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Design of pile foundations following Eurocode 7

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ABSTRACT
After a short introduction about the programme of 'Structural Eurocodes', the two parts of Eurocode 7 on 'Geotechnical Design' are presented, namely 'Part 1: General rules' (EN 1997-1) and 'Part 2 : Ground investigation and testing' (EN 1997-2). The provisions and requirements of Eurocode 7 for the design of pile foundations are reviewed and commented upon (Section 7 of EN 1997-1). Finally, two design examples of piles under axial loads are given, one from ground test results and one from pile load test results.

Keywords: Eurocode 7, soil-structure interaction, pile, bearing capacity, compressive resistance, tensile resistance, pile settlement, ultimate limit state, serviceability limit state, partial factors of safety

1 INTRODUCTION : THE EUROCODE PROGRAMME

The Structural Eurocodes are design codes for buildings, bridges and other civil engineering structures. They are based on the Limit State Design (LSD) approach used in conjunction with a partial factor method. They consist of 10 sets of standards : 'Eurocode: Basis of structural design' (EN 1990) and Eurocodes 1 to 9 (EN 1991 to EN 1999; EN is for 'European Norm')

Eurocodes 2, 3, 4, 5, 6 and 9 are 'material' Eurocodes, i.e. relevant to a given material (reinforced concrete, steel, etc.). EN 1990 (Basis of design), Eurocode 1 (Actions), Eurocode 7 (Geotechnical design) and Eurocode 8 (Earthquake resistance) are relevant to all types of construction, whatever the material.

Eurocode 7 should be used for all the problems of interaction of structures with the ground (soils and rocks), through foundations or retaining structures. It allows the calculation of the geotechnical actions on the structures, as well the resistances of the ground. It also gives all the prescriptions and rules of good practice for conducting the geotechnical part of a structural project or, more generally speaking, a purely geotechnical project.

The development of Eurocode 7 has been strongly linked to the development of EN 1990: 'Eurocode: Basis of structural design' (CEN, 2002) and the format for verifying ground-structure interaction problems is, of course, common to both documents.

After giving the main contents of Eurocode 7, this contribution summarises the requirements relevant to pile design (without recalling the principles of LSD and of the partial factor method), and describes two design examples of piles under vertical compressive loadings taken from the recent workshop of ERTC 10 on the evaluation of Eurocode 7 (Orr, 2005; Frank, 2005).

2 CONTENTS OF EUROCODE 7

Eurocode 7 consists of two parts:
EN 1997-1 Geotechnical design – Part 1: General rules (CEN, 2004);
EN 1997-2 Geotechnical design – Part 2: Ground investigation and testing (CEN, 2005a).

2.1 *Part 1: General rules*

Eurocode 7 - Part 1: 'General rules' is a rather general document giving only the principles for geotechnical design inside the general framework of LSD. These principles are relevant to the calculation of the geotechnical actions on the structural elements in contact with the ground (footings, piles, basement walls, etc.), as well as to the deformations and resistances of the ground submitted to the actions from the structures. Some detailed design rules or calculation models, i.e. precise formulae or charts are only given in informative Annexes.

Eurocode 7 – Part 1 includes the following sections (CEN, 2004) :

Section 1 General
Section 2 Basis of geotechnical design
Section 3 Geotechnical data
Section 4 Supervision of construction, monitoring and maintenance
Section 5 Fill, dewatering, ground improvement and reinforcement
Section 6 Spread foundations
Section 7 Pile foundations
Section 8 Anchorages
Section 9 Retaining structures
Section 10 Hydraulic failure
Section 11 Overall stability
Section 12 Embankments

A number of Annexes are included. They are all informative, except Annex A which is 'normative' (i.e. mandatory). They are the following :

Annex A (normative) Partial and correlation factors for ultimate limit states and recommended values

Annex B Background information on partial factors for Design Approaches 1, 2 3

Annex C Sample procedures to determine limit values of earth pressures on vertical walls

Annex D A sample analytical method for bearing resistance calculation

Annex E A sample semi-empirical method for bearing resistance estimation

Annex F Sample methods for settlement evaluation

Annex G A sample method for deriving presumed bearing resistance for spread foundations on rock

Annex H Limiting values of structural deformation and foundation movement

Annex J Checklist for construction supervision and performance monitoring

Annex A is important, as it gives the partial factors for ULS in persistent and transient design situations ('fundamental combinations'), as well as correlation factors for the characteristic values of pile bearing capacity (see below). But the numerical values for the partial or correlation factors given in Annex A are only recommended values. These values can be changed in the National Annex to EN 1990-1, which is published by each country. All other Annexes are informative (i.e. not mandatory in the normative sense). Some of them, though, contain valuable material which can be accepted, in the near future, by most of the countries.

