European Commission

Deep foundations – design of pile foundations

Dr Trevor Orr

Trinity College Dublin

Convenor TC250 / SC7 / EG3

Outline of the talk

Scope and contents

Design situations, limit states, design approaches and load tests

Ultimate limit state design

Serviceability limit state design

Pile design in Ireland

Summary of key points

Design of pile foundations - by testing and calculation

SCOPE AND CONTENTS

Scope of EN 1997-1 Section 8 Pile foundations

- The provisions of Section 7 apply to:
  - End-bearing piles
  - Friction piles
  - Tension piles, and
  - Transversely loaded piles
- Piles installed by:
  - Driving,
  - Jacking and screwing or
  - Boring
  - With or without grouting
- But note:
  - The provisions of this Section should not be applied directly to the design of piles that are intended as settlement reducers, such as in some piled raft foundations

Reference to other relevant CEN standards

Reference is made in Eurocode 7 to other CEN standards that are relevant to the design of pile foundations:

- Design standard
  - EN 1993-5: Eurocode 3, Part 5: Design of Steel Structures – Piling
- Execution of special geotechnical works standards
  - EN 1536:1999 - Bored Piles
  - EN 12063:1999 - Sheet pile walls
  - EN 12699:2000 - Displacement piles
  - EN 14199:2005 - Micropiles

Another CEN standard relevant to the design of piles is the material standard:

- EN 12794:2005 – precast concrete products. Foundation piles

Contents of EN 1997-1 Section 7 Pile foundations

Section 7 has the following sub-sections and paragraphs:

§7.1 General (3 paragraphs)
§7.2 Limit states (1)
§7.3 Actions and design situations (18)
§7.4 Design methods and design considerations (8)
§7.5 Pile load tests (20)
§7.6 Axially loaded piles (89)
§7.7 Transversely loaded piles (15)
§7.8 Structural design of piles (5)
§7.9 Supervision of construction (8)

Contents of Section 7.6 Axially loaded piles

Most common type of pile and largest sub-section

§7.6.1 General (7 paragraphs)
§7.6.2 Compressive ground resistance(51)
§7.6.3 Ground tensile resistance (23)
§7.6.4 Vertical displacements of pile foundations (Serviceability of supported structure) (8)

Section 7 is the longest section in EN 1997-1, having 20 pages

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DESIGN SITUATIONS, LIMIT STATES, DESIGN APPROACHES AND LOAD TESTS

Design situations

- Actions should be considered when selecting the design situation
- Piles can be loaded axially and/or transversely
- Piles can also be loaded due to displacement of the surrounding soil
- This may be due to:
  - Consolidation
  - Swelling
  - adjacent loads
  - creeping soil
  - Landslides, or
  - Earthquakes.
- These need to be considered as they can affect piles by causing downdrag (negative skin friction), heave, stretching, transverse loading and displacement

Downdrag

- Ground movement can give rise to downdrag (negative skin friction), heave, stretching, transverse loading and displacement
- If ultimate limit state design calculations are carried out with the downdrag load as an action, its value shall be the maximum, which could be generated by the downward movement of the ground relative to the pile
- Usually the design values of the strength and stiffness are upper values in these situations (more conservative)
- Although EN 1997-1 indicates downdrag can be included in ultimate limit state calculations, normally downdrag is only relevant in serviceability limit states, causing additional pile settlement

Limit states

§7.2(1)P states the following limit states shall be considered and an appropriate list shall be compiled:

- Loss of overall stability;
- Bearing resistance failure of the pile foundation;
- Uplift or insufficient tensile resistance of the pile foundation;
- Failure in the ground due to transverse loading of the pile foundation;
- Structural failure of the pile in compression, tension, bending, buckling or shear;
- Combined failure in the ground and in the pile foundation;
- Combined failure in the ground and in the structure;
- Excessive settlement;
- Excessive heave;
- Excessive lateral movement;
- Unacceptable vibrations.

Selection of pile type

Checklist of factors affecting selection of pile type

Selection of Pile Type	Checked
The ground and ground-water conditions, including the presence or possibility of obstructions in the ground.	
The stresses generated in the pile during installation	
The possibility of preserving and checking the integrity of the pile being installed	
The effect of the method and sequence of pile installation on piles, which have already been installed and on adjacent structures or services.	
The tolerances within which the pile can be installed reliably	
The deleterious effects of chemicals in the ground	
The possibility of connecting different ground-water regimes	
The handling and transportation of piles	

