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The Impact of EC 7 in Axial Load Capacity Estimation of Pile Foundations

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Abstract

The pile foundation is generally used in Albania. Until today their design is based on what it is called The Albanian Practice of Design. In these days, the implementation of the Eurocode in the design, is considered very fundamental. Thus, the objective of this paper is to show the impact that the application of the Principals and Application Rules of the Eurocode 7 has on the estimation of the axial load capacity of pile foundations. The paper will present the estimation of the axial load capacity of the pile according to the Albanian Practice of Design and to the Eurocode 7. Also, the results of calculations for two hypothetical study cases related to the bored and driven piles, installed in sandy and clay soils will be shown. In these cases will be determined the Axial Load Capacity of the pile, as well as the degree of its utilization. In both cases the Axial Load Capacity of the pile which is estimated according to the analytical Method. From the calculations and discussions of the examined cases will be obtained some conclusions.

Keywords: *pile foundation; bearing capacity; load capacity; design approach; partial factor; reliability.*

1. Introduction

Pile foundations are deep foundations. Generally they are used to support the structures and bridges, especially when the upper layers of the soil don't have a sufficient bearing capacity to afford the loadings or when the settlement of a shallow footing exceeds the acceptable limit of the structure.[1]

Pile foundations transfer the axial loadings into the soil within two ways: through the base and the lateral friction. We can refer to Limit Load Capacity, which is the requested load causing failure, or to Allowed Load Capacity which is the Limit Load Capacity divided by a safety factor. The Limit Load Capacity is estimated in an analytical way by different authors. The Load Capacity estimation of the pile is very fundamental in the pile foundation design**.**

This paper presents the estimation of the axial load capacity of the pile according to the Albanian Practice of Design[2] and to the Eurocode 7[3]. In both cases the estimation is based on the analytical Methods. There are also shown the results of calculations for two hypothetical study cases related to the bored and driven piles, installed in sandy and clay soils. In these cases is determined the Axial Load Capacity of the pile, as well as the degree of its utilization.

The objective of this paper is to show the impact that the application of the Principals and Application Rules of the Eurocode 7 has on the estimation of the Axial Load Capacity of pile foundations.

2. Axial Load Capacity of the pile according to the Albanian Practice of Design

This paper presents the estimation of the Axial Load Capacity of two different piles specified in this practice, depending on the installation mode such as the bored and driven piles.

The Allowable Axial Load Capacity of the bored and driven piles is estimated by the following formula:

$$F_d = \gamma_c \left(\gamma_{cR} R A + u \sum \gamma_{cf} f_i h_i \right) \tag{1}$$

Where

γ_c = coefficient of working conditions; γ_c= 1 for driven piles; for bored piles into silty - clay soils with degree of saturation Sr < 0.9, and into the organic soils $\gamma_c = 0.9$, and in other cases $\gamma_c = 1$;

A = toe-bearing contact area, m^2;

u = perimeter of the cross section of the pile, *m*;

f_i = unit shaft resistance, *kPa*, taken from Table 1 for both types of piles;

h_i = depth of the *i*-layer, adjacent to the lateral surface of the pile, *m*;

Table1 Unit shaft resistance

Depth Z (m)	Unit shaft resistance, f_i, kPa								
	Medium dense granular soils								
	Dense, medium sand	Loose sand	Very loose sand						
	Consistency Index I_c of cohesive soils								
	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1	35	23	15	12	8	4	4	3	2
2	42	30	21	17	12	7	5	4	4
3	48	35	25	20	14	8	7	6	5
4	53	38	27	22	16	9	8	7	5
5	56	40	29	24	17	10	8	7	6
6	58	42	31	25	18	10	8	7	6
8	62	44	33	26	19	10	8	7	6
10	65	46	34	27	19	10	8	7	6
15	72	51	38	28	20	11	8	7	6
20	79	56	41	30	20	12	8	7	6
25	86	61	44	32	20	12	8	7	6
30	93	66	47	34	21	12	9	8	7
35	100	70	50	36	22	13	9	8	7

$\gamma_{cR,} \gamma_{cf}$ = coefficients of working conditions for the base resistance and the shaft resistance; for the driven pile depends on the driven manner, taken from the table. Their values vary $\gamma_{cR.} = 0.6 - 1.2$ and $\gamma_{cf} = 0.5 - 1$; for bored piles in water table condition $\gamma_{cR} = 0.9$ and in the other cases it is generally equal to 1.0, γ_{cf} depends on the installation manner and the type of pile, taken from the table. Their values vary $\gamma_{cf} = 0.6 - 1.0$.