2.2 *Part 2: Ground investigation and testing*

Part 2 of Eurocode 7 makes the link between the design requirements of Part 1, in particular Section 3 ‘Geotechnical data’, and the results of a number of laboratory and field tests.

It does not cover the standardisation of the geotechnical tests themselves. Test standards for geotechnical design are presently being published by the Technical Committee 341 of CEN (TC 341) on 'Geotechnical investigation and testing' . In this respect the role of Part 2 of Eurocode 7 is to ‘use’ and refer to the detailed rules for test standards covered by TC 341.

Eurocode 7 – Part 2 includes the following Sections (CEN, 2004b) :

Section 1 – General
Section 2 – Planning of ground investigations
Section 3 – Soil and rock sampling and groundwater measurements
Section 4 – Field tests in soil and rock
Section 5 – Laboratory tests on soil and rock
Section 6 – Ground investigation report

The Section on field tests in soil and rock includes cone and piezocone penetration tests CPT(U), pressuremeter tests PMT, flexible dilatometer test (rock and soil) FDT, standard penetration test SPT, dynamic probing tests DP, weight sounding test WST, field vane test FVT, flat dilatometer test DMT and plate loading test PLT.

The Section on laboratory testing of soils and rocks deals with the preparation of soil and rock specimens for testing, tests for classification, identification and description of soil, chemical testing of soil and groundwater, strength index testing of soil, strength testing of soil, compressibility and deformation testing of soil, compaction testing of soil, permeability testing of soil, tests for classification of rocks, swelling testing of rock material and strength testing of rock material.

Part 2 also includes a number of informative Annexes with examples of correlations and derivations of values of geotechnical parameters from field test results. The informative Annexes D.6 & D.7, for CPT tests, and E.3, for PMT tests, are such examples for determining the compressive resistance of a single pile.

As is the case in Part 1, most of the derivations or calculation models given are informative, but there is also fairly good agreement about using them in the future throughout Europe.

3 SUMMARY OF SECTION 7 ON 'PILE FONDATIONS'

The core of Section 7 of EN 1997-1 is devoted to the behaviour of pile foundations under axial (vertical) loads. The importance of static load tests is clearly recognised as the basis of pile design methods. An innovative concept introduced in this section, with regard to traditional pile design, is the use of correlation factors ξ for deriving the characteristic compressive and tensile resistances of piles either from static pile load tests or from ground test results. In both cases, the correlation factor ξ depends mainly on the number of tests performed, whether pile load tests or profiles of ground tests.

The general requirements of EN 1997-1 for ultimate limit states are given in clauses 2.4.7.3.4.2(2)P for *Design Approach 1*, 2.4.7.3.4.3(1)P for *DA 2* and 2.4.7.3.4.4(1)P for *DA 3*. The corresponding recommended values of the partial factors γ are given in Table A.3 for the *actions or effects of actions* (γ_F or γ_E), Table A.4 for the *ground parameters* (γ_M), Tables A.6 through A.8 for the *resistances* for piles (γ_R) and Tables A.9 through A.11 for the correlations factors ξ for piles (see Tables 1 to 5 below).

In Section 7, clause 7.6.2.2 applies to the '*Ultimate compressive resistance from static load tests*', clause 7.6.2.3 applies to the '*Ultimate compressive resistance from ground test results*', in particular, clause 7.6.2.3(5)P and Equation 7.8 for the '*model pile*' method, and clause 7.6.2.3(8) for the '*alternative*' method, clause 7.6.4 deals with the vertical displacements of pile foundation (Serviceability of supported structures) and clause 7.7 deals with '*Transversely loaded piles*'. These clauses are summarized below. More detailed comments are given in the Designers' Guide by Frank et al. (2004).

3.1 *Limit states and specific actions*

A number of limit states need to be considered.

Ultimate limit states (ULS)

- overall stability
- bearing resistance failure, uplift or tensile resistance failure, and transverse failure in the ground
- structural failure of the pile in compression, tension, bending, buckling or shear
- excessive settlement, heave and lateral movement

Serviceability limit states (SLS)

- excessive settlement, heave and lateral movement
- vibrations

The actions caused by ground movements are very specific to pile foundations. The following typical actions to be considered are:

- downdrag (negative friction)
- heave
- transverse loading.

Eurocode 7 requires to apply calculation methods for which the ground displacement is treated as an action and an interaction analysis is carried out, or for which an upper bound of the force transmitted to the pile is introduced as the design action.

