Pile design according to EN 1997-3:2024 - Overview of Clause 6: Pile foundations

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Outline

1. Introduction: Evolution of pile design in EN 1997:2024
2. Overview: Structure and content of EN 1997-3:Clause 6
   2.1 Scope of Clause 6
   2.2 Link to EN 1990 and EN 1997-1
   2.3 Design by calculation, by testing, by prescriptive rules, …
   2.4 Ground model method and model pile method
   2.5 Confirmation of pile design by testing
3. Major modifications in comparison to 1st generation
   3.1 Single pile vs. pile group – piled raft
   3.2 Harmonized verification principles
   3.3 Design for effect of ground displacements
   3.4 Splitting of previous correlation factors in correlation & model factors
   3.5 Application of numerical methods
4. Conclusions
Introduction: Timeline - Evolution of Clause on Pile Design

- EG1-14: Evolution Groups
- EG 7: ‘Pile Design’
- PT1: Harmonization and ease-of-use
- PT2: General rules
- PT3: Ground investigation
- PT4: Slopes, Foundations, GI
- PT5: Retaining structures, Anchor...
- PT6: Rock, Dynamic design, …
- TC 250 responds to Mandate M466
- TC 250 responds to Mandate M515
- Systematic review of EN 1997
- European Commission gives go ahead
- EG Evolution Group
- PT: Project Team
- WG: Working Group
- TG: Task Group
- long-term evolution process
- many European experts involved
- intensive review and commenting (NSBs, …) at regular intervals
Introduction: Pile Design based on EN 1997:2024

1st generation

EN 1990: 2002
Basis of structural design

2nd generation

EN 1990: 2024
Basis of structural and geotechnical design

EN 1997-1: 2004
General rules

EN 1997-2: 2007
Ground investigation and testing

EN 1997-3: 2024
Geotechnical structures

Conceptual and General Framework

content relevant for pile design:

- principles, e.g. Consequence Classes, consequence factors $K_F$
- partial factors on actions $\gamma_F$ and stresses $\gamma_E$
- verification cases VC1 to VC4
- ...
- Geotechnical Category GC
- representative values $X_{\text{rep}}$, $X_{\text{nom}}$, $X_k$ etc.
- partial factors $\gamma_M$ on ground properties (M1/M2)
- consequence factors $K_M$, $K_R$
- type of ULS
- SLS criteria
- ...
- Clause 6: ´Piled foundations´
  - geotechnical analysis of piled foundations (calculation and testing)
  - ULS and SLS verifications
  - model factors $\gamma_{\text{rd}}$
  - correlation factors $\zeta$
  - partial factors $\gamma_R$ on pile resistances
  - ...
## Introduction: prEN1997-3 ´Geotechnical Structures´ - Contents

<table>
<thead>
<tr>
<th>EN 1997-3:2024</th>
<th>EN 1997-1:2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>0  Introduction</td>
<td></td>
</tr>
<tr>
<td>1  Scope</td>
<td>Chapter 11 ´Overall Stability´ + 12 ´Embankments´</td>
</tr>
<tr>
<td>2  Normative references</td>
<td>Chapter 6 ´Spread Foundations´</td>
</tr>
<tr>
<td>3  Terms, definitions, and symbols</td>
<td></td>
</tr>
<tr>
<td>4  Slopes, cuttings, and embankments</td>
<td>Chapter 7 ´Pile Foundations´</td>
</tr>
<tr>
<td>5  Spread foundations</td>
<td></td>
</tr>
<tr>
<td><strong>6  Piled foundations</strong></td>
<td></td>
</tr>
<tr>
<td>7  Retaining structures</td>
<td>Chapter 9 ´Retaining Structures´</td>
</tr>
<tr>
<td>8  Anchors</td>
<td>Chapter 8 ´Anchorages´</td>
</tr>
<tr>
<td>9  Reinforced fill structures</td>
<td>new (section 5.5 ´Ground improvement &amp; reinforcement´)</td>
</tr>
<tr>
<td>10 Ground reinforcing elements</td>
<td>new</td>
</tr>
<tr>
<td>11 Ground improvement</td>
<td>new (section 5.5)</td>
</tr>
<tr>
<td>12 Groundwater control</td>
<td>new (section 5.4 ´Dewatering´)</td>
</tr>
<tr>
<td>› Annexes A, B, C, D, E, F, G</td>
<td></td>
</tr>
<tr>
<td>(to Clauses 4, 5, 6, 7, 8, 9 and 11)</td>
<td></td>
</tr>
<tr>
<td>Bibliography</td>
<td></td>
</tr>
</tbody>
</table>
## Introduction: prEN1997-3 ‘Geotechnical Structures´ - Contents

