Journal of Civil Engineering and Construction Technology Vol. 4(3), pp. 70-80, March 2013
Available online at http://www.academicjournals.org/JCECT
DOI: 10.5897/JCECT12.051
ISSN 2141-2634 ©2013 Academic Journals

Full Length Research Paper

Pile design using Eurocode 7: A case study

Abdelazim Makki Ibrahim[1]*, Ibrahim Malik[2] and Omar Altaj Omar[2]

[1]Technische Universität Bergakademie Freiberg-Germany and Al Neelain University, Sudan.
[2]Al Neelain University, Sudan.

Accepted 25 January, 2013

Eurocode 7(EC7) introduces the characteristic and design values with partial factors to reduce uncertainties associated with soil parameters, applying load, etc. The characteristic and design values of soil parameters according to this code were determined, three design approaches of EC7 were evaluated and pile foundation design was assessed suitability using the better one. Moreover the limitation of this code is discussed. The study also shows that for the same load applied, a reduction of 24% of number of piles is achieved when (EC7) was used for pile foundation design compare with traditional German code taking global safety factor equal to two.

Key words: Ultimate limit state, partial factor, EC7.

INTRODUCTION

Eurocode 7 (EC7) is based on the limit state design concept and characteristic values, and the world's first geotechnical design code to share a common philosophy with the design methodology for structures. The basic Eurocode design requirements, given in EN 1990, are that a structure shall be designed and executed in such a way that it will, during its intended life, with appropriate degrees of reliability and in an economical way sustain all actions likely to occur during execution and use.

To achieve these basic requirements, the limit state design concept is adopted in the entire Euro zone Orr et al. (2008). The limit state is Ultimate Limit States (ULSs) and Serviceability Limit States (SLSs).

According to European Norm (EN 1990), designs to ensure that the occurrence of the limit state is sufficiently unlikely maybe carried out using either of the following methods:

(i) The partial factor method, or
(ii) Probabilistic methods

Eurocode 7 consists of three design approaches, Design Approach 1 (Combination 1 and 2, DA1.C1, DA1.C2), Design Approach 2 (DA2) and Design Approach 3 (DA3); the selection of one of them will be by National Determination (Bauduin, 2002). These design approaches depend totally on partial factors (Table 1).

Eurocode 7 has been criticized (Smith and Gilbert, 2010) because the suggested load (or action) factor (Design Approach 1, Design Combination 1) and load/resistance factor (Design Approach 2) methods appear not to readily lend themselves to numerical analysis. Whereas DA3 and DA1 (2) are the most straightforward to implement in FEA because they involve a material factoring approach.

Study area

The study area is part of Al-sunt project at Khartoum state-Sudan (Figure 1). Khartoum is the capital of the Sudan and it is a site of many projects and concrete buildings are taking place. This project is probably the biggest project going on in Sudan and one of the biggest in Africa. The subsurface soil in the study area is known by it and is low bearing capacity excessive, differential settlement and groundwater fluctuation. Therefore extensive geotechnical study, economic and proper geotechnical design code is needed to reduce expenses and to insure that the structure is safe during its life time.

*Corresponding author. Email: abdelazimi@yahoo.com.

Table 1. Partial factor for EC7 design approaches.

Parameter	Factor	DA1.C1	DA1.C2	DA2	DA3	
Partial factor on action (γ_F) or effect of action (γ_E)	Set	A1	A2	A1	A1* Struct.	A2 Geotech.
Permanent unfavourable action	γ_G	1.35	1.00	1.35	1.35	1.00
Permanent favourable action	γ_G	1.00	1.00	1.00	1.00	1.00
Variable unfavourable action	γ_Q	1.5	1.3	1.5	1.5	1.3
Variable favourable action	γ_Q	0	0	0	0	0
Accidental action	1.00	1.00	1.00	1.00	1.00	1.00
Partial factor for soil parameters (γ_M)	Set	M1	M2**	M1	M2	
Angle of shearing resistance, tanφ'	$\gamma_{tan\varphi'}$	1.00	1.25	1.00	1.25	
Effective cohesin c'	$\gamma_{c'}$	1.00	1.25	1.00	1.25	
Undrained shear strength c_u	γ_{cu}	1.00	1.4	1.00	1.4	
Unconfined strength q_u	γ_{qu}	1.00	1.4	1.00	1.4	
Weight density og ground γ_γ	γ_y	1.00	1.00	1.00	1.00	
Partial resistance factors (γ_R)						
Spread foundation and retainig structures	Set	R1	R4	R2	R3	
Bearing resistance	$\gamma_{R,y}$	1.00	1.00	1.4	1.00	
Sliding resistance	$\gamma_{R,d}$	1.00	1.00	1.10	1.00	
Earth resistance-retaining structure	$\gamma_{R,e}$	1.00	1.00	1.10	1.00	
Earth resistance-slope and overall stabiltiy	$\gamma_{R,e}$	1.00	1.00	1.00	1.00	

