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Application of the 'CPT 2012' model of AFNOR standard for column design in Poland – Jazowa case study

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Abstract. This paper presents the 'CPT 2012' model incorporated into the AFNOR NF P94-262:2012-07, French standard for pile design fully compatible with Eurocode 7, to the wider Polish audience. The bearing capacity of three reference columns for Vistula Marshlands have been calculated according to 'CPT 2012' model and AFNOR recommendations. Then, the design resistances have been compared with ultimate column bearing capacity measured during static load tests conducted on reference columns. The results of comparison are discussed and the discrepancies between measured and calculated bearing capacities are shortly commented.

1 Introduction

Pile design using field geotechnical investigation involves using direct or indirect methods. In direct methods the soil properties are estimated using field tests and then these properties are used to calculate the pile unit base and shaft resistances. In direct methods the results of the field testing, e.g. Cone Penetration Test (CPT), are directly used to assess the pile unit base and shaft resistances. The CPT is a standard site investigation tool widely used in Polish geotechnical practice. There are many pile design methods where CPT results are used [1]. One of the recent is 'CPT 2012' [2] included in AFNOR NF P94-262:2012-07 standard for pile design. The AFNOR standard is fully compatible with Eurocode 7, which is additional advantage of 'CPT 2012' model. In this paper, three representative columns constructed in Vistula Marshlands are chosen as reference ones for bearing capacity calculation according to 'CPT 2012' model and AFNOR standard. Then, the results are compared with the results of column static loading tests. The aim of this paper is to present the 'CPT-2012' model to the Polish audience and to show its application to local conditions. The discrepancies occurred are shortly discussed and the general performance of the 'CPT 2012' model within the Polish site conditions is commented.

2 'CPT 2012' model

The AFNOR NF P94-262:2012-07, revised due to Eurocode 7 recommendations [3], offers two pile calculation methods based on in-situ investigation, i.e., new pressuremeter model (PMT 2012) and new penetrometer model (CPT 2012), both fully compatible with Eurocode 7. The basic concept in new French standard is to distribute piles into 8 classes and 20 categories, see Table 1. The 'CPT-2012' model uses only cone resistance q_c (or corrected cone resistance q_t). The sleeve friction f_s is omitted due to possible high variability of this reading [4]. The unit pile base resistance q_b is calculated using the following equation [5]:

$$q_b = k_c \times q_{ce} \tag{1}$$

where k_c is a function of the soil type and pile class and q_{ce} is equivalent cone resistance. The q_{ce} averaging method in the base neighbourhood suggested by NF P94-262:2012-07 standard is modified version of Bustamante and Ginaselli [6] recommendations. The equivalent cone resistance q_{ce} is defined as [5]:

$$q_{ce} = \frac{1}{b+3a} \int_{D-b}^{D+3a} q_{cc}(z)dz \tag{2}$$

where a and b are the characteristic lengths, see Figure 1, q_{cc} is a corrected cone resistance profile which is obtained by elimination of extreme values (higher than 1.3 times of average q_c) and D is pile length measured from the surface level. The k_c factor depends on effective embedded depth D_{ef} [5]:

$$D_{ef} = \frac{1}{q_{ce}} \int_{D-h_D}^{D} q_c(z)dz \tag{3}$$

where D_{ef} is defined as the effective embedded length in pile end bearing layer, h_D is equal to $10B$ (B is the pile diameter). When $D_{ef}/B \geq 5$ then $k_c = k_{cmax}$, where k_{cmax} is the maximum bearing resistance factor, see Table 2. When $D_{ef}/B \leq 5$ the following equations are valid:

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$$k_c = 0{,}3 + \left(k_{c\max} - 0{,}3\right) \times \left(D_{ef} / B\right) / 5 \tag{4}$$

for clays and silts,

$$k_c = 0{,}2 + \left(k_{c\max} - 0{,}2\right) \times \left(D_{ef} / B\right) / 5 \tag{5}$$

for intermediate soils,

$$k_c = 0{,}3 + \left(k_{c\max} - 0{,}3\right) \times \left(D_{ef} / B\right) / 5 \tag{6}$$

for sands and gravels and

$$k_c = 0{,}15 + \left(k_{c\max} - 0{,}15\right) \times \left(D_{ef} / B\right) / 5 \tag{7}$$

