6.4 Calculation models

*COMMENTARY ON **6.4***

BS EN 1997-1 allows the ultimate bearing resistance of an individual pile to be determined from any of the following:

- *static pile formulae based on ground parameters;*
- *direct formulae based on the results of field tests;*
- *the results of static pile load tests;*
- *the results of dynamic impact tests;*
- *pile driving formulae; and*
- *wave equation analysis.*

6.4.1 Bearing resistance

6.4.1.1 General

6.4.1.1.1 Unless otherwise stated, the total bearing resistance of an individual pile (R_t) should be calculated from:

$$R_t = R_s + R_b \tag{30}$$

where:

R_s is the resistance of the pile shaft; and
R_b is the resistance of the pile base.

6.4.1.1.2 The bearing resistance of a pile foundation should be determined for the appropriate failure criterion corresponding to an ultimate limit state of the foundation.

*NOTE BS EN 1997-1:2004+A1:2013, **7.6.1.1(3)** recommends that settlement of the pile top equal to 10% of the pile base diameter be adopted as the failure criterion when it is difficult to define the ultimate limit state.*

6.4.1.1.3 The base resistance calculated from models that assume plunging failure of the pile should be reduced appropriately to match failure criterion appropriate to the ultimate limit state of the pile.

6.4.1.2 Models based on ground parameters

6.4.1.2.1 General

*COMMENTARY ON **6.4.1.2.1***

BS EN 1997-1 uses several terms that differ from traditional British practice:

- *"unit resistance" refers to resistance per unit area (i.e. over an area of 1 m^2);*
- *"ultimate unit shaft resistance" (with symbol q_s) is equivalent to "limiting shaft (or skin) friction" (traditional symbol f_s); and*
- *"ultimate base resistance" is the same as "limiting end-bearing pressure".*

A static pile formula based on ground parameters provides an estimate of the ultimate bearing resistance of the pile. The method's accuracy depends on the reliability of the chosen formula, the soil strength data to which it is applied, and site-specific pile installation methods.

6.4.1.2.1.1 The ultimate bearing resistance of a pile foundation may be calculated from static pile formulae using values of ground parameters obtained from field or laboratory tests on soil and rock.

6.4.1.2.1.2 The consequences of differences between the true ultimate bearing resistance of a pile and its calculated value (which might occur, for example, owing to differences between actual and the assumed ground conditions) should be considered where reasonably foreseeable.

6.4.1.2.1.3 The calculation of ultimate compressive resistance from ground parameters should conform to the "alternative method" given in BS EN 1997-1:2004+A1:2013, **7.6.2.3**.

6.4.1.2.1.4 If this method is used, the characteristic ultimate compressive resistance of an individual pile ($R_{c,k}$) should be calculated as:

$$R_{c,k} = R_{s,k} + R_{b,k} \quad (31)$$

where:

$R_{s,k}$ is the pile's characteristic ultimate shaft resistance; and
$R_{b,k}$ is the pile's characteristic ultimate base resistance.

6.4.1.2.1.5 The characteristic ultimate shaft resistance ($R_{s,k}$) may be calculated from:

$$R_{s,k} = \frac{\sum_{j=1}^{n} (A_{s,j} \times q_{s,j})}{\gamma_{Rd}} \quad (32)$$

where:

$A_{s,j}$ is the total circumferential area of the pile shaft (in layer j);
$q_{s,j}$ is the average ultimate unit shaft resistance (in layer j) calculated from ground parameters;
n is the total number of layers in contact with the pile shaft; and
γ_{Rd} is a model factor. The value of γ_{Rd} should conform to the UK National Annex to BS EN 1997-1:2004+A1:2013.

6.4.1.2.1.6 The characteristic ultimate base resistance ($R_{b,k}$) may be calculated from:

$$R_b = \frac{A_b \times q_b}{\gamma_{Rd}} \quad (33)$$

where:

A_b is the total cross-sectional area of the pile base;
q_b is the ultimate unit base resistance calculated from ground parameters; and
γ_{Rd} is a model factor. The value of γ_{Rd} should conform to the UK National Annex to BS EN 1997-1:2004+A1:2013.

