assuming the pile bearing capacity of 3000 kN, the spread of 45% necessary to calculate a pile's length with a diameter of 0.8 m was obtained, while for piles with a diameter of 0.6 m, lengths differ by 26%, in regard to the shortest of the piles (Fig. 8).

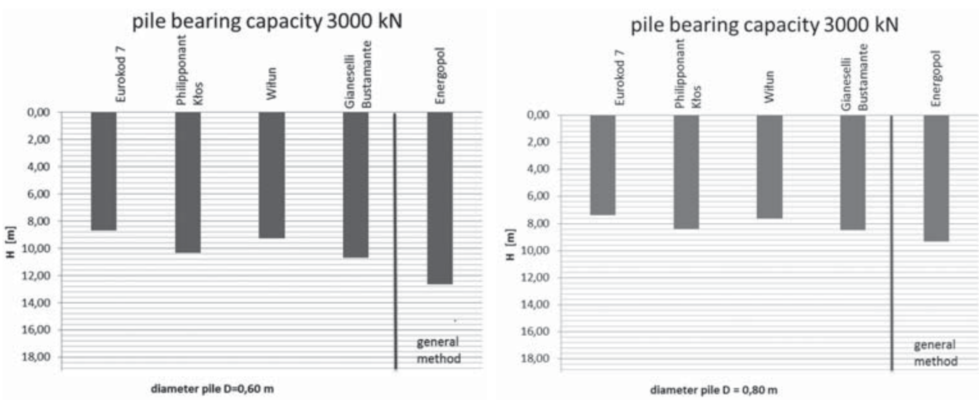

Fig. 8. The estimation of the length of piles constructed in soil without a shield pipe

The analysis showed that once again the lowest estimation came from the general Energopol method in determining a pile's capacity and in determining the length of the pile at a constant capacity.

3.4. Drilled large diameter piles

Seven methods were used for estimating the bearing capacity of piles with a diameter of 1.0 and 1.2 m. The capacities were defined with the assumption of three defined pile foundation depths: 7.00 m, 11.00 m and 14.00 m (Fig. 9). For piles of 7 m, the highest bearing capacity was determined with the Wilun', Philipponante and Klos methods, and the smallest with the Gwizdała method. For the remaining lengths, the highest values of capacity were obtained using the Eurocode 7 method, and the lowest with the Gwizdała method, regardless of the pile diameter.

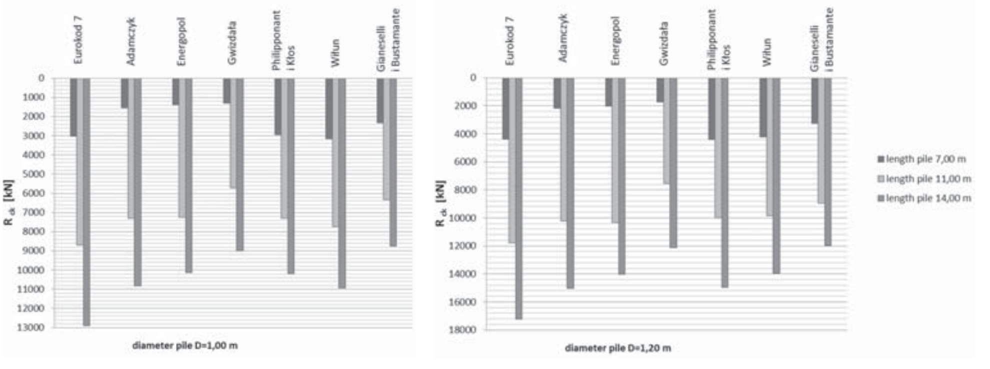

Fig. 9. The estimation of the bearing capacity of large diameter piles

Assuming a pile bearing capacity of 4000 kN, a spread of 22% is necessary to calculate a pile's length with a diameter of 1.0 m and was obtained, while for the piles with a diameter of 1.2 m, lengths differ by 30%, in regard to the shortest of the piles (Fig. 10).