For most of the calculation methods, "*the design values of the strength and stiffness of the moving ground should usually be upper values*".

3.2 *The role of pile load tests*

The methods accepted by Eurocode 7 for the design of piles must nearly all be based, directly or indirectly, on the results of static pile load tests. The document clearly states that :

"*The design shall be based on* […] :

- *the results of static load tests,* […]
- *empirical or analytical calculation methods whose validity has been demonstrated by static load tests* […]
- *the results of dynamic load tests whose validity has been demonstrated by static load tests*[…]
- *the observed performance of a comparable pile foundation, provided that this approach is supported by the results of site investigation and ground testing.*"

Pile load tests

Pile load tests shall be carried out :

- when using a new type of pile or installation method;
- when there is no comparable soil and loading conditions;
- theory and experience do not provide sufficient confidence in the design;

- installation indicate pile behaviour that deviates from the anticipated behaviour and additional ground investigations do not clarify the reasons.

The static pile load test procedure "*shall be such that conclusions can be drawn about*

- *the deformation behaviour*
- *creep*
- *and rebound […]*"
- ultimate failure load, for trial piles.

For tension piles, the tests should be carried out to failure.

About loading procedures, EN 1997-1 mentions, in a note, the method suggested by ISSMGE (1985). A European standard for the static load tests in compression has recently been drafted by CEN /TC 250 and is presently at the enquiry stage (CEN 2005b).

"*Dynamic load tests may be used to estimate the compressive resistance provided:*

- *an adequate site investigation has been carried out*
- *and the method has been calibrated against static load tests on the same type of pile, of similar length and cross-section, and in comparable soil conditions.*"

3.3 *Check of axially loaded piles-general*

The following limit states are to be considered:

- "*ULS of compressive or tensile resistance failure of a single pile;*
- *ULS of compressive or tensile resistance failure of the pile foundation as a whole;*
- *ULS of collapse or severe damage to a supported structure by excessive displacement or differential displacements of the pile foundation;*
- *SLS in the supported structure by displacements of the piles.*"

For piles in groups, two failure mechanisms should be taken into account :

- compressive or pull-out resistance failure of the piles individually
- compressive or pull-out resistance failure of the piles and the soil contained between them acting as a block.

3.4 *ULS compressive or tensile resistance failure*

The basic equations and conditions of Eurocode 7 - Part 1 for checking ultimate compressive or tensile resistance are presented below in a synthetic manner.

The characteristic value of the compressive or tensile resistance R_k is obtained from the values R (measured value(s)R_m or calculated value(s) R_{cal}):

$$R_k = R / \xi \qquad (1)$$

where ξ is the correlation factor. The recommended values for ξ are given in:

- Table 1 for the design from static pile load test results
- Table 2 for the design from ground test results
- Table 3 for the design from dynamic load tests (compressive resistance only).

The design values R_d are then obtained from

$$R_d = R_k/\gamma_t \quad \text{or} \quad R_d = R_{bk}/\gamma_b + R_{sk}/\gamma_s \qquad (2)$$

where γ_t , or γ_b and γ_s, are the partial resistance factors (γ_R) for the total resistance R_k, or for the base and shaft resistances R_{bk} and R_{sk} , respectively. Their recommended values are given in Table 4 (for piles in tension R_{bk} = 0 and $\gamma_{st} > \gamma_s$ is recommended).

On the other hand the design value of the applied compression/tension load F_d is:

$$F_d = \gamma_F F_k \qquad (3)$$

where F_k is the characteristic value of the applied load(s) and γ_F is the partial factor on actions (or effects of actions), given in Table 5 for permanent and transient design situations ($\gamma_F F_k$ in (3) represents several actions, if appropriate). For accidental design situations, all γ_F = 1.0.

The basic condition for ULS being :

$$F_d \leq R_d \qquad (4)$$

equations (1) to (4) lead to :

$$F_k \leq R / \gamma_F.\gamma_t.\xi = R / FS \qquad (5)$$

where FS = $\gamma_F.\gamma_t.\xi$ is analogous to the traditional overall factor of safety (it is understood that γ_F can represent several values and γ_t can be replaced by γ_b and γ_s where relevant).

3.5 *Values of correlations factors ξ and partial factors γ*

All values given in Annex A (normative) of EN 1997-1 are recommended values. They can be changed in the National Annex.

When designing piles from static load tests, the following equation should be used:

$$R_k = \text{Min} \{ R_{m,mean} / \xi_1 \,;\, R_{m,min} / \xi_2 \} \qquad (6)$$

where R_m is (are) the measured resistance(s) and $\xi = \xi_1$ on the mean value and $\xi = \xi_2$ on the minimum value, function of the number of pile test(s) *n*, are given in Table 1.