Design approaches

- 7.4(1)P states that the design of piles *shall be based on one of the following approaches:*
  - *The results of <u>static load tests</u>, which have been demonstrated, by means of calculations or otherwise, to be consistent with other relevant experience*
  - *Empirical or analytical calculation methods whose validity has been demonstrated by <u>static load tests</u> in comparable situations*
  - *The results of dynamic load tests whose validity has been demonstrated by <u>static load tests</u> in comparable situations*
  - *The observed performance of a comparable pile foundation, provided that this approach is supported by the results of site investigation and ground testing*
- The importance of static pile load tests is emphasised in Eurocode 7 as the first three methods refer to static load tests

Static load tests

- Some important paragraphs in Eurocode 7 relating to pile static load tests:
  - *Static load tests may be carried out on trial piles, installed for test purposes only, before the design is finalised, or on working piles, which form part of the foundation* (7.4.1(3))
  - *If one pile load test is carried out, it shall normally be located where the most adverse ground conditions are believed to occur* (7.5.1(4)P)
  - *Between the installation of the test pile and the beginning of the load test, adequate time shall be allowed to ensure that the required strength of the pile material is achieved and the pore-water pressures have regained their initial values* (7.5.1(6)P)

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ULTIMATE LIMIT STATE DESIGN

Axially loaded piles in compression

Equilibrium equation for ULS design:

$$F_{c;d} \leq R_{c;d}$$

where:

- $F_{c;d}$ is the ULS design axial compression load determined using partial action factors, γ_F applied to the representative loads relevant to the DA being used

$$F_{c;d} = \gamma_G G_{rep} + \gamma_Q Q_{rep}$$

- $R_{c,d}$ is the pile compressive design resistance

Table A3: Partial factors on actions (γ_F) or the effects of actions (γ_E)

Action		Symbol	Set	
			A1	**A2**
			DA1.C1 DA3 (geotech actions)	DA1.C2, DA2 DA3 (structural actions)
Permanent	Unfavourable	γ_G	1.35	1.0
	Favourable		1.0	1.0
Variable	Unfavourable	γ_Q	1.5	1.3
	Favourable		0	0

Obtaining the design pile load

- The self-weight of the pile should be included in $F_{c;d}$, along with downdrag, heave or transverse loading, however the common practice of assuming that the weight of the pile is balanced by that of the overburden allowing both to be excluded from $F_{c;d}$ and $R_{c;d}$ is permitted, where appropriate

- The pile weight may not cancel the weight of the overburden if
  a) Downdrag is significant
  b) The soil is light
  c) The pile extends above the ground surface

Obtaining the characteristic pile resistance

- Eurocode 7 describes three procedures for obtaining the characteristic compressive resistance, $R_{c;k}$ of a pile :
  a) Directly from static pile load tests
  b) By calculation from profiles of ground test results
  c) By calculation from soil shear strength parameters

- In procedures a) and b) EC7 provides correlation factors to convert the measured or calculated pile resistances into characteristic resistances

- In c) the characteristic pile resistance is calculated using the characteristic soil parameter values.
  – This is referred to as the "alternative procedure" in EC7 although it is the most common methods in some countries, for example in Ireland and the UK

a) Characteristic pile resistance, $R_{c;k}$ obtained from static load tests

- Eurocode 7 states that: *For piles in compression it is often difficult to define a ULS from a load-settlement plot showing a continuous curvature. In these cases, settlement of the pile top equal to 10% of the pile base diameter should be adopted as the "failure" criterion* (7.6.1.1(3))
- $R_{c;k}$ is then determined directly (i.e. not estimated) from the measured pile resistance, $R_{c;m}$ values (ULS resistances) by applying correlation factors, ξ_1 and ξ_2, related to number of piles tested, to the mean and minimum measured resistances according to equation:

$$R_{c;k} = \text{Min}\left\{ \frac{(R_{c;m})_{mean}}{\xi_1} ; \frac{(R_{c;m})_{min}}{\xi_2} \right\}$$

Correlation factors ξ_1 and ξ_2 to derive the characteristic resistance from static load tests

- Recommended values for ξ_1 and ξ_2 given in Table A.9 in EN 1997-1 Annex A are:

n	1	2	3	4	≥ 5
ξ_1	1.4	1.3	1.2	1.1	1.0
ξ_2	1.4	1.2	1.05	1.0	1.0

- The advantage of doing more loads tests is that the determined $R_{c;k}$ is higher since the correlation values are lower as the number of load tests, n increases
- For structures which have sufficient stiffness to transfer loads from ‘weak’ to ‘strong’ piles, ξ may be divided by 1.1 provided it is not less than 1.0 (7.6.2.2(9))