6.4.1.2.1.7 The value of q_b should include the contribution due to the total overburden pressure at the level of the pile base.

6.4.1.2.1.8 If the self-weight of the pile is omitted from the calculation of the action, as allowed by BS EN 1997-1, **7.6.2.1(2)**, then the overburden pressure should be omitted from the calculation of $R_{b,k}$ so that:

$$R_{b,k} = \frac{A_b \times (q_b - \sigma_{v,b})}{\gamma_{Rd}} \quad (34)$$

where:

$\sigma_{v,b}$ is total overburden pressure at the pile base.

6.4.1.2.1.9 The value of the model factor γ_{Rd} should be taken from the UK National Annex to BS EN 1997-1:2004+A1:2013.

NOTE The value of the model factor γ_{Rd} given in the UK National Annex to BS EN 1997-1:2004+A1:2013 varies with the amount of static pile load testing that is available to corroborate the calculation of bearing resistance. Background information about the purpose of the model factor can be found in Decoding Eurocode 7 [47] and Pile design to Eurocode 7 and the National Annex: Part 2 [48].

6.4.1.2.2 Coarse soils

6.4.1.2.2.1 In coarse soils, the ultimate unit shaft resistance in layer *j* ($q_{s,j}$) may be calculated from effective stress parameters, as follows:

[A1⟩ $$q_{s,j} = K_{s,j} \times \tan\delta_j \times \sigma'_{v,j}$$ ⟨A1] (35)

where:

$K_{s,j}$ is an earth pressure coefficient (for layer *j*) against the pile shaft;

δ_j is the angle of interface (also known as "wall") friction between the pile and layer *j*; and

[A1⟩ $\sigma'_{v,j}$ ⟨A1] is the average vertical effective stress acting in the soil in layer *j*.

6.4.1.2.2.2 In the absence of reliable test data, values of K_s may be taken from Table 8. Alternative values of K_s may be used, provided there is previously documented evidence of the successful performance of the same type of pile in similar ground conditions using these alternative values.

Table 8 — *Suggested values of K_s for piles installed in coarse silica soils*

Pile type		Soil type	Typical coefficient, K_s A)B)
Large displacement	Precast concrete (solid) Closed-ended tubular steel Timber Driven cast-in-place concrete	(all)	1.0–1.2
Small displacement	H-section steel bearing piles Open-ended tubular steel Helical steel	(all)	80% of large displacement value
Replacement C)	Continuous flight auger (CFA)	Clean medium-coarse sand Fine sand Silty sand Interlayered silt and sand	0.9 0.7–0.8 0.6–0.7 0.5–0.6
	Bored cast-in-place concrete Micro piles D)		0.7

A) K_s values may vary due to details of specific installation methods, soil layering, groundwater pressures, and elapsed time between installation and testing.

B) K_s values may be superseded by local static pile test data, provided comprehensive documentation is provided (i.e. factual test data, interpretation, local ground conditions, specific pile installation details, etc.).

C) Values taken from the *ICE manual of geotechnical engineering (2012), Volume II, Chapter 54* [1].

D) Higher values of K_s may be used for micropiles grouted under pressure.

6.4.1.2.2.3 Values of δ may be estimated from:

$$\delta = min\begin{cases} k_{\delta} \times \varphi'_{\mathrm{pk}} \\ \varphi'_{\mathrm{cv}} \end{cases} \quad (36)$$

where:

φ'_{pk} is the soil's peak angle of shearing resistance;

φ'_{cv} is the soil's constant-volume angle of shearing resistance determined in accordance with **4.6.2.4**; and

k_{δ} is a dimensionless coefficient.