Table 1.Recommended values for the correlation factors ξ for R_k from *n* – static pile load tests (*Table A.9* of *Annex A* in EN 1997-1)

ξ for *n* =	1	2	3	4	≥ 5
ξ_1	1,40	1,30	1,20	1,10	1,00
ξ_2	1,40	1,20	1,05	1,00	1,00
For piles in compression, if transfer from "weak" to "strong" piles is possible, these values may be divided by 1,1, provided $\xi_1 \geq 1.0$					

When using calculation rules and ground test results, the following equations applies:

$$R_k = R_{bk} + R_{sk}$$
$$= (R_{b,cal} + R_{s,cal}) / \xi = R_{cal}/\xi$$
$$= \text{Min} \{ R_{cal,mean} / \xi_3 \,;\, R_{cal,min} / \xi_4 \} \qquad (7)$$

where $\xi = \xi_3$ on the mean value and $\xi = \xi_4$ on the minimum value, function of the number of soil test profile(s) *n*, are given in Table 2 and R_{cal} is(are) the calculated value(s) of the resistance from ground test results.

Table 2. Recommended values for the correlation factors ξ for R_k from *n* – soil test profiles (*Table A.10* of *Annex A* in EN 1997-1)

ξ for *n*=	1	2	3	4	5	7	10
ξ_3	1,40	1,35	1,33	1,31	1,29	1,27	1,25
ξ_4	1,40	1,27	1,23	1,20	1,15	1,12	1,08
For piles in compression, if transfer from "weak" to "strong" piles is possible, these values may be divided by 1,1, provided $\xi_3 \geq 1.0$							

This procedure is often referred to as the 'model pile' procedure (Frank et al., 2004), because it requires the resistance to be calculated for each soil profile, whatever the pile locations in the final project.

When designing from ground test results an alternative procedure is allowed. It corresponds to the traditional practice in many countries of Europe. In consist in determining directly the characteristic values of base resistance and shaft friction q_{bk} and q_{sik} from the values of ground parameters, using the equations or charts of the relevant calculation method. Then

$$R_{bk} = q_{bk} A_b \text{ and } R_{sk} = \sum q_{sik} A_{si} \qquad (8)$$

where A_b and A_{si} are the pile base area and shaft surface in layer *i* respectively.

The code does not specify if characteristic values of the ground parameters, or more 'traditional' values should be used in this alternative procedure. On the other hand, it mentions, in a note, that if it is used "*the values of the partial factors γ_b and γ_s recommended in Annex A may need to be corrected by a model factor larger than 1,0. The value of the model factor may be set by the National Annex*". This is because in this procedure, no correlation factor ξ is explicitly applied.

The compressive resistance can also be determined from dynamic load tests:

- either by dynamic impact tests, or
- by applying pile driving formulae, or
- from wave equation analysis.

Note also that the code requires that re-riving results must be taken into account

The equation for R_k becomes :

$$R_k = \text{Min} \{ R_{m,mean} / \xi_5 \,;\, R_{m,min} / \xi_6 \} \qquad (9)$$

where R_m are the measured resistances and $\xi = \xi_5$ on the mean value and $\xi = \xi_6$ on the minimum value, function of the number of pile test(s) *n*, are given in Table 3.

Partial factors γ for resistances and for actions

For checking ULS in persistent and transient design situations, three Design Approaches are proposed by Eurocode 7 – Part 1 (CEN, 2004): DA 1, for which 2 different combinations of actions must be checked, DA 2 and DA 3.

The corresponding partial factors γ_t, or γ_b and γ_s, for the resistances and γ_F for the actions are given in Tables 4 and 5, respectively.

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Table 3. Recommended values for ξ factors for R_k from dynamic impact tests [1,2,3,4,5] from *n* – number of pile load tests (*Table A.11* of *Annex A* in EN 1997-1)

ξ for n=	**≥ 2**	**≥ 5**	**≥ 10**	**≥ 15**	**≥ 20**
ξ_5	1,60	1,50	1,45	1,42	1,40
ξ_6	1.50	1,35	1,30	1,25	1,25

[1] The ξ-values in the table are valid for dynamic impact tests. [2] The ξ-values may be multiplied with a model factor of 0,85 when using dynamic impact tests with signal matching. [3] The ξ- values should be multiplied with a model factor of 1,10 when using a pile driving formula with measurement of the quasi-elastic pile head displacement during the impact. [4] The ξ -values shall be multiplied with a model factor of 1,20 when using a pile driving formula without measurement of the quasi-elastic pile head displacement during the impact. [5] If different piles exist in the foundation, groups of similar piles should be considered separately when selecting the *n* of test piles.

