Pile design to Eurocode 7 and the UK National Annex. Part 1: Eurocode 7

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Summary

This two-part paper presents a summary of the provisions for pile design according to Eurocode 7 and the UK National Annex.

The design process for piling depends on both calculation and testing of piles, by either static loading or dynamic methods. Although Eurocode 7 recognises the importance of combining these, its provisions treat them separately. Furthermore, pile design has usually linked, at least implicitly, consideration of ultimate and serviceability limit states; this remains the case in Eurocode 7. In the event, specifying how calculation and testing should be used together proved to be a major challenge in drafting the UK National Annex. An extensive consultation among pile designers was undertaken to reach the consensus, which was published in November 2007.

The paper is published in two parts. Part 1 covers the provisions of Eurocode 7 itself (ENs 1997-1 and -2), which apply throughout Europe except where amended by a National Annex. Part 2 will present the values of the various factors required by the UK National Annex, together with a description of the process by which they were derived. Part 2 will also include two worked examples showing the application of the Eurocode rules.

Introduction

Background to Eurocode 7

Eurocode 7 Part 1 (EN 1997-1)[1] was released by the European Committee for Standardisation (CEN) in November 2004 for publication as a national standard in 30 countries throughout the European Union and the European Free Trade Association (EFTA). The British Standards Institution published this standard as BS EN 1997-1[2] in December 2004.

The design of pile foundations is the subject of Section 7 of Eurocode 7 Part 1, covering topics such as: limit states; actions and design situations; design methods and design considerations; pile load tests; axially loaded piles; transversely loaded piles; structural design of piles; and supervision of construction. Section 7 comprises 167 paragraphs, of which 98 are Principles (general statements and definitions that must be followed) and the remainder Application Rules (generally recognised rules that comply with the Principles and satisfy their requirements). Principles are identified by their use of the verb "shall"; Application Rules employ such verbs as "may"and "should". Section 7 applies to end-bearing, friction, tension, and transversely-loaded piles installed by driving, jacking, screwing, and boring (with or without grouting).

Under CEN rules, each National Standards Body (NSB) may provide in a National Annex (NA) decisions regarding certain national choices, where such choices are allowed in the Eurocode. These include values for Nationally Determined Parameters (NDPs), such as partial, correlation, and model factors; the procedure to be used where alternative procedures are given; decisions regarding the status of the Eurocode's informative annexes; and references to Non-Contradictory, Complementary Information (NCCI). The UK National Annex to BS EN 1997-1[3] was published in November 2007.

In this paper, the provisions for pile design in the Eurocode system are briefly described. The values of the various factors required by the UK National Annex are then presented, together with a description of the process by which they were derived. Finally, some examples of application are shown.

References to paragraphs in Eurocode 7 Part 1 are denoted by the symbol §. For brevity, Part 1 of Eurocode 7 will subsequently mainly be referred to as EC7.

Ground investigation for pile foundations

Annex B.3 of Eurocode 7 Part 2[4] provides outline guidance on the depth of investigation points for pile foundations, as illustrated in Figure 1. The recommended minimum depth of investigation below the base of the deepest pile, z_a, is the greatest of:

(1) $z_a \geq b_g$

where b_g is the smaller width of the pile group on plan;

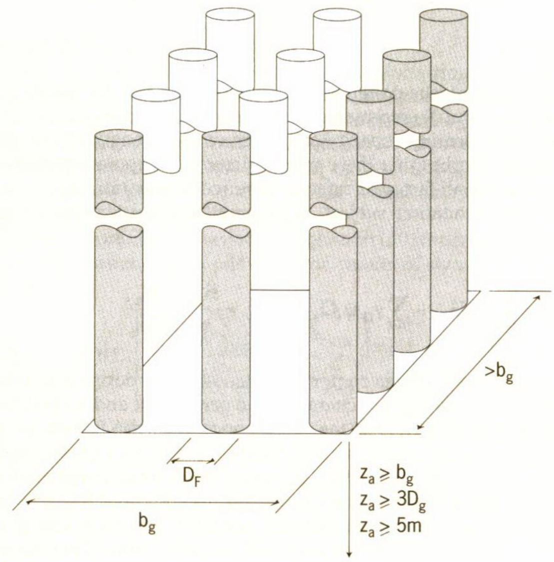

Figure 1: Recommended depth of investigation for pile foundations (after Bond and Harris[9])

(2) $z_a \geq 3D_F$

where D_F is the base diameter of the largest pile; and

(3) $z_a \geq 5m$

The depth z_a may be reduced to 2m if the pile foundation is built on competent strata with "distinct" (ie known) geology. With "indistinct" geology, at least one borehole should go to at least 5m. If bedrock is encountered, it becomes the reference level for z_a. Greater depths of investigation may be needed for very large or highly complex projects or where unfavourable geological conditions are encountered.