Compressive resistance from ground test results

- Part 2 of EN 1997 provide the Annexes with methods to determine the compressive resistance of a single pile from the results of in situ tests:

D.6 Example of a correlation between compressive resistance of a single pile and cone penetration resistance

Tables are provided relating the pile's unit base resistances p_b at different normalised pile settlements, s/D, and the shaft resistance p_s to average cone penetration resistance q_c values

D.7 Example of a method to determine the compressive resistance of a single pile from an electrical cone penetration test

Equation are provided to calculate the maximum base resistance and shaft resistance from the q_c values obtained from an electrical CPT

E.3 Example of a method to calculate the compressive resistance of a single pile from an MPM test:

$$Q = A \times k\,[p_{LM} - p_0] + P\Sigma[q_{si} \times z_{si}]$$

b) Characteristic pile resistance from profiles of test results

- In this method a 'number of profiles of tests' are carried out, e.g. CPTs, that are used to calculate the pile resistance(s), at the locations of the test profiles

- The characteristic pile resistances $R_{t;k}$ or $R_{b;k}$ and $R_{s;k}$ may then be determined directly by applying correlation factors ξ_3 and ξ_4 to the calculated pile resistances

- This procedure is referred to as the Model Pile procedure by Frank et al. in the Designers' Guide to Eurocode 7

Correlation factors ξ_3 and ξ_4 to derive the characteristic resistance from test result profiles

- Correlation factors ξ_3 and ξ_4, whose values depend on the number of test profiles, n are applied to the mean and minimum $R_{c,cal}$ values according to the following equation:

$$R_{t,k} = (R_{b,k} + R_{s,k}) = \mathrm{Min}\left\{ \frac{(R_{c;cal})_{mean}}{\xi_3} ; \frac{(R_{c;cal})_{min}}{\xi_4} \right\}$$

Eqn. 7.8

- The recommended values for ξ_3 and ξ_4 are shown in the following table and differ from the ξ factor values for design from pile load tests

n	1	2	3	4	5	7	10
ξ_3	1.4	1.35	1.33	1.31	1.29	1.27	1.25
ξ_4	1.4	1.27	1.23	1.20	1.15	1.12	1.08

c) Characteristic pile resistance from ground parameters

- The characteristic pile resistances $R_{t;k}$ or $R_{b;k}$ and $R_{s;k}$ may also be determined from directly from ground parameters
- In this procedure, the characteristic base and shaft resistances, $q_{b;k}$ and $q_{s;k}$, are calculated using appropriate values for the ground parameters:

$$R_{b;k} = A_b \times q_{b;k} \quad \text{and} \quad R_{s;k} = \Sigma A_{si} \times q_{si;k}$$

where:

A_b = the nominal plan area of the base of the pile;

A_{si} = the nominal surface area of the pile in soil layer I

- Although called the "alternative" procedure, this procedure is the most common pile design method used in Ireland and the UK

Design pile compressive resistance

- The compressive pile resistance may be treated either as a total resistance or separated into a base and shaft component
- Treating the resistance as a total resistance, the design pile resistance, $R_{c;d}$ is obtained by dividing the characteristic total compressive resistance, $R_{c;k}$ by the relevant partial factor, γ_t:

$$R_{c;d} = R_{c;k}/\gamma_t$$

- Dividing the pile resistance into its base and shaft components, the design resistance is obtained by dividing the characteristic base and shaft resistances, $R_{b;k}$ and $R_{s;k}$ by the relevant partial factors, γ_b and γ_s:

$$R_{c;d} = R_{b;k}/\gamma_b + R_{s;k}/\gamma_s$$

Partial resistance factors

- EN 1997-1 provides different recommended sets of partial resistance factor values for driven, bored and CFA piles
- The following should be noted:
  - The R1 partial factors are greater than 1.0 for bored and CFA piles in compression, but equal to 1.0 for driven piles
  - The R2 partial factors are the same for all three types of pile
  - The R3 partial factors are all equal to 1.0
  - The R4 partial factors are all greater than 1.0 and greater then the R2 values
  - The partial factors for shafts in tension are the same for all three types of pile

Table A.6- Partial resistance factors (γ_R) for driven piles

Resistance	Symbol	Set			
		R1	*R2*	*R3*	*R4*
Base	γ_b	1,0	1,1	1,0	1,3
Shaft (compression)	γ_s	1,0	1,1	1,0	1,3
Total/combined (compression)	γ_t	1,0	1,1	1,0	1,3
Shaft in tension	$\gamma_{s;t}$	1,25	1,15	1,1	1,6