Table 4. ULS, permanent and transient design situations - Recommended values for γ_b , or γ_s and γ_t (from *Tables A.6, A.7* and *A.8* of *Annex A* in EN 1997-1)

	Design Approach 1						DA 2	DA3*
	Combination 1			Combination 2				
Type of pile	γ_b	γ_s	γ_t	γ_b	γ_s	γ_t	$\gamma_b=\gamma_s=\gamma_t$	$\gamma_b=\gamma_s=\gamma_t$
Compression								
Driven	1.0	1.0	1.0	1.3	1.3	1.3	1.1	1.0
Bored	1.25	1.0	1.15	1.6	1.3	1.5	1.1	1.0
CFA	1.1	1.0	1.1	1.45	1.3	1.4	1.1	1.0
Tension								
γ_{st}		1,25			1,6		1,15	1,1

* for D.A 3 : partial coefficients are applied to soil parameters. DA 3 is not applicable when the resistance is derived from pile load tests.

Table 5. ULS, permanent and transient design situations - Recommended values for γ_F on actions or effects of actions (from *Table A.3* of *Annex A* in EN 1997-1)

Action		**DA1-1 (B)**	**DA1-2 (C)** *	**DA2**	**DA3 ****
Perma-nent	unfavour-able γ_G	1,35	1,0	1,35	1,35
	favourable	1,0	1,0	1,0	1,0
Variable	Unfavour-able γ_Q	1,5	1,3	1,5	1,5
	favourable	0	0	0	0

* the partial factors are applied to the ground strength parameters.
** values for structural actions only ; for geotechnical actions, the partial factors are applied to the ground strength parameters.

For ULS in accidental design situations, all values of γ_F are taken equal to 1.0 and the values of the partial factors on resistances γ_t, or γ_b and γ_s, depend on the particular circumstances of the accidental situation and can be set by the National Annex.

3.6 *Vertical displacements of pile foundations: serviceability of the supported structure*

Displacements under serviceability limit state conditions should be assessed and checked against limiting values.

For piles in compression, account should be taken of downdrag where probable and of group settlement. For piles in tension, the upward displacements are also checked accordingly.

3.7 *Design of transversely loaded piles*

The clauses of EN 1997-1 for the design of transversely loaded piles correspond to the commonly accepted practice. They can be summarised as follows.

For all ULS, the design value of the transverse resistance $R_{tr,d}$ must be such that:

$$F_{tr,d} \leq R_{tr,d} \qquad (10)$$

where $F_{tr,d}$ is the design value of the applied transverse loads.

Eurocode 7 –Part 1 then states that

“*One of the following failure mechanisms should be considered:*

- for short piles, rotation or translation as a rigid body;

- for long slender piles, bending failure of the pile, accompanied by local yielding and displacement of the soil near the top of the pile.”

The transverse load resistance R_{tr} can be determined:

- from pile load tests;
- from ground test results and pile strength parameters. The beam theory with the subgrade reaction modulus may be used.

The assessment of the transverse displacement should take account should of :

- the non-linear ground stiffness;
- the flexural stiffness of the piles;
- the fixity conditions with the structure;
- the group effect;
- the effect of load reversals or of cyclic loading.

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4 DESIGN EXAMPLES

The two following examples of piles under vertical compressive loadings are taken from the recent workshop of ERTC 10 on the evaluation of Eurocode 7.

4.1 *Pile design from ground test results*

The design example is defined in Figure 1 and Table 6 (Orr, 2005).

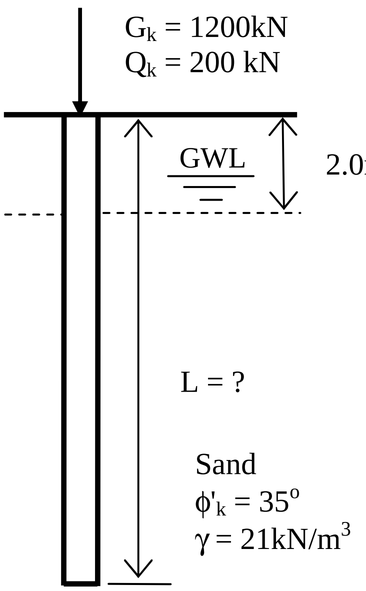

Figure 1. Data for example of pile design from ground test results (Example 3 of ERTC10-WP2 Workshop)