Design situations and limit states

Possible limit states for pile foundations include geotechnical failure in compression, tension, and under transverse loading; and structural failure by buckling, shear, and bending.

Eurocode 7 Part 1 contains a long list of design considerations for pile foundations, some of which are mandatory ("shall be taken into account") and some of which are optional ("should receive attention"). For example, the choice of pile type must account for stresses generated during installation and the effect of installation on adjacent structures; while installation-induced vibrations and soil disturbance from boring should be considered.

Limit state design

EC7 considers both ultimate and serviceability limit states (ULS and SLS) and generally aims, as far as practicable, to deal with these separately. Consideration of ULS design tends to dominate the code text, perhaps because SLS requirements are more difficult to standardise. However, for piling it states in §7.6.4.1(2) 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."

Although it is not entirely clear, it is considered that "medium-to-dense soils" is intended to include stiff, high-strength clays. Thus the require- »

» ments for ULS and SLS design are linked for most ground conditions in which piles might be bearing. This must be borne in mind in considering the text which is directed primarily at ULS, as discussed below.

The fundamental requirement of EC7 for ULS design is that pile foundations must be verified against failure or excessive deformation of the ground in which the strength of the ground is significant in providing resistance (limit state "GEO"); and against internal failure or excessive deformation of the structure in which the strength of the structure is significant in providing resistance (limit state "STR"). Both of these ultimate limit states are governed by the same requirement:

$$(4) \quad E_d \le R_d$$

where E_d represents the design effect of actions, such as the ultimate design loads on a pile, and R_d represents the corresponding resistance, such as the design ultimate bearing capacity or the structural strength of the pile. The term "design" implies that these values already incorporate partial factors, so no further overall factor of safety is required in equation (4).

For a pile foundation subject to compression, this inequality may be rewritten as:

$$(5) \quad F_{c,d} = \sum_j \gamma_{G,j} G_{k,j} + \sum_i \gamma_{Q,i} \psi_i Q_{k,i} \le R_{c,d} = \frac{R_{s,k}}{\gamma_s} + \frac{R_{b,k}}{\gamma_b}$$

where $F_{c,d}$ is the total design compressive action (ie the design action-effect in equation 4); $G_{k,j}$ and $Q_{k,i}$ are characteristic permanent and variable actions, respectively; $\gamma_{G,j}$ and $\gamma_{Q,i}$ are the corresponding partial factors for permanent and variable actions; ψ is a combination factor for variable actions, as specified in ENs 1990[5] and 1991[6]; $R_{c,d}$ is the pile's total design compressive resistance (ie the design resistance in equation 4); $R_{s,k}$ and $R_{b,k}$ are the pile's characteristic shaft and base resistances, respectively; and γ_s and γ_b are the corresponding partial factors for shaft and base resistance. The summations allow for multiple permanent and/or variable actions being applied to the pile.

The values of characteristic actions are derived from ENs 1990 and 1991, but these requirements beg the question: how are characteristic pile resistances derived? The process required is the responsibility of EC7 and its National Annex. EC7 states that the characteristic value should be a "cautious estimate of the value affecting the occurrence of the limit state". The approach adopted in the UK National Annex is explained in this paper.

If the pile's shaft and base resistances cannot be determined separately, the previous inequality may be simplified to:

$$(6) \quad F_{c,d} = \sum_j \gamma_{G,j} G_{k,j} + \sum_i \gamma_{Q,i} \psi_i Q_{k,i} \le R_{c,d} = \frac{R_{c,k}}{\gamma_t}$$

where $R_{c,k}$ is the pile's total characteristic compressive resistance; and γ_t is the corresponding partial factor for total resistance.