for chalk, marl and rock. The pile unit shaft resistance q_s is given by formula [5]:

$$q_s = \alpha \times f_{sol} \tag{8}$$

where α is empirical coefficient depending on soil type and pile category, see Table 3 and f_{sol} is soil-depended function [5]:

$$f_{sol} = (a \times q_c + b)(1 - \exp(-c \times q_c)) \tag{9}$$

where a, b, c are soil-type parameters, see Table 4. The unit shaft resistance expressed by equation (8) has to fulfill condition of $q_s \leq q_{smax}$ where q_{smax} is maxiumum pile unit shaft resistance (see Table 5). The calculated pile bearing capacity in compression R_c (or in tension R_t) is as follows [3, 5]:

$$R_c = q_b A_b + \Sigma q_{si} A_{si} \tag{10}$$

$$R_t = \Sigma q_{si} A_{si} \tag{11}$$

where q_b is pile unit base resistance, A_b is the pile base area, q_{si} is pile shaft resistance corresponding to i layer and A_{si} is pile shaft area corresponding to the i layer. In AFNOR standard the design approach 2 and 'ground model' procedure is used. Consequently, the design value of pile resistance can be expressed as follows [3, 5]:

$$R_{d,c} = R_c / \left(\gamma_{Rd} \gamma_{gm} \gamma_t\right) \tag{12}$$

for compression and

$$R_{d,t} = R_t / \left(\gamma_{Rd} \gamma_{gm} \gamma_t\right) \tag{13}$$

for tension, where $R_{d,c}$ is design pile bearing capacity in compression, $R_{d,t}$ is design pile bearing capacity in tension, γ_{Rd} is model factor, γ_{gm} is second model factor and γ_t is the resistance factor. The values of factors γ_{Rd} are defined within the AFNOR and they are presented in table 6. The ground model safe factor γ_{gm} is equal to 1.1 and the resistance factor γ_t on the total characteristic resistance is equal 1.1 for compression piles and 1.15 for tension piles.

The above presented procedure is relatively straightforward in terms of pile shaft resistance calculation. However, the embedded length in pile end bearing stratum (see h distance in Fig. 1) is problematic to interpret. In AFNOR standard the h distance is defined as a embedded length in bearing soil strata. In terms of friction pile or pile that is based on bearing strata, the definition of h distance is not clear.

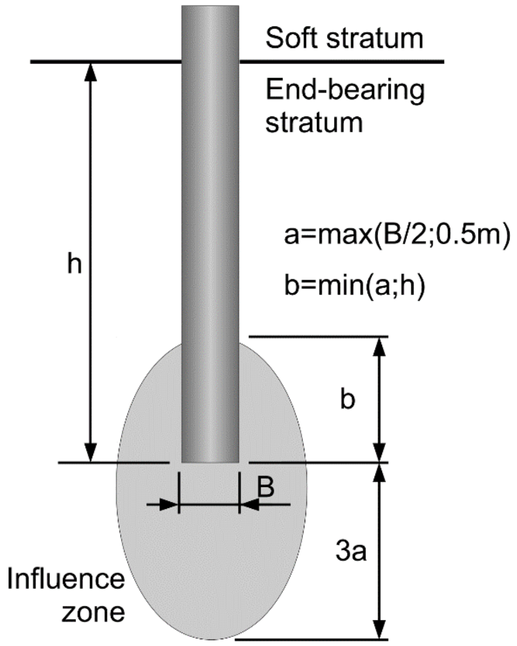

Fig. 1. Model for equivalent cone resistance (q_{ce}) determination.

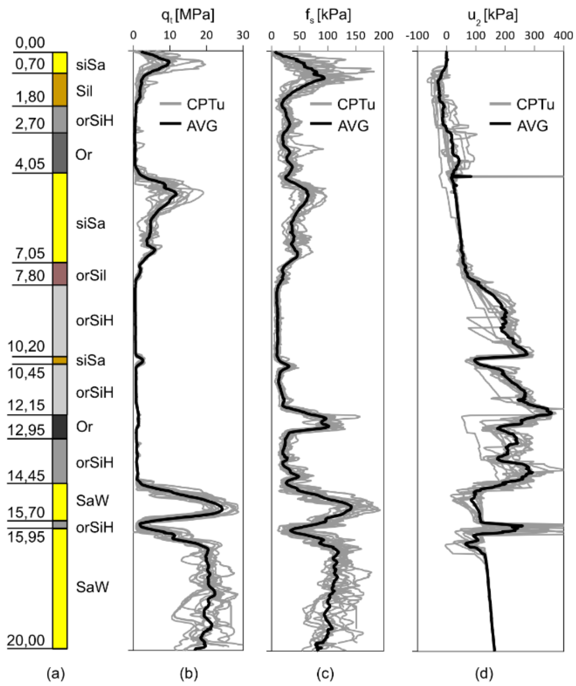

Fig. 2. Soil profile (a), and CPTU results (b)-(c) for Jazowa testing site.