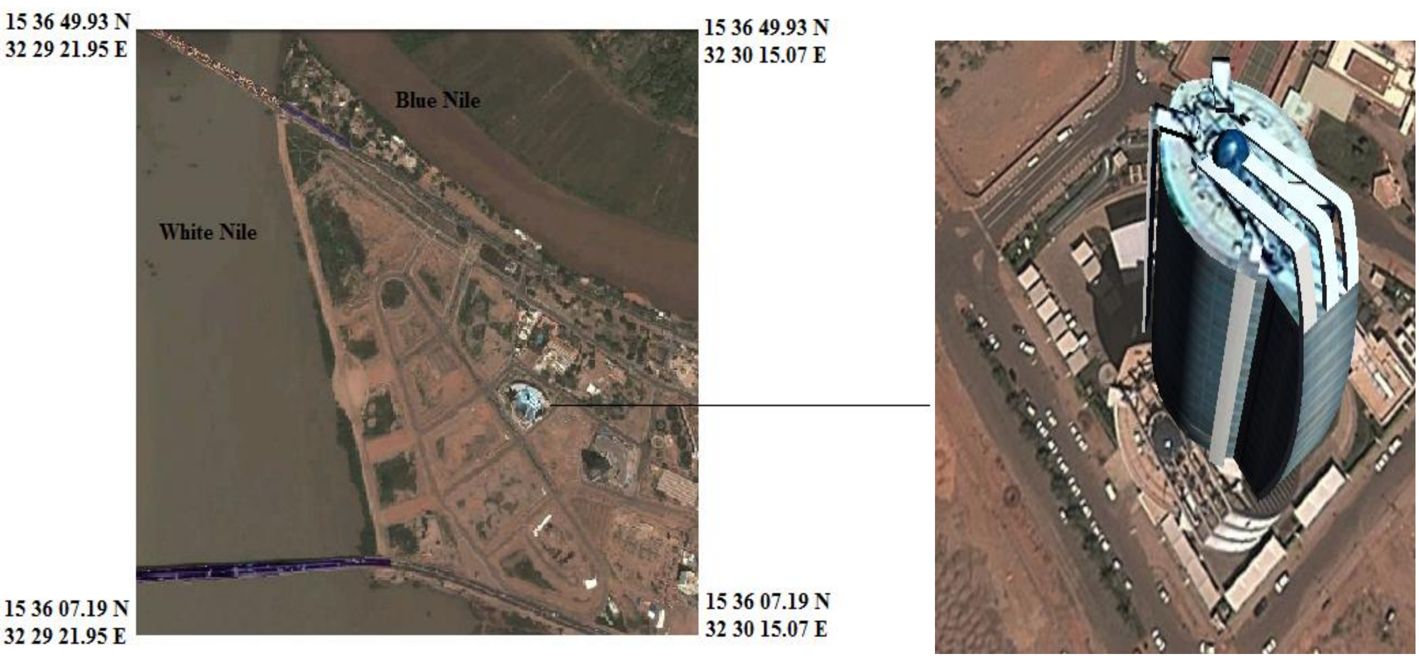

Figure 1. Study area shows complete new building at Al-sunt project Sudan (after Google earth).

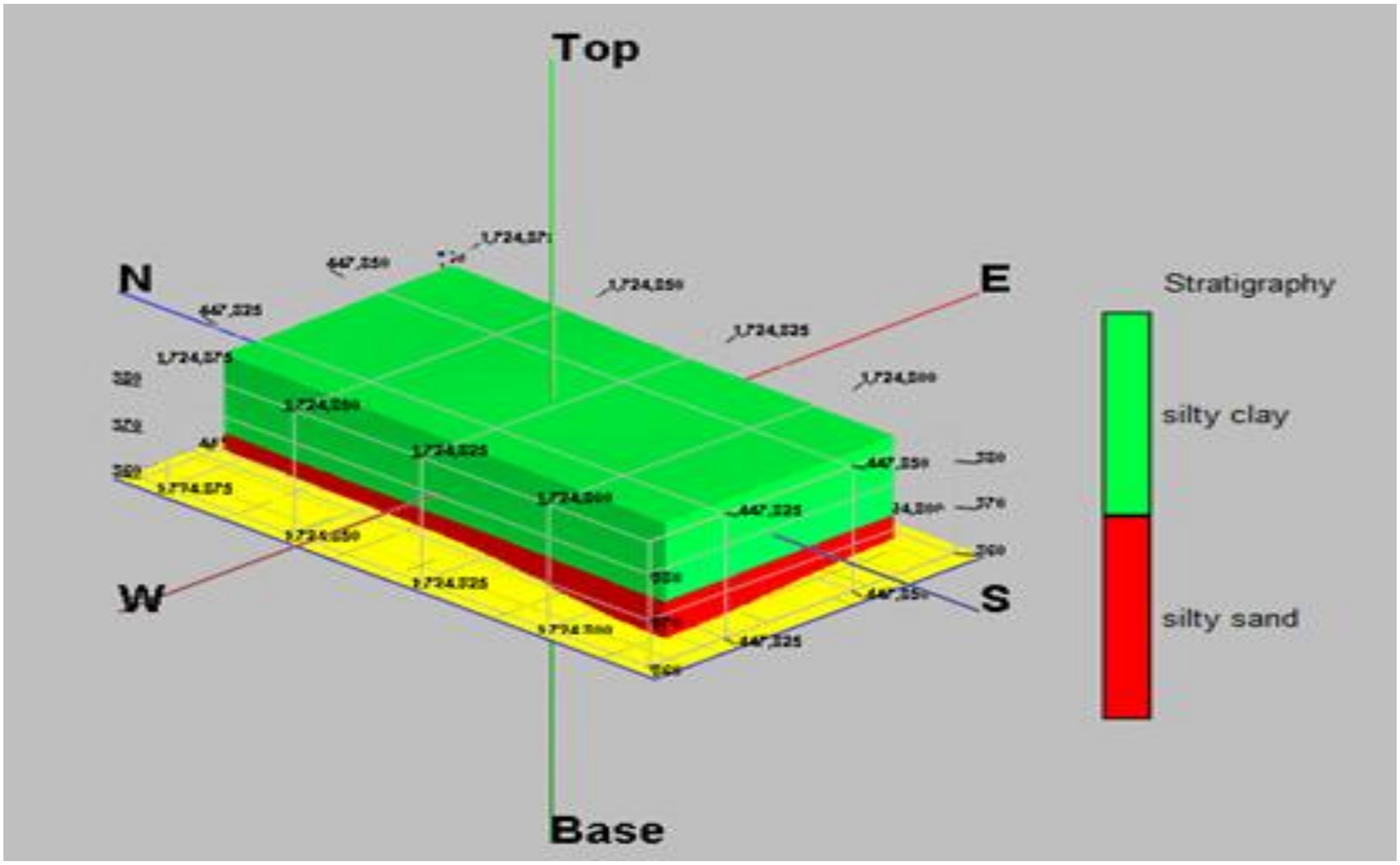

Figure 2. Three dimension model show the subsurface soils (Khartoum-Mogran area).