For a pile foundation subject to tension, requirement (5) may be written as:

$$(7) \quad F_{t,d} = \sum_j \gamma_{G,j} G_{k,j} + \sum_i \gamma_{Q,i} \psi_i Q_{k,i} \le R_{t,d} = \frac{R_{st,k}}{\gamma_{st}}$$

where $F_{t,d}$ is the total design tensile action; $R_{t,d}$ is the pile's total design tensile resistance; $R_{st,k}$ is the pile's characteristic shaft resistance in tension; and γ_{st} is the corresponding partial factor for tensile shaft resistance.

Design Approaches

Eurocode 7 Part 1 allows the limit states GEO and STR to be verified according to one of three Design Approaches. In Design Approach 1 (DA1), reliability is ensured by applying partial factors in two separate checks: first to actions (in Combination 1) and second to material properties or pile resistances (in Combination 2). Design Approach 2 (DA2) ensures reliability by applying factors to actions (or their effects) and resistance, simultaneously. And Design Approach 3 (DA3) applies factors to actions and material properties, again simultaneously.

Just over half of the countries in CEN have chosen DA2 for foundation design, in most cases switching to DA3 for problems involving slope stability. Approximately 30% have chosen DA1, and about 10% DA3.[7] The UK National Annex states that "only Design Approach 1 is to be used in the UK" and hence this paper is limited to discussion of DA1 alone. Information about the other Design Approaches can be found in a number of texts on Eurocode 7.[8,9]

The partial factors suggested by CEN for use in geotechnical design are given in Annex A of Eurocode 7 Part 1. Several of the factors relevant to pile design are modified in the UK National Annex to BS EN 1997-1, as allowed by CEN's rules for Nationally Determined Parameters. The values that must be used in the UK will be given in Part 2 of this paper.

For pile foundations, Combination 1 applies partial factors significantly greater than unity to unfavourable actions and only small factors (1.0-1.3) to resistances. Ground strengths (when used) are left unfactored (ie $\gamma_M = 1.0$). These factors are taken from what Eurocode 7 Part 1 calls Sets A1, M1, and R1. Thus, verification of Combination 1 may be expressed as:

$$(8) \quad \sum_j \boxed{\gamma_G} G_{k,j} + \boxed{\gamma_Q} Q_{k,1} + \sum_{i>1} \boxed{\gamma_Q} \psi_i Q_{k,i} \le \frac{R_{s,k}}{\gamma_s} + \frac{R_{b,k}}{\gamma_b}$$

where $Q_{k,1}$ is the leading characteristic variable action (for which $\psi = 1.0$); $Q_{k,i}$ (for $i > 1$) are accompanying characteristic variable actions; and $R_{s,k}$ and $R_{b,k}$ are the pile's characteristic shaft and base resistances, respectively. In this equation, we have placed boxes around the partial factors that are numerically ≥ 1.3 and hence provide the most significant contribution to reliability. Values of these factors for use in the UK will be given in Part 2.

Combination 2 applies significant partial factors (≥ 1.3) to resistances and to variable actions. Permanent actions and ground strengths (when used in deriving pile resistances) are left unfactored. These factors are taken from Sets A2, M1, and R4. Thus, verification of Combination 2 may be expressed as:

$$(9) \quad \sum_j \gamma_G G_{k,j} + \boxed{\gamma_Q} Q_{k,1} + \sum_{i>1} \boxed{\gamma_Q} \psi_i Q_{k,i} \le \frac{R_{s,k}}{\boxed{\gamma_s}} + \frac{R_{b,k}}{\boxed{\gamma_b}}$$

Supervision, monitoring, and maintenance

EC7 requires a pile installation plan to form the basis of the piling works. Piles should be monitored and records made as they are installed. These records should be kept for at least five years after completion of the works. Separate execution standards give detailed guidance on pile installation: EN 1536[10] for bored piles; EN 12063[11] for sheet pile walls; EN 12699[12] for displacement piles; and EN 14199[13] for micropiles.

Methods of design

EC7 discusses three methods of designing pile foundations, as summarised in Table 1 below.

Method	Use	Constraints
Testing	Results of static load tests, provided they are consistent with relevant experience.	Validity must be demonstrated by calculation or other means.
	Results of dynamic load tests.	Validity must be demonstrated by static load tests in comparable situations.
Calculation	Empirical or analytical calculation methods.	
Observation	Observed performance of comparable pile foundation.	Must be supported by results of site investigation and ground testing.