<table>
<thead>
<tr>
<th>EN 1997-3:2024</th>
<th>uniform structure of Clauses 4 to 11</th>
<th>EN 1997-1:2024</th>
</tr>
</thead>
<tbody>
<tr>
<td>0  Introduction</td>
<td>x.1  Scope and field of application</td>
<td>0  Introduction</td>
</tr>
<tr>
<td>1  Scope</td>
<td>x.2  Basis of design</td>
<td>1  Scope</td>
</tr>
<tr>
<td>2  Normative references</td>
<td>x.3  Materials</td>
<td>2  Normative references</td>
</tr>
<tr>
<td>3  Terms, definitions, and symbols</td>
<td>x.4  Groundwater</td>
<td>3  Terms, definitions, and symbols</td>
</tr>
<tr>
<td>4  Slopes, cuttings, and embankments</td>
<td>x.5  Geotechnical analysis</td>
<td>4  Basis of design</td>
</tr>
<tr>
<td>5  Spread foundations</td>
<td>x.6  Ultimate limit states</td>
<td>5  Materials</td>
</tr>
<tr>
<td>6  Piled foundations</td>
<td>x.7  Serviceability limit states</td>
<td>6  Groundwater</td>
</tr>
<tr>
<td>7  Retaining structures</td>
<td>x.8  Implementation of design</td>
<td>7  Geotechnical analysis</td>
</tr>
<tr>
<td>8  Anchors</td>
<td>x.9  Testing</td>
<td>8  Ultimate limit states</td>
</tr>
<tr>
<td>9  Reinforced fill structures</td>
<td>x.10 Reporting</td>
<td>9  Serviceability limit states</td>
</tr>
<tr>
<td>10 Ground reinforcing elements</td>
<td></td>
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</tr>
<tr>
<td>11 Ground improvement</td>
<td></td>
<td>11 Testing</td>
</tr>
<tr>
<td>12 Groundwater control</td>
<td></td>
<td>12 Reporting</td>
</tr>
</tbody>
</table>

- Annexes A, B, C, D, E, F, G (to Clauses 4, 5, 6, 7, 8, 9 and 11)
- Bibliography
6.1 Scope and field of application

(1) This Clause shall apply to single piles, pile groups and piled rafts.

(2) Piles should be classified according to their method of execution.

Table 6.1 — (NDP) Classification of piles

<table>
<thead>
<tr>
<th>Pile type</th>
<th>Description</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement pile</td>
<td>Pile installed in the ground without excavation of material</td>
<td>Full displacement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Partial displacement</td>
</tr>
<tr>
<td>Replacement pile</td>
<td>Pile installed in the ground after the excavation of material</td>
<td>Replacement</td>
</tr>
<tr>
<td>Pile not listed above</td>
<td>---</td>
<td>Unclassified</td>
</tr>
</tbody>
</table>

- Pile class (only) used to determine resistance factors $\gamma_R$
- Annex C.3: Examples of pile types in different classes
6.2 Basis of design

- Basic considerations for
  - Design situations
  - Geometrical properties
  - Zone of influence
  - Actions
    → permanent and variables actions
    → cyclic and dynamic actions
    (↗ effect on long-term pile resistance)
    → actions due to ground displacements
  - Limit states (ULS / SLS)
  - Robustness

with reference to EN 1997-1 plus some additional rules for piles
Overview of Clause 6 ‘Piled foundations’

6.2 Basis of design

- Ground investigations
  - general requirements (field and lab investigations, properties, …)
  - minimum extent of field investigations