R = unit base resistance;

2.1 The Unit Base Resistance

For bored piles, the unit base resistance, should be taken:

- when it's installed into sandy soils, it is estimated by the following formula:

$$R = 0.75\alpha_4(\alpha_1\gamma_1{}'d + \alpha_2\alpha_3\gamma_1 h) \quad (2)$$

Where: $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ = coefficients depend on the friction angle of the soil on the pile base and on the ratio h/d, taken in the table;
$\gamma_1{}'$ = unit weight of the soil on the pile base, KN/m^3, or saturated unit weight when the soil is under water table condition;
γ = average unit weight of the soils adjacent to the pile body, kN / m^3;
d = diameter of the bored pile, *m*;
h = depth of pile base installation, *m*;

- when it's installed into silty-clay soils, from Table 2

Table 2 Unit base resistance for bored piles

Depth of the pile base	Unit base resistance for bored piles into silty-clay soils with Consistency Index I_c equal to						
	0.0	0.1	0.2	0.3	0.4	0.5	0.6
3	850	750	650	500	400	300	250
5	1000	850	750	650	500	400	350
7	1150	1000	850	750	600	500	450
10	1350	1200	1050	950	800	700	600
12	1550	1400	1250	1100	950	800	700
15	1800	1650	1500	1300	1100	1000	800
18	2100	1900	1700	1500	1300	1150	950
20	2300	2100	1900	1650	1450	1250	1050
30	3300	3000	2600	2300	2000	-	-
40	4500	4000	3500	3000	2500	-	-

For driven piles, unit base resistance should be taken from Table 3

Table 3 Unit base resistance for driven piles

Depth of the pile base	Unit base resistance for driven piles, R, kPa						
	Medium dense granular soils						
	Gravel	Dense sand	-	Medium sand	Loose sand	Very loose sand	-
	Consistency Index I_c of cohesive soils						
	0	0.1	0.2	0.3	0.4	0.5	0.6
3	7500	6600 4000	3000	3100 2000	2000 1200	1100	600
4	8300	6800 5100	3800	3200 2500	2100 1600	1250	700
5	8800	7000 6200	4000	3400 2800	2200 2000	1300	800
7	9700	7300 6900	4300	3700 3300	2400 2200	1400	850
10	10500	7700 7300	5000	4000 3500	2600 2400	1500	900
15	11700	8200 7500	5600	4400 4000	2900	1650	1000
20	12600	8500	6200	4800	3200	1800	1100

				4500			
25	13400	9000	6800	5200	3500	1950	1200
30	14200	9500	7400	5600	3800	2100	1300
35	15000	10000	8000	6000	4100	2250	1400

The first values on the table refer to sandy soils and the second ones refer to silty-clay soils.

2.2 Verification of Load Capacity

The Load capacity of the pile is verified by the following formula:

$$N \leq \frac{F_d}{\gamma_k} \quad (3)$$

where:
N = design load transmitted to the pile from the loads acting on the foundation with their appropriate load combination;

$$N = \lfloor \gamma_G * (W_{Gk} + V_{Gk}) + \gamma_Q * V_{Qk} \rfloor \quad (4)$$

Fd = bearing capacity of a single pile estimated as the formula (1);
γ_k = safety factor, equal to 1.4, when the bearing capacity is estimated by analytical Method.
The degree of pile utilization

$$\Lambda = \frac{N}{F_d} \quad (5)$$

3. Axial Load Capacity of pile according to EN 1997-1

The Eurocode 7 "Geotechnical design" is based on "Limit State Design". EN 1990 defines Limit states as "states beyond which the structure no longer fulfils the relevant design criteria". There are two different types of Limit state and each of them has own relevant design criteria: the Ultimate Limit State (ULS) and the Service Limit State (SLS).