Table 1. Classes and Categories of Piles [3, 5]

Pile class	Pile category
C1: Bored Piles	1: No support 2: With Slurry 3: Permanent casing 4: Recoverable casing 5: Dry bored pile/or slurry; bored pile with grooved sockets
C2: CFA Piles	6: CFA Piles
C3: Screw Piles	7: Screw cast-in-place pile 8: Screw piles with casing
C4: Closed-Ended driven Piles	9: Pre-cast or pre-stressed concrete-driven pile 10: Coated driven steel pile (coating: concrete, mortar, grout) 11: Driven cast-in-place pile 12: Driven steel pile ; closed ended
C5: Open-ended driven Piles	13: Driven steel pile ; open ended
C6: Driven H Piles	14: Driven H pile 15: Driven grouted H pile
C7: Driven Sheet Pile Walls	16: Driven sheet pile
C8: MicroPiles	17: Micropile I (gravity pressure) 18: Micropile II (low pressure) 19: Micropile III (high pressure) 20: Micropile IV (high pressure with TAM)

Table 2. Bearing resistance factor k_{cmax} for the 'CPT 2012' model [3, 5]

Pile class	Soil Type					
	Silt and Clay % $CaCO_3$<30%	Intermediate soil	Sand and gravel	Chalk	Marl and calcareous marl	Weathered rock
1	0.4	0.3	0.2	0.3	0.3	0.3
2	0.45	0.3	0.25	0.3	0.3	0.3
3	0.5	0.5	0.5	0.4	0.35	0.35
4	0.45	0.4	0.4	0.4	0.4	0.4
5	0.35	0.3	0.25	0.15	0.15	0.15
6	0.4	0.4	0.4	0.35	0.2	0.2
7	0.35	0.25	0.15	0.15	0.15	0.15
8	0.45	0.3	0.2	0.3	0.3	0.25

Table 3. Values of installation factor α for 'CPT 2012' model [3, 5]

Pile class	Soil Type					
	Silt and Clay % $CaCO_3$<30%	Intermediate soil	Sand and gravel	Chalk	Marl and calcareous marl	Weathered rock
1	0.55	0.65	0.70	0.80	1.40	1.50
2	0.65	0.80	1.00	0.80	1.40	1.50
3	0.35	0.40	0.40	0.25	0.85	-
4	0.65	0.80	1.00	0.75	0.13	-
5	0.70	0.85	-	-	-	-
6	0.75	0.90	1.25	0.95	1.50	1.50
7	0.95	1.15	1.45	0.75	1.60	-
8	0.30	0.35	0.40	0.45	0.65	-
9	0.55	0.65	1.00	0.45	0.85	-
10	1.00	1.20	1.45	0.85	1.50	-
11	0.60	0.70	1.00	0.95	0.95	-
12	0.40	0.50	0.85	0.20	0.85	-
13	0.60	0.70	0.50	0.25	0.95	0.95
14	0.55	0.65	0.70	0.20	0.95	0.85
15	1.35	1.60	2.00	1.10	2.25	2.25
16	0.45	0.55	0.55	0.20	1.25	1.15
17	-	-	-	-	-	-
18	-	-	-	-	-	-
19	1.35	1.60	2.00	1.10	2.25	2.25
20	1.70	2.05	2.65	1.40	2.90	2.90

Table 4. Determination of the *a* ,*b*, *c* parameters [3, 5]

Parameter	Soil Type					
	Silt and Clay % $CaCO_3$<30%	Intermediate soil	Sand and gravel	Chalk	Marl and calcareous marl	Weathered rock
a	0.0018	0.0015	0.0012	0.0015	0.0015	0.0015
b	0.1	0.1	0.1	0.1	0.1	0.1
c	0.4	0.25	0.15	0.25	0.25	0.25