Table 6.4 — (NDP) Minimum depth of field investigation for piled foundations

<table>
<thead>
<tr>
<th>Application</th>
<th>Minimum depth</th>
<th>Illustration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piled foundation</td>
<td>(d_{\min}=\max(3B; 5 \text{ m}))</td>
<td>[Illustration]</td>
</tr>
</tbody>
</table>

B is the equivalent size of the pile base (the diameter for a circular pile, the width of a square pile or the equivalent diameter)

- for pile groups: \(d_{\min} = \max(5 \text{ m}; 3B_{b,eq}; p_{\text{group}})\)
- reduced minimum depths in strong rock masses: \(d_{\min} = \max(3 \text{ m}; 3B_{p,eq})\)
Overview of Clause 6 ´Piled foundations´

EN 1997-3:2024, Clause 6

6.1 Scope and field of application
6.2 Basis of design
6.3 Materials
6.4 Groundwater
6.5 Geotechnical analysis
6.6 Ultimate limit states
6.7 Serviceability limit states
6.8 Implementation of design
6.9 Testing
6.10 Reporting
Annex C

6.3 Materials

- Ground properties: - reference to EN 1997-2, 7-12
  - properties after pile execution relevant
- Plain and reinforced concrete: - reference to EN 1997-1, 5.5
  - concrete cover acc. to EN 1992-1-1
  - exposure classes acc. to EN 206
- Grout and mortar: - reference to EN 1997-1, 5.4
- Steel: - reference to EN 1997-1, 5.6
- Ductile cast iron: - reference to EN 1563
- Timber: - reference to EN 1997-1, 5.7
EN 1997-3:2024, Clause 6

6.1 Scope and field of application
6.2 Basis of design
6.3 Materials
6.4 Groundwater
6.5 Geotechnical analysis
6.6 Ultimate limit states
6.7 Serviceability limit states
6.8 Implementation of design
6.9 Testing
6.10 Reporting
Annex C

6.4 Groundwater

- just reference to EN 1997-1, 6
- no specific rules for piles.
6.5 Geotechnical analysis

- **Effect of ground displacement:**
  - Downdrag
  - Heave
  - Transverse loading
  
  \[\text{detailed rules for calculation of downdrag for SLS- and ULS- verification}\]

- **Axially loaded single piles:**
  - Calculation
  - Testing
  - Prescriptive rules
  
  \(\text{design by calculation using}\)
  - ground properties determined from field & laboratory tests (Ground Model Method)
  - individual pile resistance profiles determined from correlations with field test results (Model Pile Method).

  \(\text{design by testing using}\)
  - static pile load tests for ULS- and SLS-verification of piles in compression and tension
  - dynamic impact or rapid load tests for ULS-verification of piles in compression

- **Transversely loaded single piles**
6.5 Geotechnical analysis

- Pile groups
  \[ R_{\text{group}} = \min \left( \sum_{i=1}^{n} R_i ; R_{\text{block}} \right) \]

- Piled rafts
  \[ R_{\text{piled-raft}} = \left( \sum_{i=1}^{n} R_{c,i} + R_{\text{raft}} \right) \]

  → requirement to consider interaction effects
  → numerical, analytical, or empirical calculation methods

- Displacements of piled foundations
  - Singe piles
  - Pile groups and piled rafts

  → requirements on effects to be considered for calculation
  → specification of possible approaches
6.5 Geotechnical analysis

- Confirmation of pile design by site-specific load testing or comparable experience
  - Pile design should be validated using site-specific static load testing (…)
  - Pile resistance to axial compression may be confirmed using dynamic impact or rapid load tests provided that these tests have been validated by static pile load tests.
  - Site-specific ultimate control test may be omitted where there is comparable experience

<table>
<thead>
<tr>
<th>Type of load test</th>
<th>Confirmation of design by Ultimate Control Tests</th>
<th>Confirmation of design by Serviceability Control Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static load test</td>
<td>max (1, 0.5 % N)</td>
<td>max (2, 1 % N)</td>
</tr>
<tr>
<td>Rapid load test</td>
<td>max (3, 1.0 % N)</td>
<td>max (6, 5 % N)</td>
</tr>
<tr>
<td>Dynamic impact load test</td>
<td>max (3, 1.0 % N)</td>
<td>max (6, 5 % N)</td>
</tr>
</tbody>
</table>