EN 1997-1 distinguishes five different types of Ultimate Limit State and it also uses some abbreviations for them, that are defined in EN 1990: Ultimate state limit EQU, Ultimate state limit STR, Ultimate state limit GEO, Ultimate state limit UPL, Ultimate state limit HYD. Ultimate state limit GEO represents "*failure or excessive deformation of the ground, in which the strength of soil or rock is significant in providing resistance*".[4]

3.1 Calculation methods

Models of calculation involve some elements: actions, material properties and geometrical data. They are used to verify that the limit states are not exceeded. As for serviceability limit states, these models must demonstrate that the predicted displacements do not exceed limiting values, which are commonly specific for a certain project. For Ultimate limit states, they must demonstrate that effects of actions do not exceed the available resistance.[1]

EN 1997-1 specifies three Design Approaches (Design Approach-DA) which are abbreviately written down, respectively DA-1, DA-2 and DA-3. Each of the Design Approaches offers a choice on the way of verification of Ultimate limit state GEO and STR.

A new conception, involved in Section 7 of EN 1997-1, in relation with the traditional pile design is: the application of partial factors in characteristic values and the application of model factors to take into account the inaccuracies in calculation. [4]

These partial factors are: factors for actions (set A) γ_G permanent actions and $\gamma_Q$variable actions, factors for ground strength (set M) γ_M, factors for resistance (set R) γ_R. The values of these factors are given in certain Tables, set in Annex A of EN 1997-1.

The above partial factors are selected based on the combination of Design Approaches as follows:

- Design Approach 1 (DA 1) combination 1: $A1 + M1 + R1$
- Design Approach 1 (DA 1) combination 2: $A2 + M1 + R4$
- Design Approach 2 (DA 2), $A1 + M1 + R2$
- Design Approach 3 (DA3), $A1 ose\ A2 + M2 + R3$

Design Approach 1 DA-1. Design Approach DA-1 checks reliability with two different combinations of partial factors. In combination 1 for pile foundations, the partial factors are applied to actions and to resistances while ground strengths (when used) are not factored. In combination 2, the partial factors are applied to resistance, and to variable actions, while the permanent actions and ground strengths (when used) are not factored.[1]

Design Approach 2 DA-2. Second Design Approach DA-2 checks the reliability by applying partial factors to actions and to resistance, while ground strengths (when used) are not factored.[1]

Design Approach 3 DA-3. Third Design Approach DA-3 checks the reliability by applying partial factors to actions and to material properties (when used) while, resistances are not factored.[1]

EN 1997-1 proposes three design approaches to check the failure in the soil (GEO) and in the structure (STR). The choice of design approach has to be qualified in National Annex. As well as the values of partial and model factors which are applied to the selected design Approach. [3]

The verification of strength for pile foundations as regard to the three design approaches is demonstrated by the following formula:

$$V_d \leq R_d \tag{6}$$

Where:

V_d = design vertical action

$$V_d = \lfloor \gamma_G * (W_{Gk} + V_{Gk}) + \gamma_Q * V_{Qk} \rfloor \tag{7}$$

R_d = total design resistance

$$R_d = R_{bd} + R_{sd} \tag{8}$$

R_{bd} dhe R_{sd} respectively design base resistance and design shaft resistance

$$R_{bd} = \frac{R_{bk}}{\gamma_b}\ ; \quad and \quad R_{sd} = \frac{R_{sk}}{\gamma_s} \tag{9}$$

R_{bk} dhe R_{sk} respectively characteristic base resistance and characteristic shaft resistance

$$R_{bk} = \frac{\gamma_c * \gamma_{cR} * R * A}{\gamma_{Rd}} ; \quad and \quad R_{sk} = \frac{\gamma_c * u * \sum \gamma_{cf} f_i h_i}{\gamma_{Rd}} \tag{10}$$

Degree of utilization

$$\Lambda = \frac{V_d}{R_d} \tag{11}$$

4. Calculations

Axial load capacity of pile based on the analytical method according to Albanian Practice Design is defined through:

• The direct application of calculating formula

• The application of the Principles and Application Rules of the Eurocode 7 in the calculating formula

There are considered two hypothetical study cases related to a driven pile (diameter d = 40cm) and to a bored pile (square with side 40 cm), installed in sandy and clay soils. The bearing capacity is calculated for the pile depths 10, 15 and 20m.

The sandy soil has these properties: clay fraction 9.40%, silty fraction 14.8%, sandy fraction 75.8%, w = 21.9%, $\gamma = 19.6\ kN/m^3$, e = 0.68, $\varphi = 34°$, c = 9kPa.