6.4.1.2.2.4 In the absence of reliable test data, values of k_{δ} may be taken from Table 9.

Table 9 — *Suggested values of k_{δ} for piles installed in coarse soils*

Pile type		Coefficient k_{δ}
Large displacement	Precast concrete (solid) Closed-ended tubular steel	0.67
	Driven cast-in-place concrete	0.9
	Timber	0.85
Small displacement	Steel bearing piles of H-section	0.67
	Open-ended tubular steel	
	Helical steel piles	0.67 [A] or 1.0 [B]
Replacement	Continuous flight auger (CFA) Bored cast-in-place concrete Micro piles	1.0

[A] Value along periphery of steel shaft (soil-to-steel boundary).

[B] Value along periphery of helices (soil-to-soil boundary).

6.4.1.2.2.5 Depending on the pile installation method, the presence of fine soils overlying coarse soils can adversely affect the angle of interface friction in those underlying coarse soils. The value of δ should be selected appropriately when this is the case.

6.4.1.2.2.6 In coarse soils, the ultimate effective unit base resistance (q'_{b}) may be calculated from effective stress parameters, as follows:

$$q'_{\mathrm{b}} = N_{\mathrm{q}} \times \sigma'_{\mathrm{v,b}} \quad (37)$$

where:

$\sigma'_{v,b}$ is the vertical effective stress at the pile base; and

N_{q} is a bearing pressure coefficient that depends on the soil's constant-volume angle of shearing resistance, φ_{cv}; the soil's density index, ID; and the vertical effective stress at the pile base, $\sigma'_{v,b}$.

NOTE The value of N_{q} can be obtained from a wide range of theories, including those given in Load bearing capacity and deformation of piled foundations [49], Piling Engineering (3rd edition) [50], and The Engineering of Foundations [51].

6.4.1.2.2.7 The density index, I_{D}, (which is defined in BS EN ISO 14688-2) may be estimated from the results of field tests (e.g. Standard Penetration Test, Cone Penetration Test) using correlations given in BS EN 1997-2.

6.4.1.2.3 Fine soils

6.4.1.2.3.1 In fine soils, the ultimate unit shaft resistance in layer *j* ($q_{s,j}$) may be calculated from effective stress parameters, as follows:

$$\text{[A1⟩}\; q_{s,j} = \beta_j \times \sigma'_{v,j} \;\text{⟨A1]} \tag{38}$$

where:

β_j is an empirical coefficient (for layer *j*); and

[A1⟩ $\sigma'_{v,j}$ ⟨A1] is the average vertical effective stress acting in the soil in layer *j*.

6.4.1.2.3.2 In the absence of reliable test data, values of β for fine soils may be estimated from (see *Shaft friction on piles in clay: a simple fundamental approach* [52] and *Bearing capacity and settlement of pile foundations* [53]):

$$\beta = \begin{cases} (1-\sin\varphi)\tan\varphi & \text{for normally consolidated days} \\ 1.5(1-\sin\varphi)\tan\varphi\sqrt{R_o} & \text{for overconsolidated days} \end{cases} \tag{39}$$

where:

φ is the soil's angle of shearing resistance; and

R_o is the soil's overconsolidation ratio, given by $R_o = p'_{v,max} / p'_v$;

p'_v is the effective overburden pressure; and

$p'_{v,max}$ is the maximum effective overburden pressure that the soil has previously been subjected to.

6.4.1.2.3.3 Alternatively, the ultimate unit shaft resistance in layer *j* ($q_{s,j}$) may be calculated from total stress parameters, as follows:

$$q_{s,j} = \alpha_j \times c_{u,j} \tag{40}$$

where:

α_j is an empirical coefficient (for layer *j*) that depends on the strength of the soil, the effective overburden pressure acting on it, pile type, and method of execution; and

$C_{u,j}$ is the undrained shear strength of the soil in layer *j*.

NOTE Equation (40) is an empirical relationship between undrained shear strength measured using historical sampling and laboratory test practice (e.g. quick undrained triaxial compression texts on 100 mm diameter samples) and test data from static pile load tests using maintained load.

6.4.1.2.3.4 For piles located in ground that is subject to a reduction in stress (for example, within the zone of influence of deep excavations), equation (40) should only be used if allowance is made for this stress relaxation.