Table 6. Data for example of pile design from ground test results

Pile Foundation designed from soil parameter values

- **Design situation**
  - Bored pile for a building, 600mm diameter
  - Groundwater level at depth of 2m below the ground surface
- **Soil conditions**
  - Sand: $c'_k = 0$, $\phi'_k = 35^o$, $\gamma = 21kN/m^3$
    SPT N = 25
- **Actions**
  - Characteristic permanent load G_k = 1200kN
  - Characteristic variable load Q_k = 200kN
  - Weight density of concrete = $24kN/m^3$
- **Require**
  - Pile length, L

On the basis of the SPT value N = 25, the following base, shaft and total resistances are calculated from correlations with PMT results and corresponding semi-empirical design rules used in France (Frank, 2005) :

a) The unit *base resistance* is

q_b = 1.37 MPa

The total base resistance is :

$R_{b,cal} = \pi(D^2/4)q_p$ =3.14x(0.36/4)x1.37= 387 kN

b) The unit *shaft friction* at all depths z is :

q_s = 70 kPa

The total shaft friction is (D = 0.6 m is the pile diameter) :

$R_{s,cal} = \pi D \int q_s dz$ =1.885x70 L=132L(*in kN and m*)

c) The total *compressive resistance* is :

$R_{cal} = R_{b,cal} + R_{s,cal}$ = 387 + 132 L (*in kN and m*)

Eurocode 7 - Part 1 (EN 1997-1, 2004) requires checking ultimate and serviceability limit states. In this example, as no limitation is set on the settlement of the pile, nor any accidental action is to be taken into account, the following is restricted to ULS for persistent and transient design situations.

In the case of ultimate limit states (ULS) for persistent and transient design situations, Design Approaches 1 or 2 may be used. Design Approach 3 is not relevant to semi-empirical models like the one used here, as DA 3 means using 'material' factors $\gamma_M > 1.0$ (i.e. factoring 'at the source' the parameters of shearing resistance and not the base and shaft resistances themselves, hence $\gamma_b = 1.0$ and $\gamma_s = 1.0$); these models use, on the contrary, $\gamma_M = 1.0$, together with $\gamma_b \geq 1.0$ and $\gamma_s \geq 1.0$).

For Design Approaches 1 and 2, the 'alternative' procedure, described in 3.4 and equation (8), has to be used because only the soil parameter values are given, with no indication of the number of soil profiles (the 'model pile' procedure cannot be applied).

In the following two different assumptions will be made:

A. q_s and q_b calculated above can be considered to be characteristic values in the sense of equation (7), because they are derived from a cautious estimate of N and some conservatism has been input in the calculation rules. Therefore, it is believed that the recommended values of *Annex A* of EN 1997-1 are applicable, without recourse to a resistance model factor larger than 1.0;

B. q_s and q_b calculated above cannot be considered to be characteristic values in the sense of equation (7), because they are derived from N values which are not meant to be cautious and no

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real conservatism has been input in the calculation rules. Therefore, it is believed that the recommended values of *Annex A* of EN 1997-1 are applicable, but with recourse to a resistance model factor larger than 1.0: for the purpose of this example the value $\gamma_{Rd} = 1.25$ is selected.

Thus, the two following sets of calculations are performed (*kN and m* are used):

Assumption A.

$R_k = R_{cal} = R_{b,k} + R_{s,k} = 387 + 132\ L$

Assumption B.

$R_k = R_{cal}/\gamma_{Rd} = R_{b,k} + R_{s,k}$

$= (387 + 132\ L)/1.25 = 309.6 + 105.6\ L$

In the following, Tables 4 and 5 are used.

<u>Assumption A</u> : $R_k = R_{cal}$

Design Approach 1

Combination 1:

The design load is :

$F_d = \boldsymbol{\gamma_G}.G_k + \boldsymbol{\gamma_Q}.Q_k$

$= \mathbf{1.35} \times 1200 + \mathbf{1.5} \times 200 = 1920$ kN

The design resistance of the pile is :

$R_d = R_{b,k} / \boldsymbol{\gamma_b} + R_{s,k} / \boldsymbol{\gamma_s}$

$= 387/\mathbf{1.25} + 132\ L/\mathbf{1.0} = 309.6 + 132\ L$

The condition $F_d \leq R_d$ leads to $L \geq 12.2$ m .

Combination 2:

The design load is :

$F_d = \boldsymbol{\gamma_G}.G_k + \boldsymbol{\gamma_Q}.Q_k$

$= \mathbf{1.0} \times 1200 + \mathbf{1.3} \times 200 = 1460$ kN

The design resistance of the pile is :

$R_d = R_{b,k} / \boldsymbol{\gamma_b} + R_{s,k} / \boldsymbol{\gamma_s}$

$= 387/\mathbf{1.6} + 132\ L/\mathbf{1.3} = 241.9 + 101.5\ L$

The condition $F_d \leq R_d$ leads to $L \geq 12.0$ m.