Table 1: Methods of designing pile foundations according to Eurocode 7 Part 1

The following sections of this paper will discuss design by testing and design by calculation. As can be seen in Table 1, the code makes clear that neither method should be used in isolation from the other. Despite this, separate provisions are given for the two methods. In British practice they are often used together, and the UK National Annex attempts to accommodate this combination.

In simple cases, where ground conditions are well understood, EC7 allows design to be based on comparison with other piles which are known to perform well under load, without further calculation or testing. In practice, this requires that the loading be the same for the new piles as for the existing ones, so its use may be limited to "repeat orders" on the same or a very near site.

Design by load testing

Basis of design by testing

Design by load testing involves using the results of static load or dynamic impact tests to define the total pile resistance. According to Eurocode 7 Part 1, the characteristic resistance of a pile R_k can be obtained from an equation of the form:

$$(10)\quad R_k = \min\left\{\frac{R_{mean}}{\xi_{mean}}, \frac{R_{min}}{\xi_{min}}\right\}$$

where R_{mean} and R_{min} are, respectively, the mean and minimum values of the resistances measured in individual tests; and ξ_{mean} and ξ_{min} are the corresponding correlation factors (specified in the standard) that take account of the probability that some of the constructed piles might perform worse than those in the small sample subjected to test.

The values of ξ_{mean} and ξ_{min} depend on the type and number of tests performed, as discussed below.

Design by static load tests

Eurocode 7 Part 1 places great emphasis on the use of static load tests, either as the primary design method or in providing validity to designs based on dynamic load tests or calculations.

Pile load tests are mandatory when there is no comparable experience of the proposed pile type or installation method; the results of previous tests under comparable soil and loading conditions are not available; theory and experience do not provide sufficient confidence in the design for the anticipated loading; or pile behaviour during installation deviates strongly and unfavourably from that anticipated (and additional ground investigations do not explain this deviation).

EC7 distinguishes between static load tests carried out on piles that form part of the permanent works ("working piles") and on piles installed, before the design is finalised, specifically for the purpose of testing ("trial piles"). Trial piles – commonly termed "preliminary piles" in the UK – must be installed in the same manner and founded in the same stratum as the working piles.

The load test procedure must allow for the pile's deformation behaviour, creep and rebound. For trial piles, the loading must allow "conclusions to be drawn about the ultimate failure load" (§7.5.2.1(1)); piles tested in tension should be loaded to failure to avoid having to extrapolate the load-displacement curve (§7.5.2.1(4)). The test load applied to working piles must not be smaller than the foundation's design load (§7.5.2.3(2)). These requirements are clarified further in the UK National Annex.

EC7 does not specify how many piles should be tested, leaving this decision to engineering judgement. For trial piles, this must be based on: ground conditions and their variability across the site; the structure's geotechnical category; documented evidence of relevant pile performance in similar ground conditions; and the total number and types of pile in the foundation design. For working piles, that judgement must be based additionally on the piles' installation records.

EC7 states that, if only one static load test is performed, it must normally be located where the most adverse ground conditions occur. Failing this, the characteristic compressive resistance must be adjusted accordingly. When two or more tests are performed, one must be located where the most adverse ground conditions occur and the others at locations representative of the pile foundation. In practice, it is often the case that access to the part of the site that has the most adverse conditions is not possible at the time of preliminary testing. There is often some variation between tests of soil strata and pile sizes, so some "normalising" of results may be needed in order to compare them and extrapolate from them.

Eurocode 7 Part 1 gives a more specific version of equation (10) for calculating the total characteristic resistance of a pile from the results of static load tests, as follows:

$$(11)\quad R_{c,k} = \min\left\{\frac{(R_{c,m})_{mean}}{\xi_1}, \frac{(R_{c,m})_{min}}{\xi_2}\right\}$$

where $R_{c,m}$ is an individual measurement of the pile's compressive resistance.

Values of the correlation factors recommended by CEN are given in Annex A of Eurocode 7 Part 1. Most of these factors are modified in the UK National Annex to BS EN 1997-1. The values that must be used in the UK will be given in Part 2 of this paper.