6.4.1.2.3.5 Values of α should be obtained from previous 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.

6.4.1.2.3.6 In the absence of reliable test data, values of α may be estimated from one of the methods given in this subclause (**6.4.1.2.3**).

6.4.1.2.3.7 In the absence of reliable test data, values of α for replacement piles (denoted α_{repl}) may be estimated from:

$$0.4 \le \alpha_{repl} = k_1\left(1 - k_2 \log_e \frac{c_u}{p_{ref}}\right) \le 1.0 \tag{41}$$

where:

c_u is the undrained shear strength of the fine soil;

p_{ref} is 100 kPa; and

k_1 and k_2 are coefficients whose values may be taken as 0.45 and 1.0, respectively.

6.4.1.2.3.8 For replacement piles in glacial tills, the values of k_1 and k_2 in equation (41) may be taken as 0.75 and 0.75, respectively (see *Piling in 'boulder clay' and other glacial tills* [54]).

6.4.1.2.3.9 For bored piles in stiff overconsolidated clays (such as London, Gault, Lias, Oxford and Weald Clays), provided the bore is left open for less than 12 hours, then α_{repl} may be taken as 0.5 (see *Foundations no. 1* [55]).

6.4.1.2.3.10 Alternative values of α_{repl} may be used, provided there is previously documented evidence of the successful performance of the same type of pile in similar ground conditions using these alternative values.

6.4.1.2.3.11 In the absence of reliable test data, values of α for displacement piles (denoted α_{disp}) may be estimated from:

$$\alpha_{disp} = 0.5(c_u / \sigma'_v)^{-m} \tag{42}$$

where:

c_u is the undrained shear strength of the fine soil;

σ'_v is the effective vertical stress (overburden pressure) acting on the soil; and

m is 0.25 for $c_u/\sigma'_v \geq 1$ and 0.5 for $c_u/\sigma'_v < 1$.

6.4.1.2.3.12 Alternative values of α_{disp} may be used, provided there is previously documented evidence of the successful performance of the same type of pile in similar ground conditions using these alternative values.

6.4.1.2.3.13 In fine soils, the ultimate unit base resistance (q_b) may be calculated from total stress parameters, as follows:

$$q_b = N_c \times c_{u,b} \tag{43}$$

where:

N_c is a bearing pressure coefficient that depends on the depth of the pile base; and

$c_{u,b}$ is the undrained shear strength of the soil at the pile base.

6.4.1.2.3.14 In the absence of reliable test data, the value of N_c may be calculated from:

$$N_c = 9 \times k_1 \times k_2 \tag{44}$$

where:

k_1 is a coefficient that accounts for insufficient embedment of the pile toe; and

k_2 is a coefficient that accounts for the stiffness of the bearing statum.

6.4.1.2.3.15 The value of k_1 in equation (44) should be calculated from:

[A1] $$k_1 = \begin{cases} \frac{2}{3}\left(1 + \frac{L}{6B}\right) & \text{for L/B } < 3 \\ 1.0 & \text{for L/B } \geq 3 \end{cases} \tag{45}$$ [/A1]

where:

L	is the depth of embedment of the pile toe into the bearing stratum; and
B	is the pile breadth (or diameter).

6.4.1.2.3.16 Values of k_2 should be taken from Table 10.

Table 10 — *Suggested values of k_2 for piles installed in fine soil*

Pile type	**Undrained shear strength of soil, c_u** **kPa**	k_2	$9 \times k_2$
Bored, CFA [A]	≤25	0.72	6.5
	50	0.89	8
	≥100	1.0	9
Driven [B]		1.11	10

[A] Values based on *FHWA Report No. NHI-10-016* [56]; k_2 may be interpolated for intermediate values of c_u.

[B] Value based on *Salgado* [51].

6.4.1.3 Models based on the results of ground tests

6.4.1.3.1 General

6.4.1.3.1.1 The ultimate bearing resistance of a pile foundation may be calculated directly from the results of ground tests on soil and rock (i.e. without first converting those results to ground parameters).

