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BEARING CAPACITY OF PILE FOUNDATIONS BASED ON CPT RESULTS IN ACCORDANCE TO POLISH STANDARDS AND EUROCODE 7

1. Introduction

The results of the cone penetration test (CPT) are widely applicable in calculations of bearing capacity of foundation piles [1]. During the test two basic parameters were measured: cone tip resistance q_c and shaft friction f_s.

The results may be used indirectly — in the first stage for the soil profile recognition (determination of the soil names), then for the determination of soil density or consistency parameters I_D and I_L and in particular soil strata. This approach may be applied to the pile design in accordance with Polish Standard PN-83/B-02482 [4] as soil type and the density/consistency parameter value are in this case the basis for the determination of soil unit resistances for base and shaft of the pile.

On the other hand, the possibility of the direct use of the CPT results for thedetermination of compressive resistance of an axially loaded single pile is described in Part 2 of the Eurocode 7 [7], concerning ground investigation and testing procedures. Examples of calculating methods are presented in Annexes D.6 and D.7 of this standard. For those methods a precise recognition of soil type is not necessary.

An element which is common for both approaches is the use of the static equation for capacity of the compressed pile, in which the total resistance is calculated as a sum of pile base resistance and pile shaft resistance:

$$R_c = R_b + R_s \tag{1}$$

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with:

$$R_b = q_b \cdot A_b \tag{2}$$

$$R_s = \sum_{i=1}^{n} q_{s,i} \cdot A_{s,i} \tag{3}$$

where A_b is the area of the pile base, while $A_{s,i}$ is the pile shaft area in the soil stratum i (in case of direct approach of Eurocode 7 stratum thickness may be equal to test precision, i.e. 1 cm). Important differences between both approaches consist mainly in the methods of determination of soil unit resistances for the pile base q_b and for the pile shaft q_s.

The calculated pile capacities are additionally corrected by model factors and/or correlation factors (depending on the method) and partial factors (depending on the design approach).

2. Design in accordance with Polish Standards

The results of the cone penetration test in the procedure of Polish Standards can be used for the isolation of soil zones in which measured parameters have similar values. This leads to relatively precise soil classification (determination of soil name) and separation of the geotechnical strata. For this purpose a modified Robertson's chart [2] is used, which has been adapted for Polish soil names in the PN-B-04452:2002 standard [5] (Fig. 1).

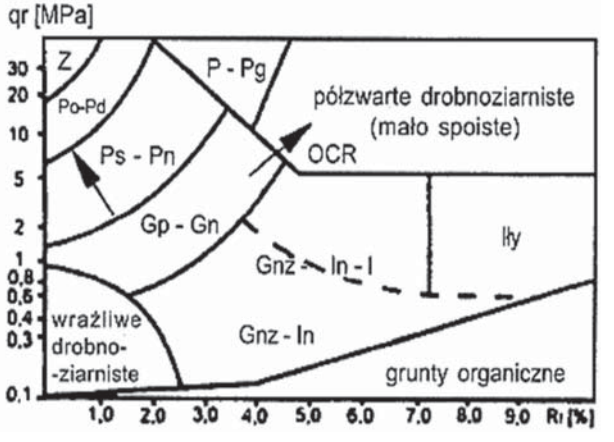

Fig. 1. An adaptation of Robertson's chart for Polish soils [5]

It needs to be emphasized, that the proper recognition of the subsoil for design purposes can never omit boreholes or at least the macroscopic description of sampled material.

After soil classification it is possible to calculate the parameters of the density and consistency of soils in a particular strata. Polish Standard [5] presents a correlative dependence between density index I_D (also referred as relative density D_r) of non-cohesive soils and CPT tip resistance q_c (Fig. 2a). The logarithmic relation is:

$$I_D = 0,709 \cdot \log(q_c) - 0,165 \quad (4)$$

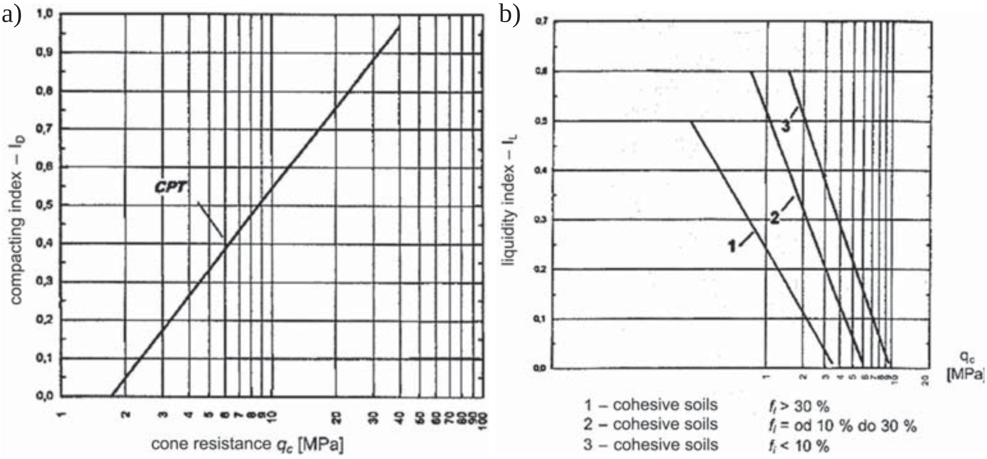

Fig. 2. Correlative dependences of soil parameters on cone tip resistance (q_c) a) density index (I_D) for fine, medium and coarse sands, b) liquidity index (I_L) for cohesive soils. 1 — $f_i > 30\%$, 2 — $10\% < f_i < 30\%$, 3 — $f_i < 10\%$, where f_i is clay fraction percentage [5]

For cohesive soils three different correlations between soil liquidity index I_L and tip resistance q_c are defined (Fig. 2b). Soil clay fraction percentage f_i needs to be determined to choose a proper logarithmic function:

$$I_L = 0,242 - 0,427 \cdot \log(q_c) \quad \text{for } f_i > 30\% \quad (5)$$

$$I_L = 0,518 - 0,653 \cdot \log(q_c) \quad \text{for } 10\% < f_i < 30\% \quad (6)$$

$$I_L = 0,729 - 0,736 \cdot \log(q_c) \quad \text{for } f_i < 10\% \quad (7)$$

Polish Standard [5] does not specify if any or which method should be used for averaging the results of CPT measurements in a single soil stratum.

Information on the soil name and the value of a corresponding density or consistency parameter is a basis for determination of soil ultimate unit resistances at the base $q = q_b$ and on the shaft of the pile $t = q_s$ in the Polish Standard for pile design PN-83/B-02482 [4].

Limit values of q for different soils are listed in the table 1 of the standard, while the design value $q^{(r)}$ additionally depends on the designed depth of the foundation base, its diameter and possible occurrence of non-bearing strata (called ‚exceptional soil conditions'). In this standard the negative influence of strata with lower values of q resistance (deposited above or below the level of pile base) on the pile base bearing capacity is not considered within the calculation procedure. The avoidance of this influence is ensured by minimum pile penetration in the bearing stratum (values in range of 1.0–2.0 m) and minimum distance between the pile base and the roof of underlying weaker stratum (range of 2.5–5.0 D_p).

Limit values of soil unit resistance on a pile shaft t are listed in table 2 of the standard. The design value $t^{(r)}$ is not dependant on pile diameter, but on the depth of considered soil stratum. The influence of the non-bearing strata is also taken into consideration in this case — in some exceptional situations the value of t may be negative.

A selection of proper values of q and t may be complicated in situations where mixtures of different soils were qualified as a single geotechnical stratum — this makes a selection of a specific rows in tables 1 and 2 impossible.

The equation for the calculation of design bearing capacity of a single compressed pile in the Polish Standard [4] is defined as:

$$N_t = N_p + N_s = S_p \cdot q^{(r)} \cdot A_p + \sum_{i=1}^{n} S_{s,i} \cdot t_i^{(r)} \cdot A_{s,i} \tag{8}$$

where S_p, S_s are coefficients depending on the pile technology listed in Table 4. The table contains values for several pile types which were commonly used in Poland in 1970’s and 80’s, but it has not been updated since 1983, so there are no values for some newer pile technologies, i.e. continuous flight auger piles (CFA).

3. Design in accordance with Eurocode 7

Eurocode 7 standard [6], in contrary to Polish Standard [4], doesn’t impose one specific procedure for pile design. Four different possible design approaches were introduced, which are based on:

a) the results of static load tests,
b) empirical or analytical calculation methods,
c) the results of dynamic load tests,
d) the observed performance of a comparable pile foundation,

It should be noted, that the validity of the application of these approaches stated in b), c) and d) needs to be demonstrated by static load tests in comparable situations. In this context the design method described in Polish Standards can be classified as an approach b) and (with some minor modifications in terms of partial factors) may be still applied in accordance with Eurocode 7.

Part 2 of Eurocode 7 [7], concerning ground investigation and testing procedures, presents two examples of methods based on the direct implementation of the results of CPT for the calculation of soil unit resistances for the pile base and shaft in case of single pile in compression. The application of these methods to pile design may be carried out in accordance with the calculation procedure for the assessment of the piles ultimate compressive resistance from ground test results stated in chapter 7.6.2.3.