Table A.7 - Partial resistance factors (γ_R) for bored piles

Resistance	Symbol	Set			
		R1	*R2*	*R3*	*R4*
Base	γ_b	1,25	1,1	1,0	1,6
Shaft (compression)	γ_s	1,0	1,1	1,0	1,3
Total/combined (compression)	γ_t	1,15	1,1	1,0	1,5
Shaft in tension	$\gamma_{s;t}$	1,25	1,15	1,1	1,6

Table A.8 - Partial resistance factors (γ_R) for continuous flight auger (CFA) piles

Resistance	Symbol	Set			
		R1	*R2*	*R3*	*R4*
Base	γ_b	1,1	1,1	1,0	1,45
Shaft (compression)	γ_s	1,0	1,1	1,0	1,3
Total/combined (compression)	γ_t	1,1	1,1	1,0	1,4
Shaft in tension	$\gamma_{s;t}$	1,25	1,15	1,1	1,6

DA1 partial factors

- DA1.C1 Set of partial factors:

  A1 "+" M1 "+" R1

- DA1.C2 Set of partial factors:

  A2 "+" M1 or M2 "+" R4

- Note:
  - In DA1.C1, Set M1 = 1.0 and the design resistance is obtained by applying partial factors to characteristic base and shaft resistances, not to ground parameters. Set R1 > 1.0 except for driven piles
  - In DA1.C2, Set R4 > 1.0 and Set M1 = 1.0 is used for calculating the design pile resistance while Set M2 > 1.0 is used for calculating unfavourable design actions on piles owing e.g. to negative skin friction or transverse loading

Table A.6- Partial resistance factors (γ_R) for driven piles

Resistance	Symbol	Set			
		R1	*R2*	*R3*	*R4*
Base	γ_b	1,0	1,1	1,0	1,3
Shaft (compression)	γ_s	1,0	1,1	1,0	1,3
Total/combined (compression)	γ_t	1,0	1,1	1,0	1,3
Shaft in tension	$\gamma_{s;t}$	1,25	1,15	1,1	1,6

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Base	γ_b	1,25	1,1	1,0	1,6
Shaft (compression)	γ_s	1,0	1,1	1,0	1,3
Total/combined (compression)	γ_t	1,15	1,1	1,0	1,5
Shaft in tension	$\gamma_{s;t}$	1,25	1,15	1,1	1,6

Table A.8 - Partial resistance factors (γ_R) for continuous flight auger (CFA) piles

Resistance	Symbol	Set			
		R1	*R2*	*R3*	*R4*
Base	γ_b	1,1	1,1	1,0	1,45
Shaft (compression)	γ_s	1,0	1,1	1,0	1,3
Total/combined (compression)	γ_t	1,1	1,1	1,0	1,4
Shaft in tension	$\gamma_{s;t}$	1,25	1,15	1,1	1,6

DA2 and DA3 partial factors

- DA2 Set of partial factors:
  A1 "+" M1 "+" R2
- DA3 Set of partial factors:
  (A1 or A2†) "+" M2 "+" R3*

  * on structural actions
  † on geotechnical actions

  – Since all the R3 values are unity, DA3 should not be used for piles designed from pile load tests or for using resistances calculated from profiles of test results as it provides no safety on the resistance
  – When using DA3 to design piles from ground parameters with the alternative procedure, partial material factors M2 are applied to suitably cautious characteristic ground parameters

Table A.6- Partial resistance factors (γ_R) for driven piles

Resistance	Symbol	Set			
		R1	*R2*	*R3*	*R4*
Base	γ_b	1,0	1,1	1,0	1,3
Shaft (compression)	γ_s	1,0	1,1	1,0	1,3
Total/combined (compression)	γ_t	1,0	1,1	1,0	1,3
Shaft in tension	$\gamma_{s;t}$	1,25	1,15	1,1	1,6

Table A.7 - Partial resistance factors (γ_R) for bored piles

Resistance	Symbol	Set			
		R1	*R2*	*R3*	*R4*
Base	γ_b	1,25	1,1	1,0	1,6
Shaft (compression)	γ_s	1,0	1,1	1,0	1,3
Total/combined (compression)	γ_t	1,15	1,1	1,0	1,5
Shaft in tension	$\gamma_{s;t}$	1,25	1,15	1,1	1,6

Table A.8 - Partial resistance factors (γ_R) for continuous flight auger (CFA) piles

Resistance	Symbol	Set			
		R1	*R2*	*R3*	*R4*
Base	γ_b	1,1	1,1	1,0	1,45
Shaft (compression)	γ_s	1,0	1,1	1,0	1,3
Total/combined (compression)	γ_t	1,1	1,1	1,0	1,4
Shaft in tension	$\gamma_{s;t}$	1,25	1,15	1,1	1,6