6.4.1.3.1.2 The calculation of ultimate compressive resistance from the results of ground tests should conform to the main method given in BS EN 1997-1:2004+A1:2013, **7.6.2.3**.

6.4.1.3.1.3 If this method is used, the characteristic ultimate compressive resistance of an individual pile ($R_{c,k}$) should be calculated as the smaller of the following two values:

$$R_{c,k} = \min\begin{cases} (R_{c,calc})_{mean} / \xi_3 \\ (R_{c,calc})_{min} / \xi_4 \end{cases} \qquad (46)$$

where:

ξ_3 and ξ_4	are correlation coefficients that depend on the number of tests performed;
$(R_{c,calc})_{mean}$	is the mean calculated ultimate compressive resistance of the pile; and
$(R_{c,calc})_{min}$	is the minimum calculated ultimate compressive resistance of the pile.

6.4.1.3.1.4 The calculated ultimate compressive resistance of an individual pile ($R_{c,calc}$) should be determined from:

$$R_{c,calc} = R_{s,calc} + R_{b,calc} \qquad (47)$$

where:

$R_{s,calc}$	is the calculated ultimate shaft resistance; and
$R_{b,calc}$	is the calculated ultimate base resistance.

6.4.1.3.1.5 The calculated ultimate shaft resistance ($R_{s,calc}$) may be determined from:

$$R_{s,calc} = \sum_{i=1}^{n} (A_{s,i} \times p_{s,i}) \qquad (48)$$

where:

$A_{s,i}$ is the total circumferential area of the pile shaft (in layer *i*);

$P_{s,i}$ is the ultimate unit shaft resistance (in layer *i*) obtained from a field test; and

n is the total number of layers in contact with the pile shaft.

6.4.1.3.1.6 The calculated ultimate base resistance ($R_{b,calc}$) may be determined from:

$$R_{b,calc} = A_b \times p_b \quad (49)$$

where:

A_b is the total cross-sectional area of the pile base; and

p_b is the ultimate unit base resistance obtained from a field test.

6.4.1.3.1.7 The values of the correlation coefficients ξ_3 and ξ_4 should be taken from the UK National Annex to BS EN 1997-1:2004+A1:2013.

6.4.1.3.2 Cone penetration tests (CPTs)

6.4.1.3.2.1 The ultimate unit shaft resistance in layer *j* ($p_{s,j}$) may be calculated from:

$$p_{s,j} = c_{s,j} \times q_{c,j} \quad (50)$$

where:

$C_{s,j}$ is an empirical coefficient (for layer *j*) that depends on soil and pile type; and

$q_{c,j}$ is the measured cone resistance in layer *j*.

6.4.1.3.2.2 The ultimate unit base resistance, at a settlement equal to 10% of pile diameter, ($p_{b,0.1}$) may be calculated from:

$$p_{b,0.1} = c_{b,0.1} \times q_{c,b} \quad (51)$$

where:

$c_{b,0.1}$ is an empirical coefficient that depends on soil and pile type; and

$q_{c,b}$ is the average cone resistance measured over a distance ±1.5 pile diameters below the pile base.

6.4.1.3.2.3 In the absence of reliable test data, values of c_s and $c_{b,0.1}$ may be estimated from Table 11.

NOTE Further information about $c_{b,0.1}$ can be found in Comparing CPT and pile base resistance in sand [57].

Table 11 — *Values of the empirical coefficients c_s and $c_{b,0.1}$ according to soil and pile type*

Soil type		c_s			$c_{b,0.1}$		
		Displacement piles		**Replacement piles**	**Displacement piles**		**Replacement piles**
		High displacement	**Low displacement**		**High displacement**	**Low displacement**	
Sand		0.0004–0.009 [A),B),C)]	0.0015–0.004 [A),B),C)]	0.003–0.006 [D),E)]	0.3–0.5 [F),G)]	0.15–0.25 [F),G)]	0.15–0.25 [H)]
Silt		0.006–0.01 [B),C)]		0.003–0.006 [D)]	Data not available		
Clay	Medium to high strength/ over-consolidated	0.007–0.017 [B),C)]		0.008–0.012 [D)]	0.8–1.3 [I)]	0.4–0.65 [I)]	0.34–0.66 [D)]
	Low strength/normally consolidated to lightly over-consolidated	Data not available			0.9–1.0		0.9–1.0

A) See *Estimation of load capacity of pipe piles in sand based on CPT results* [58].