The characteristic values for pile base and shaft resistances may be obtained by calculating:

$$R_{b,k} = A_b \cdot q_{b,k} \tag{9}$$

$$R_{s,k} = \sum_{i=1}^{n} A_{s,i} \cdot q_{s,i,k} \tag{10}$$

Unit characteristic values of base resistance $q_{b,k}$ and shaft friction in various strata $q_{s,i,k}$ may be received from correlations with cone tip resistance q_c listed in Tables D.3 and D.4 in Annex D.6 of EC7-2. The applicability of these correlations is however restricted to coarse-grained (non-cohesive) soils, which considerably narrows the range of possibilities of their practical use.

The values of unit resistances listed in the tables do not depend on any additional factors (i.e. geometry of a pile or installation method), which is probably the reason for the significant reduction of those values in comparison to measured CPT resistances.

The second example of a method to determine the compressive resistance of a single pile, described in Annex D.7, is far more complex. It takes into consideration a number of factors influencing the unit base resistance:

— type (class) of the pile and installation method,
— shape of the pile cross-section,
— geometry of the pile base.

The basis for the determination of maximum unit base resistance $p_{\mathrm{max,base}}$, is cone tip resistance q_c vs. depth measured by CPT. Friction sleeve resistance f_s is not used in this method. An influence of soil strata deposited both above and below the level of pile base is also taken into account. The value of base resistance is derived from equation:

$$p_{\mathrm{max,base}} = 0,5 \cdot \alpha_p \cdot \beta \cdot s \left\{ \frac{q_{c,I,mean} + q_{c,II,mean}}{2} + q_{c,III,mean} \right\} \tag{11}$$

where α_p, β and s are the coefficients of the influences listed above, while $q_{c,I,mean}$, $q_{c,II,mean}$ and $q_{c,III,mean}$ are mean q_c values of adequate ranges explained on the figure 3.

The zone of soil deposits which influences the calculated value of unit base resistance ranges from $8D_{eq}$ above the pile base level (D_{eq} is the equivalent diameter of the pile base) to a critical depth of d_{crit} below this level. The critical depth d_{crit} is found in the range of $0,7D_{eq}$ to $4D_{eq}$ and is chosen in such way, that the calculated pmax;base resistance is minimum. The highest allowable value of $p_{\mathrm{max,base}}$ for this method is 15 MPa.

The described procedure of determining unit base resistance refers to the pile class factor α_p which is given only for sands and gravely sands (values in the range of 0,6–1,0 listed in Table D.5). The possible values of this factor for other soils may be found in literature, i.e. for screw piles in overconsolidated clays the value proposed by Maertens and Huybrechts [3] is 0,8.

Maximum unit resistance along the pile shaft is derived directly from the measured values of q_c:

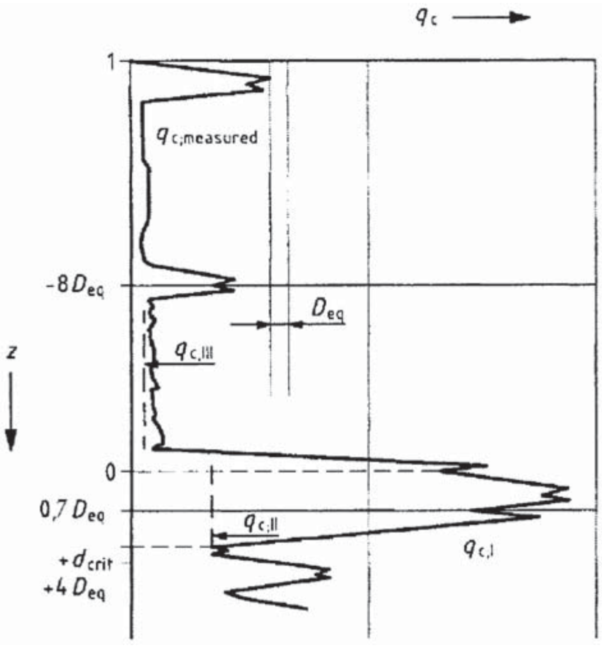

Fig. 3. Explanation of method for determination of $q_{c,I,mean}$, $q_{c,II,mean}$ and $q_{c,III,mean}$ values [7]

$$p_{\max,shaft,z} = \alpha_s \cdot q_{c,z,a} \tag{12}$$

where α_s is the factor depending on type (class) of the pile and type of the soil at the depth z. Values of this factor are listed for sands and gravely sands (in Table D.5) as well as cohesive soils: silts, clays and peats (Table D.6). The cut-off values of q_c at depth z ($q_{c,z,a}$) are reduced to 12 or 15 MPa (depending on thickness of the considered soil stratum).