Eurocode 7 allows the correlation factors for static load tests (ξ_1 and ξ_2) to be reduced by 10% when designing piles in groups, provided the structure has sufficient stiffness and strength to transfer loads from weak to strong piles (but ξ_1 must not be taken as less than 1.0).

Design using dynamic impact tests

EC7 allows the compressive resistance of a pile to be estimated using dynamic impact tests, provided the tests are calibrated against static load tests on similar piles, with similar dimensions, installed in similar ground conditions. We would add that the test results should also be shown to be credible by calculation. These requirements limit the applicability of dynamic impact tests for design purposes – but they remain useful as an indicator of pile consistency and a detector of weak piles.

EC7 gives a more specific version of equation (10) for calculating the total characteristic resistance of a pile from the results of dynamic impact tests, as follows:

$$(12)\quad R_{c,k} = \min\left\{\frac{(R_{c,m})_{mean}}{\xi_5}, \frac{(R_{c,m})_{min}}{\xi_6}\right\}$$

Again, the values that must be used in the UK will be given later in Part 2 of this paper.

The correlation factors for dynamic impact tests (ξ_5 and ξ_6) may be reduced by 15% if signal matching is used. When using pile driving formulae, they should be increased by 10% if the quasi-elastic pile head displacement during impact is measured; and by 20% if not.

Design using pile driving formulae or wave equation analysis

EC7 allows the compressive resistance of a pile to be estimated using pile driving formulae or wave equation analysis, provided the ground's stratification has been determined and the method's validity demonstrated by static load tests on similar piles, with similar dimensions, installed in similar ground conditions. The blow count used in pile driving formulae should be obtained from driving records from at least five piles.

The correlation factors for pile driving formulae are similar to those for dynamic impact tests, but adjusted by a model factor that depends on how the pile head displacement is measured (§A.3.3.3 Table A11). For wave equation analysis, correlation factors shall be "based on local experience" (§7.6.2.6).

Design using the results of ground tests

Ways of using ground test results

Eurocode 7 Part 1 gives two different approaches for calculating characteristic pile resistances from ground test results. In the first (§7.6.2.3(5)), pile resistances are calculated for each "profile" of ground test results and these resistances – effectively best estimates – are then treated in a manner similar to load test results. A ground profile could comprise the results from a single borehole or a single cone penetration test, for example. The second approach is less specific (§7.6.2.3(8)), requiring the designer to supply characteristic base and shaft resistance and suggesting that a "model factor" might also be incorporated into the calculation.

Approach based on "ground profiles"

For the first approach, EC7 gives a more specific version of equation (10) for calculating the shaft and base characteristic resistances of a pile ($R_{s,k}$ and $R_{b,k}$, respectively) from the results of ground tests, as follows:

$$(13)\quad R_{s,k} = \min\left\{\frac{(R_{s,cal})_{mean}}{\xi_3}, \frac{(R_{s,cal})_{min}}{\xi_4}\right\}$$

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(14) $$R_{b,k} = \min\left\{\frac{(R_{b,cal})_{mean}}{\xi_3}, \frac{(R_{b,cal})_{min}}{\xi_4}\right\}$$

where the subscripts "cal" denote calculated rather than measured resistance. The values that must be used in the UK will be given in Part 2 of this paper.

Eurocode 7 allows the correlation factors for ground tests (ξ_3 and ξ_4) to be reduced by 10% when designing piles in groups, provided the structure has sufficient stiffness and strength to transfer loads from weak to strong piles (but ξ_3 must not be taken as less than 1.0).

Approach based on calculation

For the second approach, offered in §7.6.2.3(8), the standard states that a pile's characteristic shaft and base resistances ($R_{s,k}$ and $R_{b,k}$) may be obtained from an "alternative procedure" using the equations:

(15) $$R_{s,k} = \sum_i A_{s,i} q_{s,k,i}$$

where $A_{s,i}$ = the pile's shaft area in layer "i" and $q_{s,k,i}$ = its characteristic unit shaft resistance in the same layer; and:

(16) $$R_{b,k} = A_b q_{b,k}$$

where A_b = the pile's base area and $q_{b,k}$ = its characteristic unit base resistance.

In the UK, the majority of pile designs are based on calculations that involve these two equations and EC7's use of the adjective "alternative" might not give them sufficient recognition.