Pile groups

- Piles in a group should be checked for failure of the piles individually and acting as a block
  - The design resistance shall be taken as the lower value caused by these two mechanisms
- Generally a pile block can be analysed as a single large diameter pile
- The strength and stiffness of the structure connecting the piles shall be considered. For a stiff structure, advantage may be taken of load redistribution. A limit state will occur only if a significant number of piles fail together; so failure involving only one pile need not be considered
- In the case of flexible structures, the weakest pile governs the occurrence of a limit state in the structure
- Special attention needs to be given to failure of edge piles by inclined or eccentric loads

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SERVICEABILITY LIMIT STATE DESIGN

Serviceability limit state design of piles - Direct method

- The small amount in Eurocode 7 on the SLS design of compression piles is provided in 7.6.4 which is called *Vertical displacement of pile foundations (Serviceability of supported structure)*
- The principle 7.6.4.1(1)P states that:

  Vertical displacements under serviceability limit state conditions shall be assessed and checked against the requirements given
- This is a direct design method – i.e. the serviceability limit state is checked by calculating the pile displacements
- Application Rule 7.6.4.1(2) makes the comment:

  It should not be overlooked that in most cases calculations will provide only an approximate estimate of the displacements of the pile foundation

Serviceability limit state design of piles - Indirect method

- 7.6.4.1(2) has the important Note that:

  For piles bearing in medium-to-dense soils and for tension piles, the safety requirements for the ultimate limit state design are normally sufficient to prevent a serviceability limit state in the supported structure

- This is an indirect design method – ensuring that a serviceability limit state is sufficiently unlikely is achieved by adopting safety requirements (i.e. partial factors) in ultimate limit state (failure) calculations

- It is for this reason that many countries have increased the ξ values for the design of pile based on ULS calculations or have included a model factor so as to satisfy SLS as well as ULS requirements

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PILE DESIGN IN IRELAND

Pile design in Ireland from ground test profiles

In Ireland it was considered necessary to increase the ξ values in Table A.10 to allow for uncertainties in deriving the characteristic compressive and tensile resistances from ground test results

The recommended ξ values given in Table A.10 and the increased values given in Table NA.3 are:

Number of profiles of tests, n	1	2	3	4	5	7	10
A.10 ξ_3 values on mean calculated resistance	1.40	1.35	1.33	1.31	1.25	1.27	1.25
NA.3 ξ_3 values on mean calculated resistance	2.10	2.03	2.00	1.97	1.94	1.91	1.88
A.10 ξ_4 values on min. calculated resistance	1.40	1.27	1.23	1.20	1.15	1.12	1.08
NA.3 ξ_4 values on min. calculated resistance	2.10	1.91	1.85	1.80	1.73	1.68	1.62

i.e. All the recommended ξ values have been increased by a factor of 1.5 in the Irish National Annex

Pile design in Ireland using alternative procedure

- EN 1997-1 states that when the alternative procedure, R = ΣAq, where q is calculated from characteristic parameter values, is used to calculate the design pile compressive or tensile resistance, the partial factors γ_b and γ_s may need to be corrected by a model factor larger than 1.0.
- In Ireland it was considered necessary to apply a model factor of 1.75 to the γ_b, γ_s, γ_t and $\gamma_{s;t}$ values to allow for uncertainties in deriving the characteristic compressive and tensile resistances from ground test results
- Hence in Ireland designing tensile piles using the alternative procedure with the model factor is equivalent to replacing the recommended $\gamma_{s;t}$ values in Tables A.6, A.7 and A.8 with the increased values as follows:

Sets of Partial Factors	R1	R2	R3	R4
Recommended $\gamma_{s;t}$ values for bored/driven/auger piles	1.25	1.15	1.10	1.60
Equivalent Irish $\gamma_{s;t}$ values after application of model factor	2.19	2.01	1. 93	2.80

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SUMMARY OF KEY POINTS

Summary of key points

- Eurocode 7 stresses the importance of static pile load tests in the design of piles
- Eurocode 7 provides an innovative method for determining the characteristic pile resistance values directly from the results of pile load tests or from 'profiles of tests' using ξ values
- The ξ values are based on the number of pile load tests or the number of soil test profiles and hence offer more economical designs for more pile load tests or more soil test profiles
- DA1 is a *resistance factor approach*
- DA3 should not be used for the design of piles from pile load tests or from soil test profiles as its resistance factors are equal to 1.0
- SLS requirements need to be satisfied and model factors or increased ξ factors have been introduced in many countries' NAs to ensure that

Geotechnical design with worked examples

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