METHODOLOGY

The methods used to evaluate the characteristic of soil parameters consist of fieldwork and laboratory tests. The site investigation consists of drilling three bored holes, and conducting three Cone Penetration tests. For the laboratory testing (Physical and mechanical properties of) disturbed and undisturbed samples were used.

Three boreholes were drilled; two were drilled to 20 m depth and the third to 25 m deep. Undisturbed samples were collected from the cohesive soils by U_{100} sampler and Standard Penetration Test (SPT) was performed wherever there are difficulties to collect undisturbed samples. Whereas groundwater is observed at 6.5 m for all 3 bored holes mete below the ground level and expected to rise 2 m in autumn season.

Three Cone Penetration Tests (CPTs) were conducted to determine soil resistance. Cone resistance values between 184 and 13340 kN/m^2 were obtained which indicates a medium to very stiff clay soil. The boreholes reveal existance of alternating layers of low to high stiff plastic silty clay (CL to CH) and very low to high clayey silt (ML to MH) in the upper 17 m. This layer is underlained by very dense silty sand (SM or SP-SM) extended to 25 m end of the borehole (Figure 2). The CPT soundings close to the Borehole were conducted and used to predict the ultimate pile capacity. Statistical analyses were used to identify the most appropriate CPT method for predicting the ultimate capacity of the investigated piles. Schmertmann (1978) method for predicting the ultimate pile capacity by CPT was selected.

Schmertmann method

Schmertmann proposed the following relationship to predict the unit tip bearing capacity of the pile (q_t) from the cone tip resistance (*qc*):

$$q_t = \frac{q_{c1} + q_{c2}}{2} \quad (1)$$

Where q_{c1} is the minimum of the average cone tip resistances of zones ranging from *0.7D to 4D* and $q_{c2}$is the average of minimum cone tip resistances over a distance *8D* above the pile tip. Figure 3 shows the procedure.

According to Schmertmann's method, the unit skin friction of the pile (*f*) is given by:

$$Q_s = \alpha\left(\sum_{y-0}^{8D} \frac{y}{8D} f_s A_s + \sum_{y-8D}^{L} f_s A_s\right) \quad (2)$$

where $\alpha$is a reduction factor can be obtained from Figure 4, which varies from 0.2 to 1.25 for clayey soil, $f_s$is the sleeve friction, *y* is the depth at which side resistance is calculated, and *L* and *D* are the length and diameter of the pile respectively (Figure 4).