The clay soil has these properties: clay fraction 37.50%, silty fraction 34.8%, sandy fraction 27.7%, $W = 31.6\%$, $W_{rr} = 44.8\%$, $W_p = 22.40\%$, ($Plasticity\ index$) $I_p = 22.4$, $\gamma = 17.8\ kN/m^3$, $\epsilon = 0.87$, $\varphi = 15°$, c = 20kPa.

The considered loads on the pile: the characteristic permanent load, $V_{Gk} = 700\ kN$ and the characteristic variable load $V_{Qk} = 300 kN$.

The unit weight of reinforced concrete $\gamma_{ck} = 25\ kN/m^3$.

For the partial factors have been applied the recommended values in Annex A of EN 1997-1. For the model factor has been chosen the value 1.5.

The design vertical load applied to the calculating formula is defined for the main combination of the loads. The combination and load factors used to define the design loads are taken according to the Albanian Design Regulation KTP6-78.[5]

5. Discussion of the results

The result of calculating the Axial load capacity of piles and the degree of its utilization in the two examined cases are shown in Tables 4, 5, 6 and 7. The values in brackets show the degree of pile utilization.

Table 4 Driven pile in sandy soil

Pile depth	Albanian Practice	Albanian Practice with the EN 1997-1 impact			
		DA1-1	DA1-2	DA-2	DA-3
10m	1480(111%)	986.6(147%)	758.7(149%)	896.8(161%)	986.6(147%)
15m	2092(80%)	1394.6(106%)	1072.7(107%)	1267.7(116%)	1394.6(106%)
20m	2760(62%)	1840(82%)	1415.3(83%)	1672.7(90%)	1840(82%)

Table 5 Driven pile in clay soil

Pile depth	Albanian Practice	Albanian Practice with the EN 1997-1 impact			
		DA1-1	DA1-2	DA-2	DA-3
10m	814 (202%)	542.9(266%)	417.5(270%)	493.5(294%)	542.9(266%)
15m	1182(142%)	788.2(187%)	606.2(190%)	716.3(206%)	788.2(187%)
20m	1546.5(110%)	1031(146%)	792.8(147%)	937.2(160%)	1031(146%)

Table 6 Bored pile in sandy soil

Pile depth	Albanian Practice	Albanian Practice with the EN 1997-1 impact			
		DA1-1	DA1-2	DA-2	DA-3
10m	2445(73%)	1427(110%)	1107.4(110%)	1481.8(105%)	916.7(170%)
15m	3619.7(52%)	2133.7(77%)	1654.7(77%)	2193.4(75%)	1415.9(116%)
20m	4923.5(40%)	2917(59%)	2261.6(59%)	2983.7(58%)	1960.4(88%)

Table 7 Bored pile in clay soil

Pile depth	Albanian Practice	Albanian Practice with the EN 1997-1 impact			
		DA1-1	DA1-2	DA-2	DA-3
10m	807(220%)	484(323%)	374.9(324%)	488.7(320%)	537.7(290%)
15m	1229(152%)	745.4(221%)	576.9(221%)	744.5(221%)	819 (201%)
20m	1702.4(115%)	1037.7(167%)	802.85(167%)	1031(168%)	1134.8(153%)

The partial factors of the EN 1997-1 were applied to the actions, the material properties and resistances, which brought about a reduction of load capacity of pile and increase of load that acts on the pile, thus action increase. This shows that the structure in the second case is more stable, i.e. designed in a more safety way. The examined cases show the tendency that application of traditional formula in the designing of pile foundation, according to the Principles and Rules for Application of the EN 1997-1 is accompanied with an excess of the Ultimate Limit States. In addition the examined cases show that the best method for EN 1997-1 Application is DA-1.

6. Conclusions

1. The degree of pile utilization according to the Albanian Practice of Design results to be smaller than the one of the Albanian Practice applied according to the EN 1997-1.

2. The Albanian Practice applied according to the EN 1997-1 gives more conservative results for Load capacity of pile than the direct Albanian Practise. Design Approach DA 1-2 gives more conservative results in comparison with the other approaches.

3. For a safe design, there must be used the suggested Methods by EN 1997-1.

4. These conclusions are refered to the above reflected examples and they are not general conclusions, as the considered load is hypothetical. If other combinations of the actions or material properties were made, the conclusions would not be the same.

7. References

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