**NOTE**  
N = total number of piles in similar ground conditions
6.6 Ultimate limit state

- Single piles:
  - Representative values of resistance
    - for design by calculation using the Ground Model Method
      \[ R_{rep} = R_{calc} \]
    - for design by calculation using the Model Pile Method
      \[ R_{rep} = \min \left\{ \frac{R_{calc,\text{mean}}}{\xi_{\text{mean}}}; \frac{R_{calc,\text{min}}}{\xi_{\text{min}}} \right\} \]
    - for design by testing
      \[ R_{rep} = \min \left\{ \frac{R_{test,\text{mean}}}{\xi_{\text{mean}}}; \frac{R_{test,\text{min}}}{\xi_{\text{min}}} \right\} \]
      with: \( \xi \) - correlation factors
Overview of Clause 6 ‘Piled foundations’

EN 1997-3:2024, Clause 6

6.1 Scope and field of application
6.2 Basis of design
6.3 Materials
6.4 Groundwater
6.5 Geotechnical analysis
6.6 Ultimate limit states
6.7 Serviceability limit states
6.8 Implementation of design
6.9 Testing
6.10 Reporting
Annex C

6.6 Ultimate limit state

- Single piles:
  - Verification of axial compressive resistance
    \[
    F_{cd} \leq R_{cd} \quad \text{with:} \quad \gamma_{Rd} - \text{model factor} \quad \gamma_{Rc}, \gamma_{Rb}, \gamma_{Rs} - \text{resistance factors}
    \]
    \[
    R_{cd} = \frac{R_{c,rep}}{\gamma_{Rc} \cdot \gamma_{Rd}} \quad \text{or} \quad \left( \frac{R_{b,rep}}{\gamma_{Rb} \cdot \gamma_{Rd}} + \frac{R_{s,rep}}{\gamma_{Rs} \cdot \gamma_{Rd}} \right)
    \]
  - Verification of axial tensile resistance
  - Verification of transverse resistance
  - Downdrag
  - Transverse ground loading
Overview of Clause 6 ‘Piled foundations’

EN 1997-3:2024, Clause 6

6.1 Scope and field of application
6.2 Basis of design
6.3 Materials
6.4 Groundwater
6.5 Geotechnical analysis

6.6 Ultimate limit states

6.7 Serviceability limit states
6.8 Implementation of design
6.9 Testing
6.10 Reporting
Annex C

6.6 Ultimate limit state

- Pile Groups:
  - Verification
  \[ F_d \leq R_{d,\text{group}} \]
  \[ R_{d,\text{group}} = \frac{R_{\text{rep,group}}}{\gamma_{R,\text{group}} \gamma_{Rd,\text{group}}} \]

- Piled Rafts:
  - Verification
  \[ F_d \leq R_{d,\text{piled-raft}} \]
  \[ R_{d,\text{piled-raft}} = R_{d,\text{group}} + \frac{R_{\text{rep,raft}}}{\gamma_{R,\text{raft}}} \]

  Model, partial and correlation factors
  for single piles, pile groups and piled rafts
6.7 Serviceability limit states

- Reference to EN 1997-1, 9

- Permission to omit explicit SLS-verification for single piles in case of comparable experience or by applying a simplified evaluation

\[ F_{cd, SLS} \leq \kappa_{b, SLS} R_{b, rep} + \kappa_{b, SLS} R_{s, rep} \]

with \( \kappa_{b, SLS} \) and \( \kappa_{s, SLS} \) mobilization factor for base resp. shaft resistance in SLS

- SLS-verification for pile groups and piled rafts should consider
  - non-linear stiffness of the ground,
  - flexural stiffness of the structure, and
  - interaction between ground, structures, and piles
6.8 Implementation of design

- Reference to standards on execution of piles (EN 1536, EN 12699, EN 14199) but also to EN 1538 (diaphragm walls), EN 12716 (jet grouting), EN 14679 (deep mixing) etc.