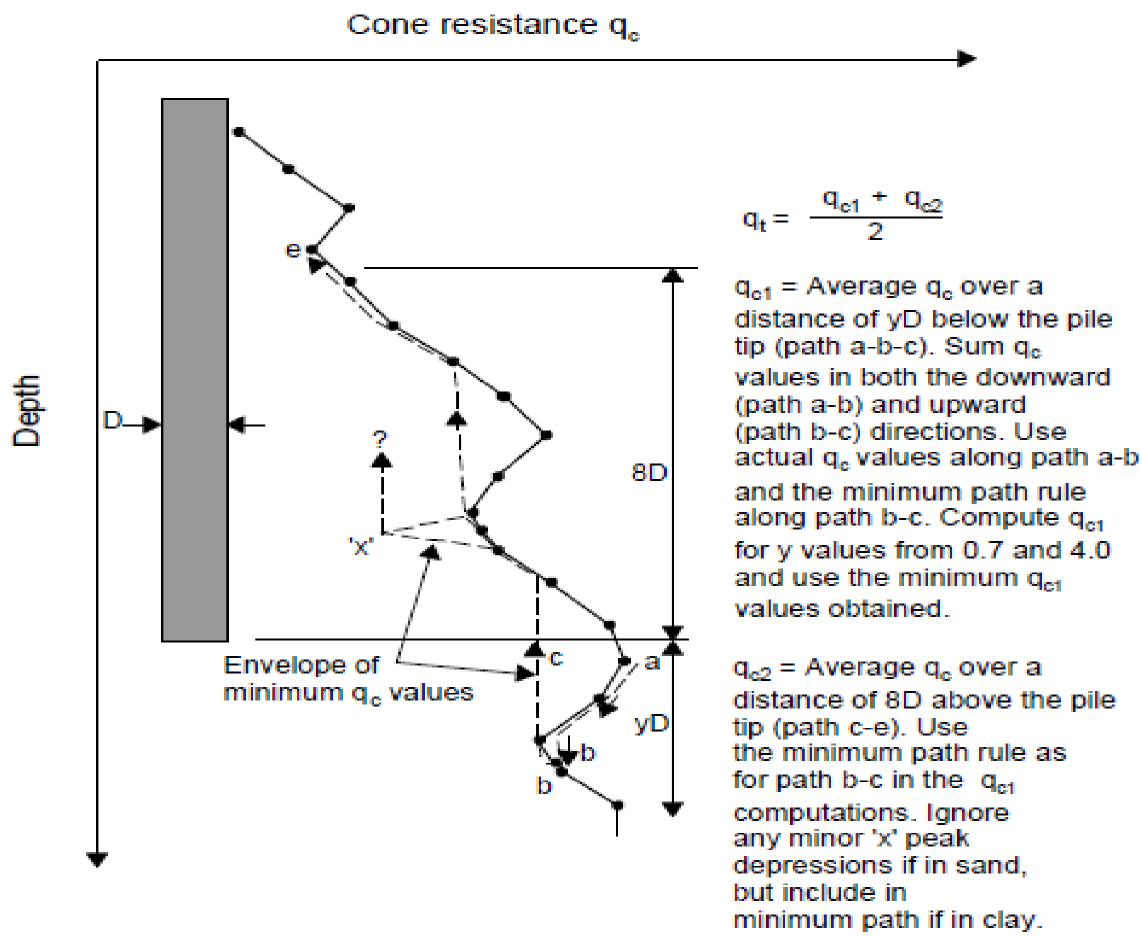

Figure 3. Calculation of the average cone tip resistance in Schmertmann method.

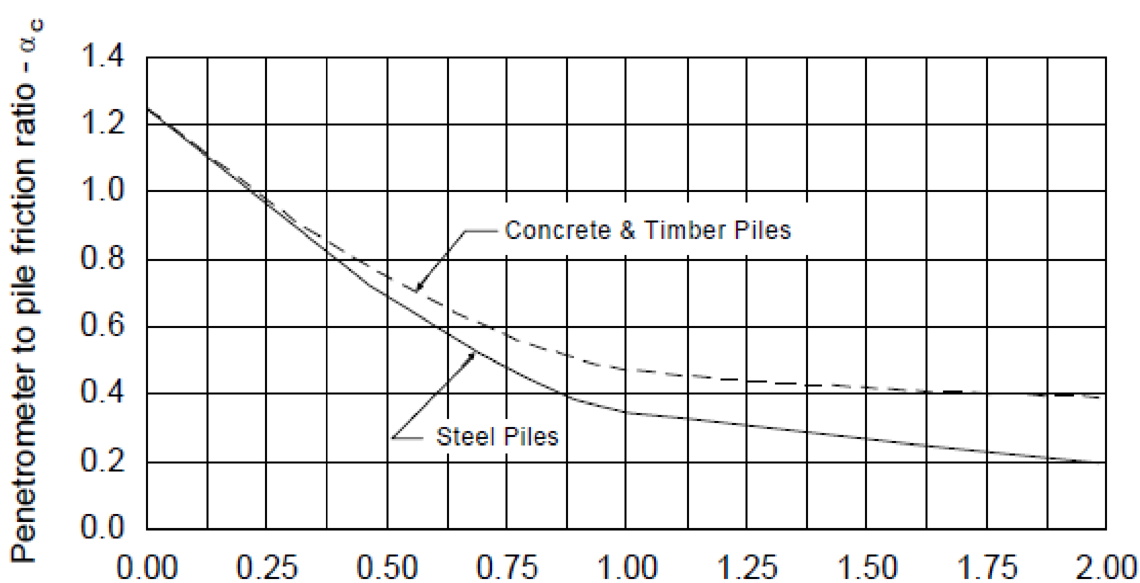

Figure 4. Penetrometer sleeve friction - f_s (kg/cm^2) Penetration design curves for pile side friction in clay of the Schmertmann method.

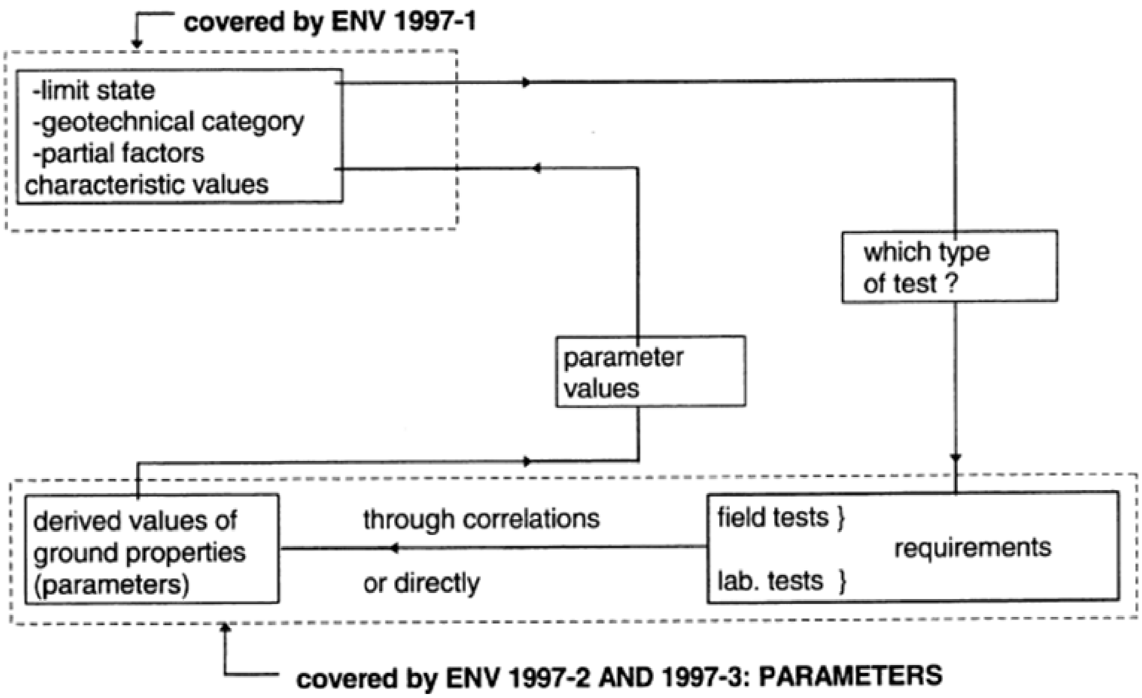

Figure 5. Flow chart demonstrates the link between design and field and laboratory tests.