In conclusion, for Design Approach 1, the result is $\boxed{L \geq 12.2\ m}$ (the larger of the two lengths is given by Combination 1).

Design Approach 2

Only one combination is relevant.

The design load is :

$F_d = \boldsymbol{\gamma_G}.G_k + \boldsymbol{\gamma_Q}.Q_k$

$= \mathbf{1.35} \times 1200 + \mathbf{1.5} \times 200 = 1920$ kN

The design resistance of the pile is :

$R_d = R_{b,k} / \boldsymbol{\gamma_b} + R_{s,k} / \boldsymbol{\gamma_s} = 387/\mathbf{1.1} + 132\ L/\mathbf{1.1}$

$= 351.8 + 120\ L$

The condition $F_d \leq R_d$ leads to $\boxed{L \geq 13.1\ m}$.

Design Approach 3 : not relevant to SPT or other semi-empirical model.

<u>Assumption B</u> : $R_k = R_{cal}/\gamma_{Rd}$

Design Approach 1

Combination 1:

The design load is :

$F_d = \boldsymbol{\gamma_G}.G_k + \boldsymbol{\gamma_Q}.Q_k$

$= \mathbf{1.35} \times 1200 + \mathbf{1.5} \times 200 = 1920$ kN

The design resistance of the pile is :

$R_d = R_{b,k} / \boldsymbol{\gamma_b} + R_{s,k} / \boldsymbol{\gamma_s}$

$= 309.6/\mathbf{1.25} + 105.6\ L/\mathbf{1.0} = 247.7 + 105.6\ L$

The condition $F_d \leq R_d$ leads to $L \geq 15.8$ m.

Combination 2:

The design load is :

$F_d = \boldsymbol{\gamma_G}.G_k + \boldsymbol{\gamma_Q}.Q_k$

$= \mathbf{1.0} \times 1200 + \mathbf{1.3} \times 200 = 1460$ kN

The design resistance of the pile is :

$R_d = R_{b,k} / \boldsymbol{\gamma_b} + R_{s,k} / \boldsymbol{\gamma_s}$

$= 309.6/\mathbf{1.6} + 105.6\ L/\mathbf{1.3} = 193.5 + 81.2\ L$

The condition $F_d \leq R_d$ leads to $L \geq 15.6$ m.

In conclusion, for Design Approach 1, the result is $\boxed{L \geq 15.8\ m}$ (the larger of the two lengths, given by Combination 1).

Design Approach 2

Only one combination is relevant.

The design load is :

$F_d = \boldsymbol{\gamma_G}.G_k + \boldsymbol{\gamma_Q}.Q_k$

$= \mathbf{1.35} \times 1200 + \mathbf{1.5} \times 200 = 1920$ kN

The design resistance of the pile is :

$R_d = R_{b,k} / \boldsymbol{\gamma_b} + R_{s,k} / \boldsymbol{\gamma_s}$

$= 309.6/\mathbf{1.1} + 105.6\ L/\mathbf{1.1} = 281.5 + 96.0\ L$

The condition $F_d \leq R_d$ leads to $\boxed{L \geq 17.1}$ m.

Design Approach 3 : not relevant to semi-empirical models.

<u>Conclusion for Assumptions A and B:</u> when using Eurocode 7-1 (EN 1997-1) for ULS in persistent or transient design situations, Design Approach 2 is the most conservative, for this example (with dominant shaft friction), as it leads respectively to $L \geq 13.1$ m (assumption A) and to $L \geq 17.1$ m (assumption B). With regard to Design Approach 1, combination 1 is more conservative than combination 2.

4.2 *Pile design from pile load test results*

The design example is defined in Figure 2 and Table 7 (Orr, 2005).

<u>Characteristic compressive resistance</u>

The measured ultimate compressive resistances are (from readings at settlement $s = 0.1D = 40$ mm) :

$R_{m1} = 5.0$ MN and $R_{m2} = 5.6$ MN

Equation (6) is applied with

$R_{m,mean} = 5.3$ MN and $R_{m,min} = 5.0$ MN.

From Table 1, for $n = 2$ pile load tests : $\xi_1 = 1.30$ and $\xi_2 = 1.20$; thus,

$R_k = \text{Min}\{5.3/1.30;\ 5.0/1.20\}$

$= \text{Min}\{4.08;\ 4.17\} = 4.08$

which shows that the mean value 'governs'.