- for ‘Inspection’, ‘Monitoring’ and ‘Maintenance’ reference to EN 1997-1, 10

- no further specific requirements for piles
EN 1997-3:2024, Clause 6

6.1 Scope and field of application
6.2 Basis of design
6.3 Materials
6.4 Groundwater
6.5 Geotechnical analysis
6.6 Ultimate limit states
6.7 Serviceability limit states
6.8 Implementation of design

6.9 Testing

6.10 Reporting
Annex C

6.9 Testing

- Reference to standards on execution of pile load tests (EN ISO 22477-x)
- Specifications on trial piles and determination of test proof loads
  
  e.g. (…) a smaller diameter trial pile may be installed provided that:
  - the ratio of the trial pile to working pile diameter is not less than 0.5; (…)
  - the trial pile is instrumented to allow separation of base and shaft resistance.

  e.g. determination of test load for Ultimate Control Tests:
  \[ P_p \geq \gamma_{Rd} \cdot \xi \cdot \gamma_R \cdot F_{d,ULS} + D_{add} + D_{sup} \]

- Specifications on planning and interpretation of static load tests, rapid load tests and dynamic impact tests

  e.g. (…), the ultimate compressive resistance may be determined as:
  - the maximum applied test load; or
  - the test load at a pile head settlement equal to 10 % of the pile’s base diameter.
EN 1997-3:2024, Clause 6

6.1 Scope and field of application
6.2 Basis of design
6.3 Materials
6.4 Groundwater
6.5 Geotechnical analysis
6.6 Ultimate limit states
6.7 Serviceability limit states
6.8 Implementation of design
6.9 Testing

6.10 Reporting

- Reference to EN 1997-1, 12, and to standards on execution of piles and on pile load tests (EN ISO 22477-x)
- No further specific regulations for piles
Overview of Clause 6 ´Piled foundations´

EN 1997-3:2024, Clause 6

6.1 Scope and field of application
6.2 Basis of design
6.3 Materials
6.4 Groundwater
6.5 Geotechnical analysis
6.6 Ultimate limit states
6.7 Serviceability limit states
6.8 Implementation of design
6.9 Testing
6.10 Reporting

Annex C

Annex C ´Piled Foundations´ (informative)

C.3 Examples of pile types (Classification)
C.4,C.5 … ground parameters
C.6 … CPT profiles
C.7 … PMT profiles
C.8 … empirical tables
C.9 Calculation of downdrag due to vertical ground movements
C.10 Pile groups subject to axial tension
C.11 Calculation model for single pile settlement using load transfer functions
C.12 Calculation model for single pile lateral displacement using load transfer functions
C.13 Calculation model for buckling and second order effects
C.14 Determination of axial pile resistance under cyclic loading
Major modifications: Single piles – pile groups – piled rafts

Equivalent consideration of single piles, pile groups and piled rafts
→ geotechnical analysis, ULS-/SLS-verification, partial resistance factors

### Design of pile groups

#### 6.5.5 Pile groups

1. Pile group design shall consider that the resistance and load-displacement behaviour of individual piles in a group might show significant variation compared to the behaviour of single piles.

2. The ultimate vertical resistance of a pile group $R_{group}$ should be determined from Formula 6.8:

$$R_{group} = \min \left\{ \sum_{i=1}^{n} R_i \cdot R_{block} \right\}$$  \hspace{1cm} (6.8)

where

- $R_i$ is the ultimate axial resistance of the $i$-th pile in the pile group, taking full account of the effects of pile interaction;
- $i$ is an index that varies from 1 to $n$;
- $n$ is the number of piles within the piled foundation;
- $R_{block}$ is the ultimate vertical resistance of the block of ground bounded by the perimeter of the pile group.

### Design of piled rafts

#### 6.5.6 Piled rafts

1. The ultimate compressive resistance of a piled raft $R_{piled-raft}$ should be determined from Formula 6.9 considering the compatibility of the displacements of the piles and the rafts:

$$R_{piled-raft} = \left( \sum_{i=1}^{n} R_{i} \cdot R_{raft} \right)$$  \hspace{1cm} (6.9)

where

- $R_{raft}$ is the ultimate compressive resistance of the raft alone;
- $R_{i}$ is the compressive resistance of the $i$-th pile;
- $i$ is an index that varies from 1 to $n$;
- $n$ is the number of piles supporting the piled-raft.