RESULTS AND DISCUSSION

Pile design value from driving formulae

Eurocode 7 stated that if pile driving formulae are used to assess the ultimate compressive resistance of individual piles in a foundation, the validity of the formulae shall have been demonstrated by previous experimental evidence of acceptable performance *in* static load tests on the same type of pile, of similar length and cross section, and in similar ground conditions. Figure 5 shows flow chart demonstrates the link between design and field and laboratory tests.

Determination of pile compressive strength using EC7

Euro Code 7 approach 1 will be considered to determine the allowable bearing capacities of the piles and compare the result with those obtained from theoretical empirical calculation. The adhesion factor (0.99) proposed by Bowles (1984) will be used to determine the undrained shear strength for all piles.

Pile design value from EC7 approach 1 and 2

The design value of pile resistance using approach 1 will be obtained in two steps:

1. The characteristic compressive resistance of the ground.
2. The design resistance.

Characteristic value of material properties

EN 1990 defines the characteristic value of material property, X_k as " the value having a prescribed probability of not being attained in a hypothetical unlimited test series". This value can be obtained as follow:

$$X_k = \mu(X) - 1.645\sigma(X) \text{ or,} \quad (3)$$

$$= \mu(1 - 1.645V(X))$$

Where
$\mu(X)$ = mean value
$\sigma(X)$= standard deviation
$V(X)$ = Coefficient of variation

Equation 3 is applicable when the test results are normally distributed (Trevor et al., 2008) and it is applicable for structure design. In a geotechnical design the failure is much greater than the volume of soil. For

Table 2. Characteristic value of undrained shear strength.

Pile length		$\mu(C_u)$ kN/m^2	σ (C_u) kN/m^2	$C_{u,k}$ kN/m^2 using Equation 3	$C_{u,k}$ kN/m^2 using Equation 4
10	Shaft	41.6855	18.6928	10.94	32.5391
	Toe	65.13735	21.99638	28.953	50.66
12	Shaft	45.0866	18.68	14.36	35.7466
	Toe	64.1	21.7	28.4	53.25
14	Shaft	51.49251	24.04218	11.94	39.47
	Toe	73.0477	14.83276	48.65	65.63
16	Shaft	53.44633	22.93448	15.72	41.98
	Toe	73.0477	14.83276	24.4	65.63

Table 3. Partial factors in approach 1 according to Annex A of prEN 1997-1: 2001(E).

Set	Action or action effect			Ground parameter			Pile
	Permanent unfavorable	Permanent favorable	Variable	tan ϕ'	C'	Cu	Resistance
Set 2	1.0	1.0	1.3	1.25	1.25	1.25	1.3-1.6 (tanφ&c':1.0)
Set 1	1.35	1.0	1.5	1.0	1.0	1.0	1.0

geotechnical design the equation proposed by Schneider (1997) (Orr and Denys, 2008) is more applicable.

$$X_k = m(X) - 0.5s(X) \qquad (4)$$

Where $m(X)$ is mean $and s(X)$ standard deviation.

Following the above procedure the characteristic value of undraind shear strength is obtained for different piles as shown in Table 2.

Equation 3 which relate characteristic value of material property with mean value and standard deviation shows incorrect results, as those results are less than the lowest measure values, and characteristic around the pile toe is greater than the characteristic value around the pile shaft. Equation 4 shows reasonable result. This study totally agreed with others, Orr and Denys, (2010).

The compressive resistance is obtained as:

$$Qu = C_{ub}N_cA_b + \alpha C_uA_s \qquad (5)$$

Where

C_{ut}= Undrained cohesion at the pile toe

C_{us} = Average undrained cohesion along the pile shaft

N_c = Bearing capacity factor for deep foundation (usually is equally to 9)

α= Addison factor, for a single pile, the contact is between pile and soil; hence the adhesion factor is used

C_u = Undrained cohesion in the embedded length of pile.

A_b = Area of the pile toe.

A_s = Area of the pile shaft.

To assess the compressive resistance of a pile foundation from ground tests, the partial factors are mainly applied at the source as load and material factors. Table 3 indicates typical values as proposed in Annex A of prEN 1997-1: 2001(E).

Using the above partial factors the compressive resistances of ground for all pile imbedded in different lengths are obtained by applying partial factor to ground parameters. The design compressive resistance of a pile, $R_{c,d}$, is derived from

$$R_{c,d} = \frac{R_{bk}}{\gamma_b} + \frac{R_{sk}}{\gamma_s} \qquad (6)$$

Where

R_{bk} = characteristic value of base resistance.

R_{sk} = characteristic value of shaft resistance.

γ_b and γ_s partial factor obtained from Table 4.

The results for characteristic values and design values are shown in Table 5. The design value for bored and driven piles is shown in Figure 6.

Table 4. Partial factors.

Type of pile	Approach 1, set 2			Appr. 1, set 1			Approach 2
	γ_b	γ_s	γ_t	γ_b	γ_s	γ_t	$\gamma_b = \gamma_s = \gamma_t$
Driven piles	1.3	1.30	1.30	1.0	1.0	1.0	1.10
Bored piles	1.3	1.60	1.45	1.25	1.0	1.15	1.10
Continuous flight auger	1.3	1.45	1.35	1.10	1.0	1.10	1.10

Table 5. Characteristic and design value using EC7 approach1 set 2.