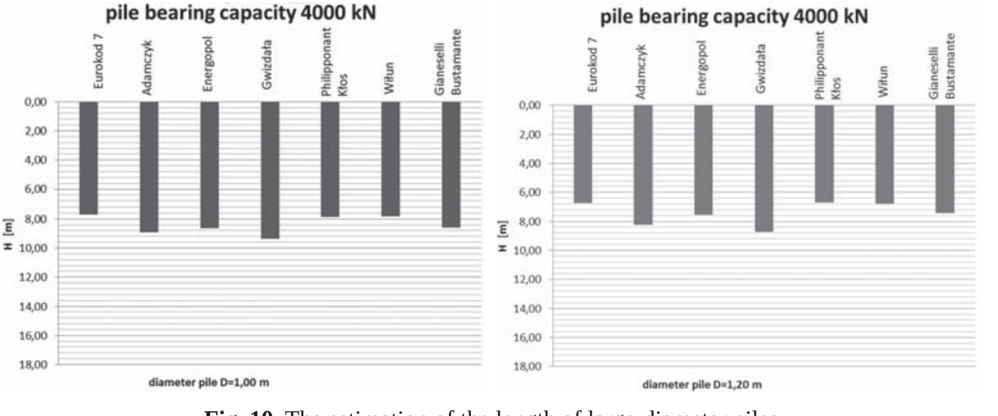

Fig. 10. The estimation of the length of large-diameter piles

4. Summary

The differences in the results of the methods presented are primarily a consequence of the diverse manner of including the values for qc and fs recorded during static probe tests in the calculations. The value of the capacity factors (ψ_1, ψ_2, ψ_3), which depend on the type and condition of the soil and the technology used for the pile manufacture are also highly influential. These values are imposed by each method and a specific value or range is indicated. This leaves the designer with the opportunity of clarifying their values by using graphs or specific functions. The value of these factors determines the precision of the design method, depending on whether it includes, in detail, the type of soil and the diversity of pile manufacture technologies. This affects the safety of the element being designed.

The most important factors contributing directly to the estimation of the value of a bearing capacity are: the type of soil and its condition; diameter, depression and technology of the pile manufacture. It is on this basis, depending on the design method factors, that ψ_1, ψ_2 and ψ_3 are determined. An equally important factor is the determination of the averaging range for calculating the values of q_c and f_s, and the length l_1 and l_2, which are multiples of the pile diameter.

Among all of the design methods used to determine the pile bearing capacity and of all the pile manufacture technologies used, the highest values of bearing capacity at the assumed length of a pile in loose soil was gained using the Eurocode 7 method. The remaining methods are based on the former. It is the most complicated and complex in terms of bearing capacity estimation methods. The remaining methods, by comparison, contain some simplifications which are designed to simplify and streamline the entire design process. However, such procedures also lead to a reduction in the accuracy of the results obtained, and consequently higher factors of capacity are applied. Therefore the standard method gives greater strength than the others in the majority of the instances included in this work.

The Energopol method allows for an approximate estimation of bearing capacity but of all the methods mentioned in this article, gives the smallest values. This is mainly due to the lack of classification in this method and for any specific manufacture technology, which also has an impact on increasing the factors for ψ_1 and ψ_2, which finally gives greater headroom for the estimated values.

The best (and recommended by an amendment to the Eurocode 7) method of pile bearing capacity design is load tests, from which a computational model factor is determined. Before carrying out probationary load tests, a designer should always decide on the type of piles and the piling technology to be used. Piles are designed, constructed and finally subjected to probationary load tests. Many factors affect this decision, among others, geotechnical, economic and technological conditions as well as the technical capabilities of building companies. The extensive analysis presented can provide information with a wide range of bearing capacity estimates using various methods. Designers can obtain information in order that the analytical design of pile bearing capacity can be worked out on the basis of CPTU tests and is worth carrying out using a number methods.

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