2. The design of piled rafts should consider the interaction effects shown in Figure 6.1:

- 1. pile-soil interaction
- 2. pile-pile interaction
- 3. raft-soil interaction
- 4. pile-raft interaction
**Major modifications: Smooth transition for foundation types**

Stringent foundation design and verification concept for all types of foundation
→ smooth transition from spread foundations via ground improvement to piled rafts and piled foundations with comparable equivalent global safety level

**Clause 5**
Spread Foundation

**Clause 11**
Ground improvement
with rigid inclusions and LTP

**Clause 6**
Piled raft
with rigid inclusions w/o LTP

**Clause 6**
Piled foundation
Major modifications: Harmonisation of verification concept

Harmonized verification concept for piles throughout Europe

- Harmonized verification approach of ULS
  - RFA for axially loaded single piles
  - MFA for laterally loaded single piles

Axial pile design in Europe acc. to 1st generation of EC 7
Major modifications: Modified set of model & correlation factors

Concept for model and correlations factors adjusted

- Set of partial, model and correlation factors for pile design modified → more stringent concept

- Adjustment of previous correlation factors $\xi$ into
  - correlation factors $\xi$ → considering (solely) spatial soil variability
  - model factors $\gamma_{Rd}$ → considering uncertainties related
    - to the calculation model (for design by calculation)
    - to the execution and evaluation of pile load tests (for design by testing)

- separate set of correlations and model factors for
  - static load tests
  - rapid load tests
  - dynamic impact tests
Major modifications: Actions due to ground displacement

More detailed guidance for consideration of actions due to vertical and horizontal ground displacement → downdrag, heave, transverse loading

Example: Downdrag

detailed rules for calculation of downdrag and consideration for ULS- and SLS-verifications

C.9 Downdrag due to vertical ground movements

6.5.2.2 Downdrag

(1) The adverse effects of the drag force caused by moving ground shall be included in the verification of serviceability and ultimate limit states.

(2) The effects of the downdrag should be modelled by carrying out a ground-pile interaction analysis, to determine the depth of the neutral plane \( L_{ul} \) corresponding to the point where the pile settlement spile equals the ground settlement.

NOTE 1 The neutral plane marks the boundary between downwards shaft friction (occurring above the neutral plane), and upwards shaft friction (occurring below the neutral plane).

NOTE 2 The depth of the neutral plane \( L_{ul} \) is usually different for serviceability and ultimate limit state conditions.

(6) The equivalent drag force \( D_{rep} \) should be determined from Formula 6.3:

\[
D_{rep} = p \int_0^{L_{ul}} \tau_s \cdot dz
\]

where

- \( p \) is the perimeter of the pile;
- \( \tau_s \) is the unit shaft friction causing downdrag at depth \( z \);
- \( L_{ul} \) is the depth to the neutral plane.
Major modifications: Numerical calculation of piled foundations

Numerical calculations established for piled foundations in addition to analytical or empirical methods

→ for pile groups and piled rafts recommended

6.5.6 Piled rafts

(3) Analysis of a piled raft may be based on numerical modelling including nonlinear stress–strain models for the ground, the structural flexural stiffness of the raft and the interactions between ground, raft and piles.

→ EN 1997-1, 8.2 provides guidance for verification by numerical models
Conclusions: Pile design in 2nd generation of Eurocode 7

- Pile design acc. to EN 1997:2024 is an evolution of 1st generation rules (*no revolution …*)
- many new design aspects are covered: pile groups, piled rafts, numerical calculations, … → additional guidance for engineering practice
- Code specifies basic requirements for analysis and verification of piled foundations, (*no comprehensive text-book …*)
  → additional national guidelines, recommendations, textbooks might be applied
- all sets of factors are ´Nationally Determined Parameters´ (NPDs)
  → can be adjusted acc. to national experience

⇒ Clause 6 reflects up to date European consensus for pile design
⇒ EN 1997:2024 provides a modern framework for state-of-the-art pile design
  that can be combined with national experience and approaches

Disclaimer: The presentation is based on August 2022 draft of prEN 1997.
Some aspects might still be subjected to change in consequence of Formal Enquiry.