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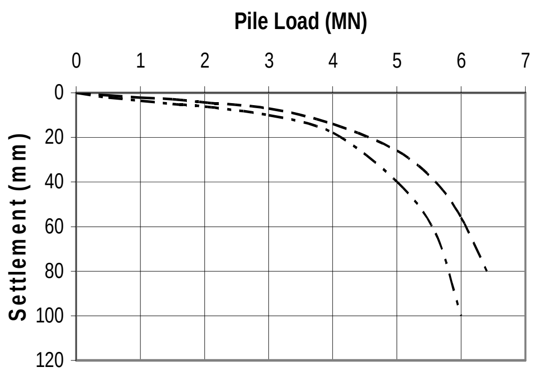

Figure 2. Data for example of pile design from static load test results (Example 4 of ERTC10 Workshop)

Table 7. Data for example of pile design from static load test results (Example 4 of ERTC10 Workshop)

- **Design Situation**
  - Pile foundation, driven piles, pile diameter D = 0.4m and length = 15m. The building supported by the piles does not have the capacity to transfer the load from weak to strong piles. The allowable pile settlement is 10mm
- **Pile Resistance**
  - 2 static pile load test results provided on driven piles of same diameter and length as design piles. Piles were loaded beyond a settlement of 0.1D = 40mm to give the limit load.
- **Characteristic values of actions**
  - Permanent vertical load G_k = 20,000kN
  - Variable vertical load Q_k = 5,000kN
- **Require number of piles needed to satisfy both ULS and SLS**

ULS in persistent and transient situations

Tables 4 and 5 are used.

Design Approach 1

Combination 2 is usually leading the geotechnical design.

The design load is :

$F_d = \boldsymbol{\gamma_G}.G_k + \boldsymbol{\gamma_Q}.Q_k$

$= \mathbf{1.0} \times 20 + \mathbf{1.3} \times 5 = 26.5$ MN

The design resistance for one pile is :

$R_d = R_k / \boldsymbol{\gamma_t} = 4.08 / \mathbf{1.3} = 3.14$ MN.

Thus, according to DA1-Comb 2, 26.5/3.14 = 9 piles are needed (neglecting group effects).

Combination 1:

The design load is :

$F_d = \boldsymbol{\gamma_G}.G_k + \boldsymbol{\gamma_Q}.\ Q_k =$

$\mathbf{1.35} \times 20 + \mathbf{1.5} \times 5 = 34.5$ MN

The design resistance for one pile is :

$R_d = R_k / \boldsymbol{\gamma_t} = 4.08/\ \mathbf{1.0} = 4.08$

According to DA1-Comb 1, 34.5/4.08 = 9 piles are also needed (neglecting group effects).

Design Approach 2

Only one combination is relevant.

The design load is :

$F_d = \boldsymbol{\gamma_G}.G_k + \boldsymbol{\gamma_Q}.Q_k$

$= \mathbf{1.35} \times 20 + \mathbf{1.5} \times 5 = 34.5$ MN

The design resistance for one pile is :

$R_d = R_k / \boldsymbol{\gamma_t} = 4.08/\ \mathbf{1.1} = 3.71$ MN

The number of piles is 34.5/3.71 = 10 piles (neglecting group effects).

SLS – Serviceability check

The characteristic load $G_k + Q_k$ = 25 MN is relevant for the characteristic combination, which is the most severe one (used for irreversible limit states, see EN 1990).

When examining the two measured load-settlement curves, the settlement is 10 mm for measured loads F_m equal to 3.0 MN and 3.5 MN (approximately), respectively. The characteristic value for 10 mm can be assessed in the same manner as the characteristic bearing resistance, i.e. $F_{m,k}$ = 2.5 MN approximately. Hence, 10 piles must be used in order to keep the pile settlement lower or equal to 10 mm.

Conclusion : according to ULS + SLS checks, 10 piles are needed, whatever the Design Approach used for ULS requirements.

5 CONCLUSION

Eurocode 7 is devoted to the geotechnical problems linked to the interaction of structures with the grounds.

Its provisions and requirements for pile foundations follow, in general, traditional practice, but also add a number of innovative features:

- introduction of correlation factors for determining the resistance of piles, to take into account the number of load tests or of ground test profiles;

- prediction of the movements of foundations, in particular for checking the serviceability of structures.

Eurocode 7 is meant to be a tool not only to help European geotechnical engineers speak the same technical language, but also a necessary tool for the dialogue between geotechnical engineers and structural engineers.

It is felt that Eurocode 7 will promote research, in particular in the field of soil-structure interactions.

One of the great challenges of contemporary geotechnical engineering is precisely the development of rational methods for predicting the movements of foundations, in order to design safe and more economical structures.

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