Table 5. Values of $q_{s,max}$ for 'CPT 2012' model [3, 5]

Pile class	**Soil Type**					
	Silt and Clay % $CaCO_3$<30%	Intermediate soil	Sand and gravel	Chalk	Marl and calcareous marl	Weathered rock
1	90	90	90	200	170	200
2	90	90	90	200	170	200
3	50	50	50	50	90	-
4	90	90	90	170	170	-
5	90	90	-	-	-	-
6	90	90	170	200	200	200
7	130	130	200	170	170	-
8	50	50	90	90	90	-
9	130	130	130	90	90	-
10	170	170	260	200	200	-
11	90	90	130	260	200	-
12	90	90	90	50	90	-
13	90	90	50	50	90	90
14	90	90	130	50	90	90
15	200	200	380	320	320	320
16	90	90	50	50	90	90
17	-	-	-	-	-	-
18	-	-	-	-	-	-
19	200	200	380	320	320	320
20	200	200	440	440	440	500

Table 6. Model factor γ_{Rd} values for 'CPT 2012' model [3, 5]

Pile type	γ_{Rd} **compression [-]**	γ_{Rd} **tension [-]**
All piles except listed below	1.18	1.45
Piles embedded in chalk	1.45	1.75
Coated and injected piles	2.0	2.0

Table 7. Column bearing capacity after AFNOR NF P94-262:2012-07 standard

Column embedded length [m]	**Base capacity [kN]**	**Shaft capacity [kN]**	R_c **[kN]**	γ_{Rd} **[-]**	γ_{gm} **[-]**	γ_t **[-]**	R_d **[kN]**
11	54	688	741				520
14.5	171	842	1013	1.18	1.1	1.1	709
17	1273	1149	2422				1696

Table 8. Calculated and design column resistance versus measured pile bearing capacity

Column embedded length [m]	R_c [kN]	R_d [kN]	Q_{ult} [kN]	R_c/Q_{ult}	R_d/Q_{ult}
11	741	520	725	1.02	0.72
14.5	1013	709	1266	0.80	0.56
17	2422	1696	1814	1.33	0.93

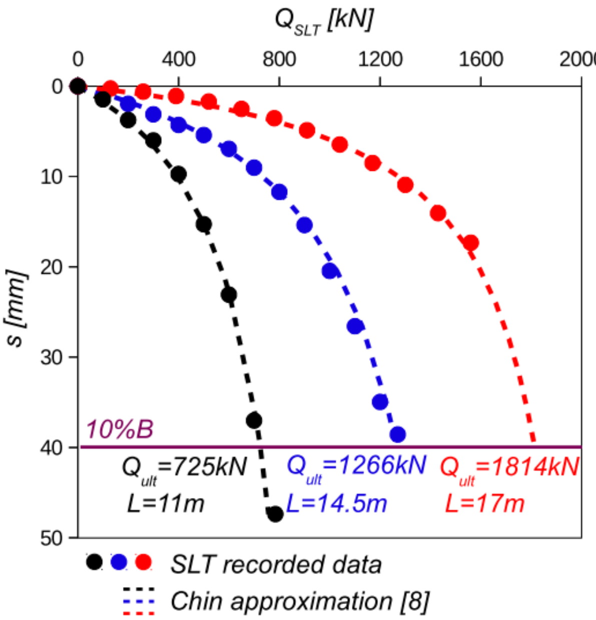

Fig. 3. Results of static load test for Jazowa reference columns.

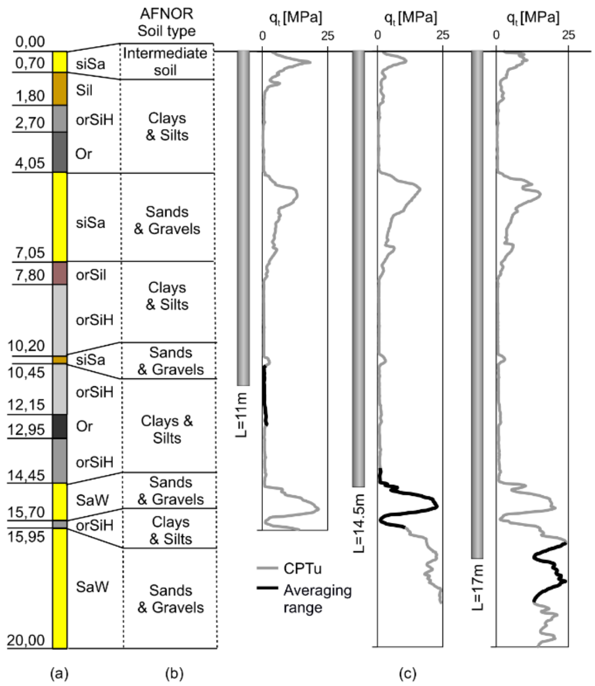

Fig. 4. Averaging depths for equivalent cone resistance determination for Jazowa reference piles.