B) See *An approximate method to estimate the bearing capacity of piles* [59].

C) See *Fundações para o silo vertical de 100000 t no Porto de Paranaguá* [60].

D) See *On the prediction of the bearing capacity of bored piles from dynamic penetration tests* [61].

E) See *Pile capacity by direct CPT and CPTu methods applied to 102 case histories* [62].

F) See *Evaluation of a minimum base resistance for driven pipe piles in siliceous sand* [63].

G) See *Investigations into the behaviour of displacement piles for offshore structures* [64].

H) See *Determination of pile base resistance in sands* [65].

I) See *ICP design methods for driven piles in sands and clays* [66]

6.4.1.3.3 Standard Penetration Tests (SPT)

6.4.1.3.3.1 The ultimate unit shaft resistance in layer *j* ($p_{s,j}$) may be calculated from:

$$p_{s,j} = n_{s,j} \times p_{ref} \times N_j \tag{52}$$

where:

$n_{s,j}$	is an empirical coefficient (for layer *j*) that depends on soil and pile type;
P_{ref}	is 100 kPa; and
N_j	is the measured (uncorrected) SPT blow count in layer *j*.

6.4.1.3.3.2 The ultimate unit base resistance, at a settlement equal to 10% of pile diameter, ($p_{b,0.1}$) may be calculated from:

$$p_{b,0.1} = n_{b,0.1} \times p_{ref} \times N_b \tag{53}$$

where:

$n_{b,0.1}$	is an empirical coefficient that depends on soil and pile type;
P_{ref}	is 100 kPa; and
N_b	is the measured (uncorrected) SPT blow count at the level of the pile base.

6.4.1.3.3.3 In the absence of reliable test data, values of n_s and $n_{b,0.1}$ may be estimated from Table 12.

Table 12 — *Values of the empirical coefficients* n_s *and* $n_{b,0.1}$ *according to soil and pile type*

Soil type	n_s		[A1⟩ $n_{b,0.1}$ ⟨A1]	
	Displacement	**Replacement**	**Displacement**	**Replacement**
Sand	0.033–0.043 [A)B)]	0.014–0.026 [A)B)C)]	2.9–4.8 [A)]	0.72–0.82 [C)]
Silt	0.018–0.03 [A)B)]	0.016–.023 [C)]	1.1–2.6 [A)B)]	0.41–0.66 [C)]
Clay	0.020–0.029 [A)B)]	0.024–0.031 [C)]	0.95–1.6 [A)B)]	0.34–0.66 [C)]

A) See *An approximate method to estimate the bearing capacity of piles* [59].

B) See *Fundações para o silo vertical de 100000 t no Porto de Paranaguá* [60].

C) See *On the prediction of the bearing capacity of bored piles from dynamic penetration tests* [61].

6.4.1.3.3.4 Correlations with SPT blow count should be treated with caution, since they are inevitably approximate and not universally applicable.

6.4.1.4 Models based on static pile load tests

COMMENTARY ON ***6.4.1.4***

In the UK, static pile load tests are mainly used to verify resistance calculated using estimated soil parameters.

Static pile load tests are ill suited for designing piles in variable ground conditions, where it is impossible to determine the resistance provided by different strata.

Pile designs based on the results of dynamic impact tests alone can be unreliable when downdrag occurs.

6.4.1.4.1 The ultimate bearing resistance of a pile foundation may be calculated directly from the results of static pile load tests.

6.4.1.4.2 The calculation of ultimate compressive resistance from static pile load tests should conform to BS EN 1997-1:2004+A1:2013, **7.6.2.2**.