Pile length	Base characteristic value kN	Shaft characteristic value kN	Ultimate characteristic value kN	Bore pile design value kN	Driven pile design value kN
10	209.63	1037.3	1246.9	809.57	959.18
12	351	1346.6	1697.7	1111.7	1438
14	508	1793.9	2302.5	1512.4	1771.1
16	397.3	2129.8	2527.2	1636.8	1944

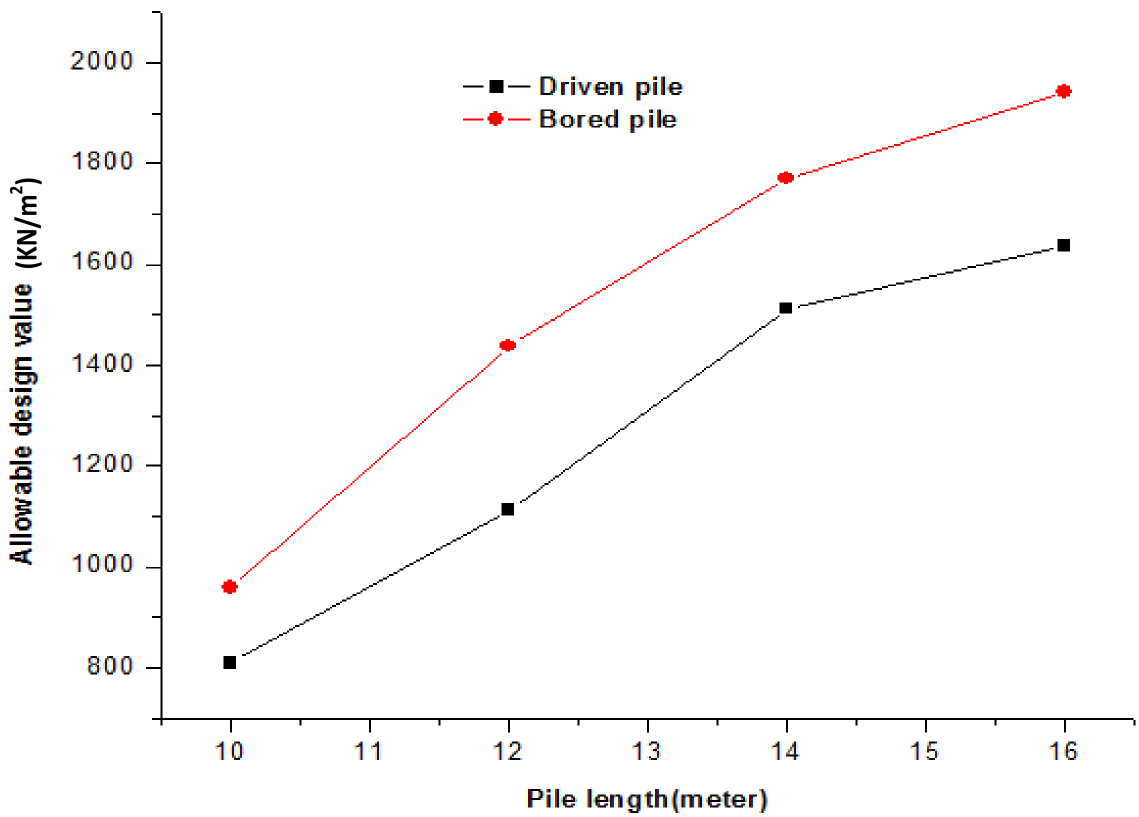

Figure 6. Design value for bored and driven piles using EC7.

As it is shown in Figure 6 at the same pile length, diameters and at the same soil and pile parameters, EC7 allows more design values for driven piles than bored piles. These differences in design values between driven and bored piles is because EC7 takes into account the installation procedure and in driven pile, installation adversely affects the pile bearing capacity.

In approach 2 the partial factors from Table 6 are applied to ground parameters to obtained the design value for resistance, whereas design value of the actions

Table 6. Partial factors in approach 2 according to Annex A of prEN 1997-1: 2001(E).

Effect of action			Ground parameter			Resistance
Permanent unfavorable	Permanent favorable	Variable	tan ϕ’	C'	Cu	
1.35	1.0	1.5	1.0	1.0	1.0	Factor>1

Table 7. Characteristic and design value using EC7 approach 2.

Pile length	Base characteristic value kN	Shaft characteristic value kN	Ultimate characteristic value kN	Pile design value kN
10	262	1296.6	1558.7	1417
12	438.9	1683.2	2122.1	1929.2
14	635.7	2242.4	2878.1	2616.4
16	493.9	2662.3	3156	2869.2

Table 8. Partial factors in approach 3 according to Annex A of prEN 1997-1: 2001(E).

Action from	Action or action effect			Ground parameters			Resistance
	permanent unfavorable	permanent favorable	variable	tan ϕ’	c’	cu	
The structure	1.35	1.00	1.50	1.25	1.25	1.4	1.0 (tan ϕ’,c’:1.25 ; cu : 1.40)
From or through the ground	1.0	1.00	1.30				

Table 9. Characteristic and design value using EC7 approach 3.

Pile length	Base characteristic value kN	Shaft characteristic value kN	Bore design value kN
10	209.6	926.2	1136
12	351.1	1202	1553
14	508	1602	2110
16	397.3	1902	2299

is obtained by multiplying their effects by the load factors (Table 3). Table 7 shows the result of calculation using EC7 approach 2.