3 Reference site

The reference testing site is located in Jazowa, northern Poland. Jazowa site is a part of the Vistula Marshlands and it lies within the S7 highway, currently under construction. The 4 testing fields have been constructed in close distance to the highway. The site geotechnical investigation consists of 15 CPTu soundings, presented in Fig. 2 with corresponding soil profile. The soil layers are distinguished according to European Soil Classification System (ESCS) [7]. The 69 CMC columns, 0.4m in diameter, have been constructed and 27 columns have been proof-tested. For the purpose of this paper the 3 characteristic columns (tested in compression) with embedded lengths 11m, 14.5m and 17m have been chosen to analysis. The results of static tests of selected columns are presented in Fig. 3. The total force which acts on column head was measured (Q_{SLT}) and the ultimate column capacity (Q_{ult}) was defined as force that involves column settlement of 10%B.

The CMC columns drilled with full displacement auger correspond to pile class C3 and category 7, see Table 1. The soil layers are matched with those used in AFNOR (see Tables 2, 3, 4). Fig. 4 presents the columns with the corresponding (the closest in the pile neighborhood) CPTu sounding result, where also the averaging length for cone resistances has been shown.

The column bearing capacity has been calculated using the procedure described in section 2. The bearing capacity factors k_c for columns with embedded length of 11m, 14.5m and 17m are equal to 0.500, 0.222 and 0.500, respectively. The maximum column unit shaft resistance is equal to 130kPa for soft soils and intermediate soil, while it corresponds to 200kPa for sands, see Table 3. The installation factor α is equal to 0.95, 1.15 and 1.45 for soft soil, intermediate soils and sand layers, respectively. The f_{sol} has been determined according to the equation (9). Then, the pile shaft capacity has been calculated and finally, the total pile resistance has been obtained as a sum of pile shaft resistance and pile base resistance. The design value of resistance is retrieved after safety factors application.

4 Results and Discussion

The calculated (R_c) and design (R_d) value of bearing capacity for selected columns is presented in Table 7, where also the column base and column shaft components have been shown. The comparison between calculated and design resistance and the measured column bearing capacity is summarized in Table 8. The calculated values of column bearing capacity are in good agreement with the measured ones for 11m and 14.5m length column. However, the bearing capacity of the 17m length column is overestimated. Application of the safety factors changes the situation. As one can see, the design value of column bearing capacity almost perfectly fits to the measured bearing capacity for the column 17m in length (end bearing column). The result for friction column (11m length) is also satisfactory. However, the bearing capacity of the 14.5m length column which is only based on the bearing soil layer (column toe is not embedded in the competent soil strata) is almost 2 times underestimated. The reason is due to 'CPT 2012' model, where French site conditions and field tests have been used for model calibration. Consequently, the revision of empirical factors used in 'CPT 2012' model may be needed for fitting the 'CPT 2012' model to local Polish conditions.

5 Conclusions

In this paper the case study of column bearing capacity calculation for Jazowa testing site has been presented where 3 representative columns are selected to analysis. The column bearing capacities have been calculated according to 'CPT 2012' model, fully compatible with Eurocode 7. The results were compared with static load tests measurements. The 'CPT 2012' model by AFNOR recommendations provides safe estimation of column capacity. However, some discrepancies are observed. The column design resistance of the end bearing column embedded in hard soil layer almost perfectly fits to the ultimate bearing capacity obtained from static load test results. In the remaining cases a significant underestimation of column design resistance is observed. In order to verify Jazowa testing site conclusions and general performance of 'CPT 2012' model, larger case study database is needed. Consequently, the calibration of the 'CPT 2012' model due to local conditions in Poland are recommended if similar results as for Jazowa site will be achieved.

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