4. Design example

In this example the results of one of CPT tests performed by the authors for the means of geotechnical documentation were used. The tests took place in an area called "Białe Morza" ("White Seas") in the southern part of Kraków. The area includes post-production calcareous deposits of the former Solvay Soda Works.

In order to compare the calculation procedures of both standards a reference pile has been adopted, for which the values of bearing capacity was calculated on the base of CPT results, using the approaches described above. A CFA pile of 800 mm in diameter and a length of 21.2 m, for which the verification of the capacity in static load test was programmed, and this was used for the calculation. The results of the CPT located near to the designed pile are shown in Figure 4.

A stratum of calcareous deposits with a soft consistency (down to 17.5 m below surface) was considered as non-bearing made ground in the calculations. The base of the analyzed pile was designed at a depth of about 26 m, in a stratum of medium-dense sands.

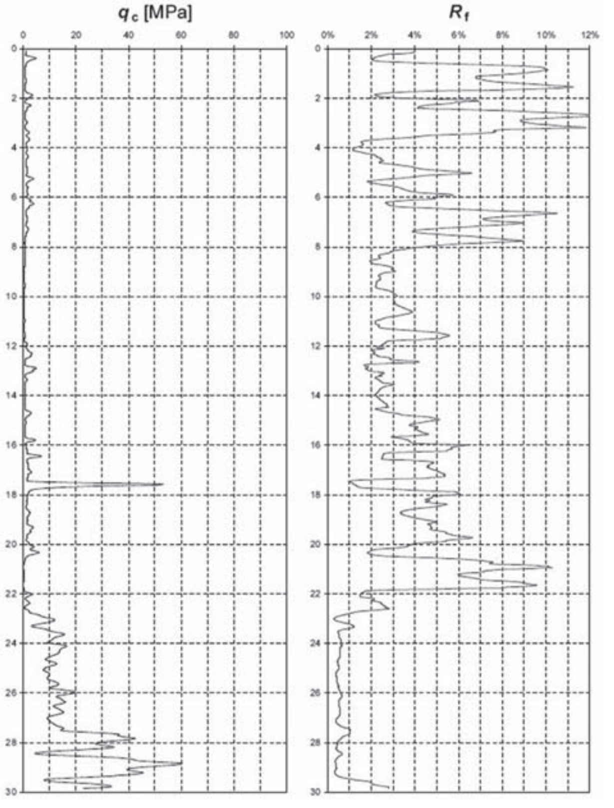

Fig. 4. CPT results at the location of reference pile

5. Results of calculation

The total bearing capacity N_t of the reference pile, calculated in accordance to Polish Standards equals 1323 kN (design value), where the capacity of the pile base is N_p = 773 kN, and the capacity of pile shaft is N_s = 550 kN.

The maximum compressive resistance of the considered pile, was calculated in accordance to the procedure described in Annex D.7 of Eurocode 7 (Part 2), is $F_{\max}$ = 4054 kN, where the resistance of the pile base is $F_{\max,base}$ = 3511 kN, and the resistance of pile shaft equals $F_{\max,shaft}$ = 543 kN. In order to calculate the characteristic values of the ultimate compressive resistance of the pile from ground test results, a correlation of factors needs to be applied, which depend on the number of tested soil profiles. For a single CPT result factor value of $\xi_3 = \xi_4 = 1.4$ applies, for which $R_{c,k}$ = 2896 kN, where base resistance is

$R_{b,k}$ = 2508 kN, and shaft resistance is $R_{s,k}$ = 388 kN. To calculate the design values a partial factor of $\gamma_t = \gamma_b = \gamma_s$ = 1,1 needs to be applied (design approach DA-2), which reduces the design value of the resistance of the reference pile to $R_{c,d}$ = 2632 kN, where base resistance is $R_{b,d}$ = 2280 kN, and shaft resistance is $R_{s,d}$ = 352 kN.

6. Verification of the design

The only reliable method for the verification of pile design is a real-scale load test. The results of such a test conducted for the analyzed case are presented in Figure 5 (solid line). The load test was performed with an inverted beam method using four anchor piles similar to the tested pile (Fig. 6).