Approach 3

In this approach the shear strength parameters are divided by partial factors and effect of load is multiply by load factor. Table 8 indicates typical values as proposed in Annex A of prEN 1997-1: 2001(E).

prEN1997 defines the characteristic value of a ground property or of a resistance as “a cautious estimate of the value affecting the occurrence of a limit state” and recommends: “If statistical methods are used, the characteristic value should be derived such that the calculated probability of a worse value governing the occurrence of a limit state is not greater than 5%”. Applying the partial factors to shear strength parameters, the design values of different piles consider in this study are determined and presented (Table 9).

Characteristic value of the pile resistance from Cone Penetration Test

Three CPTs were conducted to determine soil resistance, typical result from such a test are shown in Figure 7 and are given in the form of a plot showing the variation of the cone penetrations resistance with depth.

Three CPTs were conducted to determine soil resistance, the results of ultimate base resistance and ultimate shaft resistance are shown in Table 10.

The characteristic value of the pile compressive

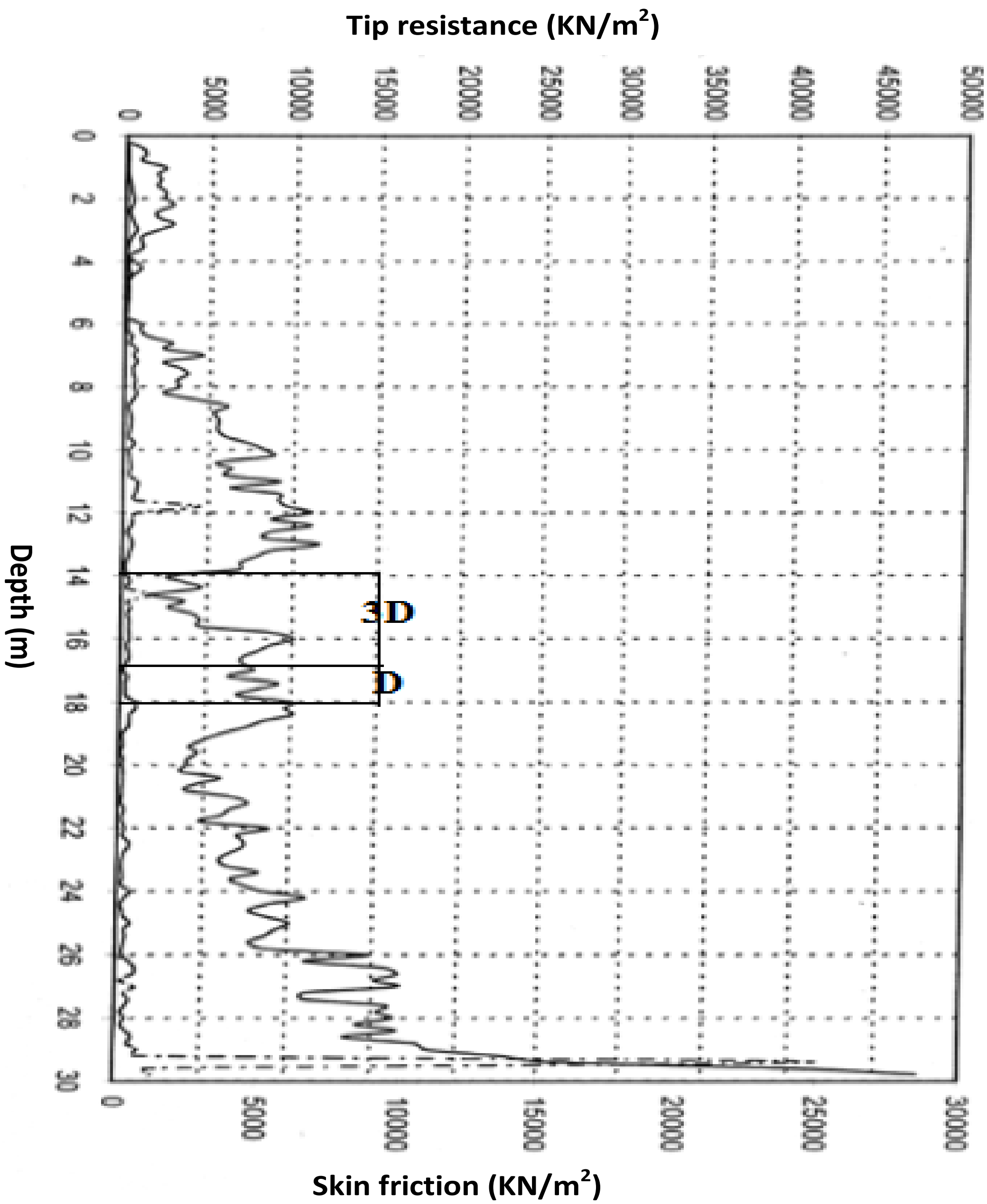

Figure 7. Variation of cone resistance with depth.

Table 10. Calculation results of predicted compressive resistance at each CPT.

CPT	$q_b\,(kN)$	$f_s(kN)$	$q_u\,(kN)$
1	1590	317	1907
2	1825	290	2115
2	1712	310	2022

resistance $R_{c,k}$ is obtained from the following equation according to EC7.

$$R_{c,k} = min\left\{\frac{(R_{c;m})mean}{\xi_3}, \frac{(R_{c;m})min}{\xi_4}\right\}: \qquad (7)$$

$(R_{c;m})$ mean: the mean value of the measured pile resistances;

$(R_{c;m})$ min: the lowest measured pile compressive resistance;

where ξ_3 and ξ_4 are correlation factors related to the number of piles tested and are applied to the mean $(R_{c;m})$ mean *and* the lowest $(R_{c;m})$min of $R_{c;m}$ respectively.

Table 11. Values of ξ3 and ξ4 for ground test results.