This approach involves the use of equations that relate soil and rock parameters to shaft friction and end bearing. Unfortunately, available calculation models do not reliably predict the ultimate capacity of piles, owing to the complex interaction between pile type, construction processes, workmanship, and group effects. Consequently, relatively large factors of safety (in the range 2.0–3.0) are conventionally applied in such calculations.

The partial factors suggested in EC7 for pile resistance (1.0–1.6 on base resistance and 1.0–1.3 on shaft) are numerically much lower than have traditionally been used in the design of pile foundations. These factors were chosen for the purpose of design by testing, in which additional "correlation factors" (numerically between 1.0 and 1.6) are used to ensure the reliability of the foundation. For this reason, Eurocode 7 Part 1 allows a "model factor" $\gamma_{Rd} > 1$ to be applied in design by calculation to "correct" the resistance factors, thereby giving:

(17) $$R_{s,k} = \frac{\sum_i A_{s,i} q_{s,k,i}}{\gamma_{Rd}}$$

and:

(18) $$R_{b,k} = \frac{A_b q_{b,k}}{\gamma_{Rd}}$$

EC7 does not specify a value for the model factor γ_{Rd} (although 1.5 was used in the draft standard, ENV 1997-1[14]). Values for γ_{Rd} are given in the UK National Annex.

Traditional UK design

The design of pile foundations in the UK has traditionally been carried out by calculation, by checking that the pile's "safe working" or "allowable" bearing capacity Q_a is not less than the applied load P:

(19) $$P \le Q_a$$

This equation is directly analogous to requirement (4) from EC7, though P is typically an "unfactored" load.

There are two common methods of introducing safety into calculations of the "allowable" (or "safe working") load Q_a. Either a single factor F is applied to the pile's ultimate capacity Q_{ult}:

(20) $$Q_a = \frac{Q_{ult}}{F}$$

or two factors F_s and F_b are applied separately to the shaft and base capacities $Q_{s,ult}$ and $Q_{b,ult}$, ie:

(21) $$Q_a = \frac{Q_{s,ult}}{F_s} + \frac{Q_{b,ult}}{F_b}$$

Q_a is often taken as the lower of the values calculated by the two methods. Equation (20) is similar to equation (6) above and equation (21) to equation (5), but the factors F are bigger than the equivalent γ_R values in EC7.

Various authors have recommended values for these factors of safety, and some of these recommendations – for bored and continuous flight auger (CFA) piles – are summarised in Table 2 below.

Reference		Factor of safety for bored/CFA piles		
		Global (F)	Shaft (F_s)	Base (F_b)
Burland et al[15]		2.0	1.0	3.0
Tomlinson[16]		2.5	1.5	3.0
Bowles[17]		2.0-4.0*	-	-
Lord et al[18]	s < 10mm† s ≥ 10mm†	2.5	1.5 1.0	3.5
Base disregarded ‡		-	1.2-1.5	∞

* "depending on designer uncertainties"; † s = pile head settlement; ‡ commonly used as a second check to limit settlement, especially when base capacity is uncertain

Table 2: Factors of safety recommended in the literature for pile design

According to Fleming: "A factor of safety of 2.0 is often deemed sufficient when test piles have been loaded to failure. However … 2.5 is recommended where only proof loads are applied to working piles."[19] When no pile tests are carried out, it is usual to apply a larger factor of safety, normally no greater than 3.0.

Figure 2 compares the equivalent global factor of safety F* obtained from the various recommendations given above, for different amounts of ultimate

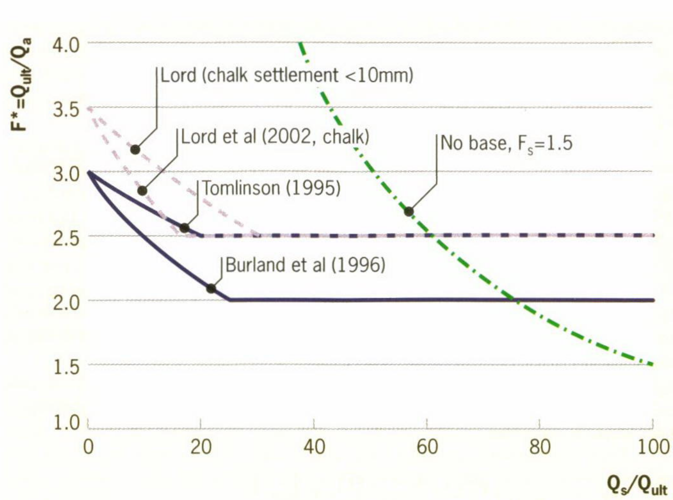

Figure 2: Equivalent global factors of safety for pile foundations, as recommended in the literature (after Bond and Harris[9])

shaft capacity (Q_s) expressed as a percentage of the total ultimate capacity (Q_{ult}). The left-hand end of the horizontal scale represents predominantly end-bearing piles and the right-hand end predominantly friction piles.