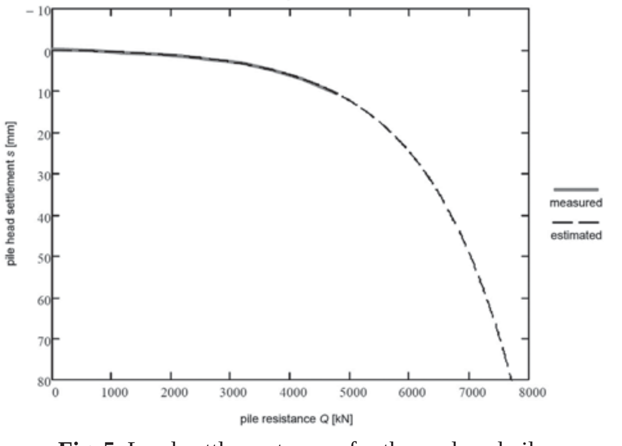

Fig. 5. Load-settlement curve for the analyzed pile

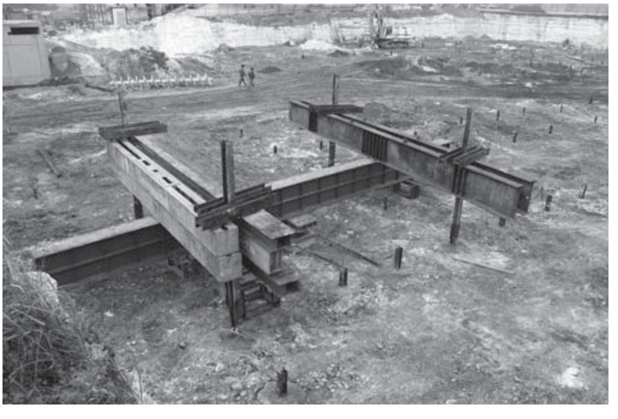

Fig. 6. Inverted beam set prepared for the pile load test (fot. by author)

The pile load test was programmed to exceed a predicted maximum resistance value of $1.5 \cdot R_{c,k} \approx 4344$ kN. The settlement of 8,0 mm, which is 1% of the pile diameter, has been measured at the final load step. As the settlement value, corresponding to pile bearing capacity in the limit state, of 10% of pile diameter is usually assumed, an extrapolation of the load--settlement curve has been made. An estimated value of the ultimate pile resistance from the pile load test is $R_{ult} \approx 7700$ kN (dashed line on figure 5).

A comparison of the results obtained in the calculations, which have been carried out using the procedures of both sets of standards, along with the results of the pile load test is shown in figure 7.

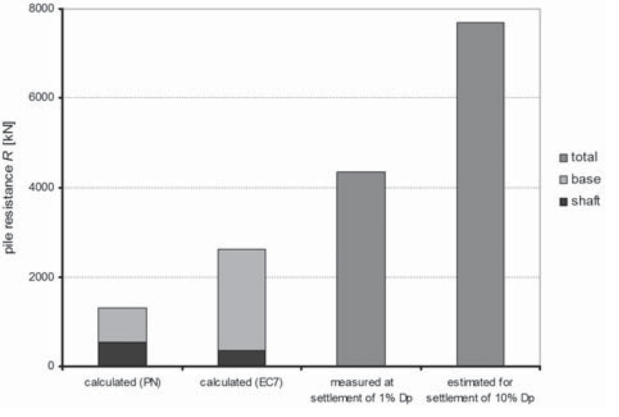

Fig. 7. Comparison of the results obtained in calculation with the results of pile load test

7. Summary

The discrepancy in the results is very significant: the design value of the compressive resistance of the pile calculated in accordance with Polish Standards [4, 5] is almost twice as low with Eurocodes [6, 7].

The primary cause of the differences is the approach to utilizing the CPT results to assess the parameters of the subsoil. The indirect approach, used in the procedure of Polish Standards, requires the use of two correlations: primarily between the parameters measured in the field and the density and liquidity indexes of the soil strata; secondarily between these indexes and unit resistances at the base and along the shaft of the pile. Each of these correlations was created in such a way that a parameter calculated with its use is a safe estimation of the actual value. The direct use of the CPT results to assess the unit resistances of the pile base and shaft, used in the procedure of Eurocode 7, leads to higher values of these parameters.

It needs to be noted that in the analyzed design situation the higher value of total pile resistance is implied by the resistance of the pile base, resulting directly from the accepted value of the unit base resistance, which was only $q = 1.71$ MPa for Polish Standards, while the value of $p_{\max,base}$ according to Eurocode method was equal to 6.99 MPa. On the other hand, the estimation of pile shaft resistance turned out to be more cautious in the procedure of Eurocode 7.

Generally, the use of CPT results in the pile design procedure usually leads to a safe estimation of the ultimate pile resistance, regardless of the selected approach.

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