Number of tested profiles	1	2	3	4	5	7	10	20
ξ_3 applied to the mean	1.40	1.35	1.33	1.31	1.29	1.27	1.25	1.20
ξ_4, applied to the lowest	1.40	1.27	1.23	1.20	1.15	1.12	1.08	1.00

Table 12. Partial factors for approaches 1 and 2 for different types of piles according to prEN 1997-1:2001(E).

Type of pile	Approach 1, set 2			Appr. 1, set 1			Approach 2
	γ_b	γ_s	γ_t	γ_b	γ_s	γ_t	$\gamma_b = \gamma_s = \gamma_t$
Driven piles	1.3	1.30	1.30	1.0	1.0	1.0	1.10
Bored piles	1.3	1.60	1.45	1.25	1.0	1.15	1.10
Continuous flight auger	1.3	1.45	1.35	1.10	1.0	1.10	1.10

(Table 11) indicates values of $\xi 3$ and $\xi 4$ proposed in prEN 1997-1: 2001(E);

The mean value out of three test result is 2014,7 kN and the minimum value is 1590 kN. Applying the criteria recommended by EC 7, the factor (ξ3 =1.23) will apply to minimum value and (ξ4 =1.33) applying to the mean value the following result is obtained - minimum, 1907/1.23 = 1550.4 kN and the mean, 2014, 7/1.33 = 1514.8kN.

According to EC 7 procedure the mean value will govern the design and if the stiffness of the structure is accounted, the mean value 1514.8 may be multiplied by the coefficient 1.1 and the characteristic value becomes 1514.8 × 1.1 = 1666.28kN.

Pile design value

The design value of pile will be obtained from the characteristic value using the following equation (Smith 2006).

$$R_{\mathrm{c,d}} = \frac{R_{ck}}{\gamma_t} \qquad (8)$$

Where

$R_{\mathrm{c,d}}$ is design value of pile resistance.

R_{ck} is characteristic value of pile resistance.

γ_t is partial factors as proposed in prENV 1997-1:2001(E) and are indicated in Table 12.

The results of pile design value for bored pile using EC 7 approach 1 set 1 and approach 1 set 2 and approach 2 is shown in Table 13.

Determination of number of piles

To determine the numbers of pile using different EC7 approaches and German Code using safety factor equal to 2, a hypothetical permanent load Q_p = 11713 kN, variable load Q_v = 2303 is supposed to be carried by the pile foundation.

Table 13. Pile design values using EC7.

Design approach	Pile design value kN
Approach 1 set 1	1448.2
Approach 1 set 2	1149.2
Approach2	1514.8

Load design value

For EC7 approach 1 set 1 permanent and variable load is multiplied by the factors 1.35 and 1.5 respectively. Approach 1 set 2 permanent and variable load is multiplied by the factors 1.0 and 1.3, where as for approach 2, 1.35 and 1.5 is used. Table 14 shows the results of numbers of pile and safety factor.

Conclusion

The study shows that for the same load applied, a reduction of 24% of number of piles is achieved when EC7 is use for pile foundation design compare with traditional German code taking global safety factor equal to two. This result reveals that EC7 is one of the most economical codes in calculation and the design equations.

The core in EC7 is the design load (E_d) must be less than or equal to the corresponding design resistance (R_d), this relation provides no measure of the

Table 14. Number of piles and safety factor using different codes.

Type of code	Load design value	Numbers of piles	(R_d/E_d)>1
approach 1 set 1	(11713 * 1.35) + (2403 * 1.5) = 19417	(19417/1448.2)= 13.41~14	(1448.2*14)/19417= 1.044 $E_d \leq R_d$ » safe
approach 1 set 2	(11713 *1) + (2403 * 1.3) = 14836.9	14836.9/1149.2=12.9 ~13	(1149.2*13)/14836.9= 1.01 $E_d \leq R_d$ » safe
approach2	(11713 * 1.35) + (2403 * 1.5) = 19417	19417/1514.8 = 12. 8 ~13	(1514.8*13)/ 19417 = 1.014 $E_d \leq R_d$ » safe
German tradition code using global safety factor	11713 + 2403 =14116	14116/795 = 17.8 ~ 18	2 (minimum safety factor) Safe

degree of over-design, as it is seen in this study the $(R_d/E_d) >$ 1.01 is accepted and the design is considered save. This safety factor cannot be accepted by many clients. Therefore amendments must be done to restrict minimum safety factor.

REFERENCES

Bauduin CB (2002). Design of axially loaded compression piles according to Euro Code 7. Proceedings - Ninth International Conference on Piling and Deep Foundations, 2002, Nice, France, (DFI).

Bowles JE (1984). Physical and Geotechnical properties of soil. McGraw-Hill book. Japan.

European Norm (EN 1990). Basis of structural design. Management Centre: rue de Stassart, 36 B-1050 Brussels.

Orr TLL, Denys B (2008). Eurocode 7 and reliability-based design. Reliability-based design in geotechnical engineering computations and applications. Taylor Francis, London and New York, p. 298.

Orr TLL, Denys B (2010). The concepts of Eurocode 7for harmonized geotechnical design in Europe. Politechnika Wrocławska Studia Doktoranckie.

pREN 1997-1 (2001) Geotechnical Design – Part 1: General Rules. European Committee for Standardization, Brussels.

Schmertmann JH (1978). Guidelines for Cone Penetration Test, Performance and Design. U.S. Department of Transportation, Report No. FHWA-TS-78-209, Washington, D.C., p. 145.

Smith CC, Gilbert M (2010). Ultimate Limit State design to Eurocode 7 using numerical methods. In Proc. 7th European Conference in Numerical Methods in Geotechnical Engineering, Trondheim, pp.947-952.

Smith I (2006). Smith's Elements of Soil Mechanics. Blackwell Publishing Company, USA.