For each curve, the allowable capacity Q_a is calculated as the lower of the values obtained from the application of a single factor F and the application of twin factors F_s and F_b described above. The equivalent global factor is then the ratio of the ultimate capacity to the allowable (ie $F^* = Q_{ult}/Q_a$).

For piles in London, the current rules of the London District Surveyors' Association (LDSA)[20] take a slightly different approach, as shown in Table 3 below. No distinction is made between resistance from base and shaft, but the factors employed are varied according to the adequacy of the site investigation information and the degree of load testing employed in association with the calculations. The assumed value of the shaft adhesion factor α is also varied.

Adequate site investigation?	Pile load test		Factor of Safety, F	Shaft adhesion factor
	Working	Preliminary		
No	None	None	3.0	0.5
Yes	On 1% of working piles, to 1.5 times working load		2.5	0.6
		Constant rate of penetration test	2.25	
		Maintained load test	2	0.5

Table 3: Factors of safety required by the London District Surveyors' Association

Part 2

Part 2 of this paper, which will be published in the next issue of *Ground Engineering*, will present the values of the various partial factors required by the UK National Annex, together with a description of the process by which they were derived. Part 2 will also include two worked examples showing the application of the Eurocode rules.

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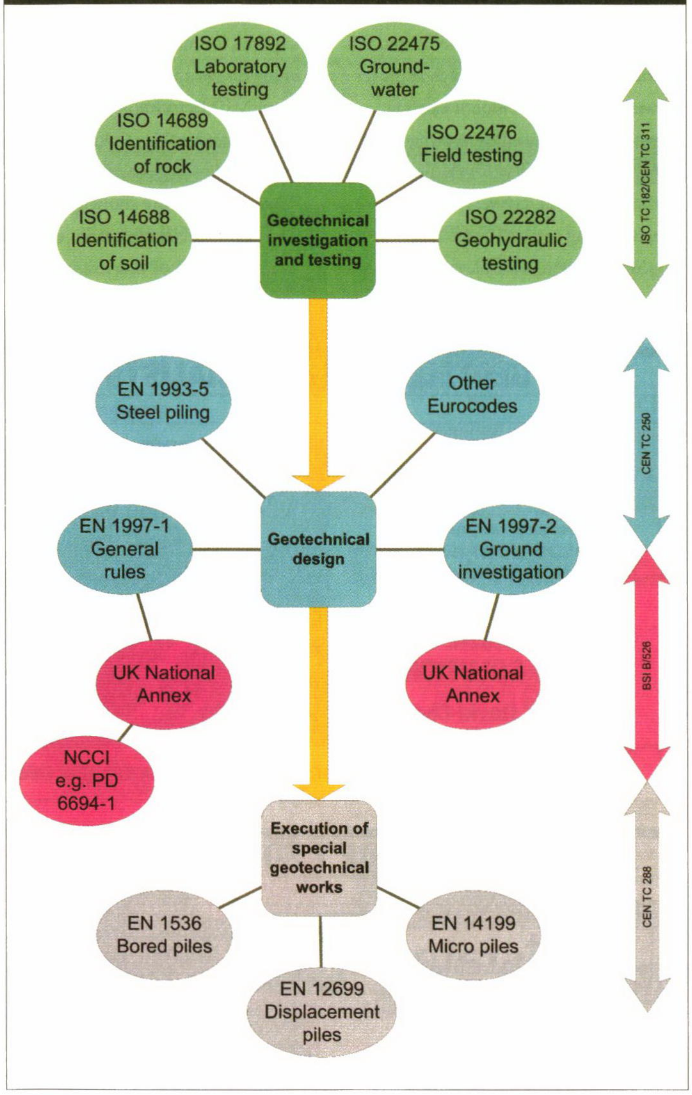

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