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

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Outline

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   - 2.3 Design by calculation, by testing, by prescriptive rules, …
   - 2.4 Ground model method and model pile method
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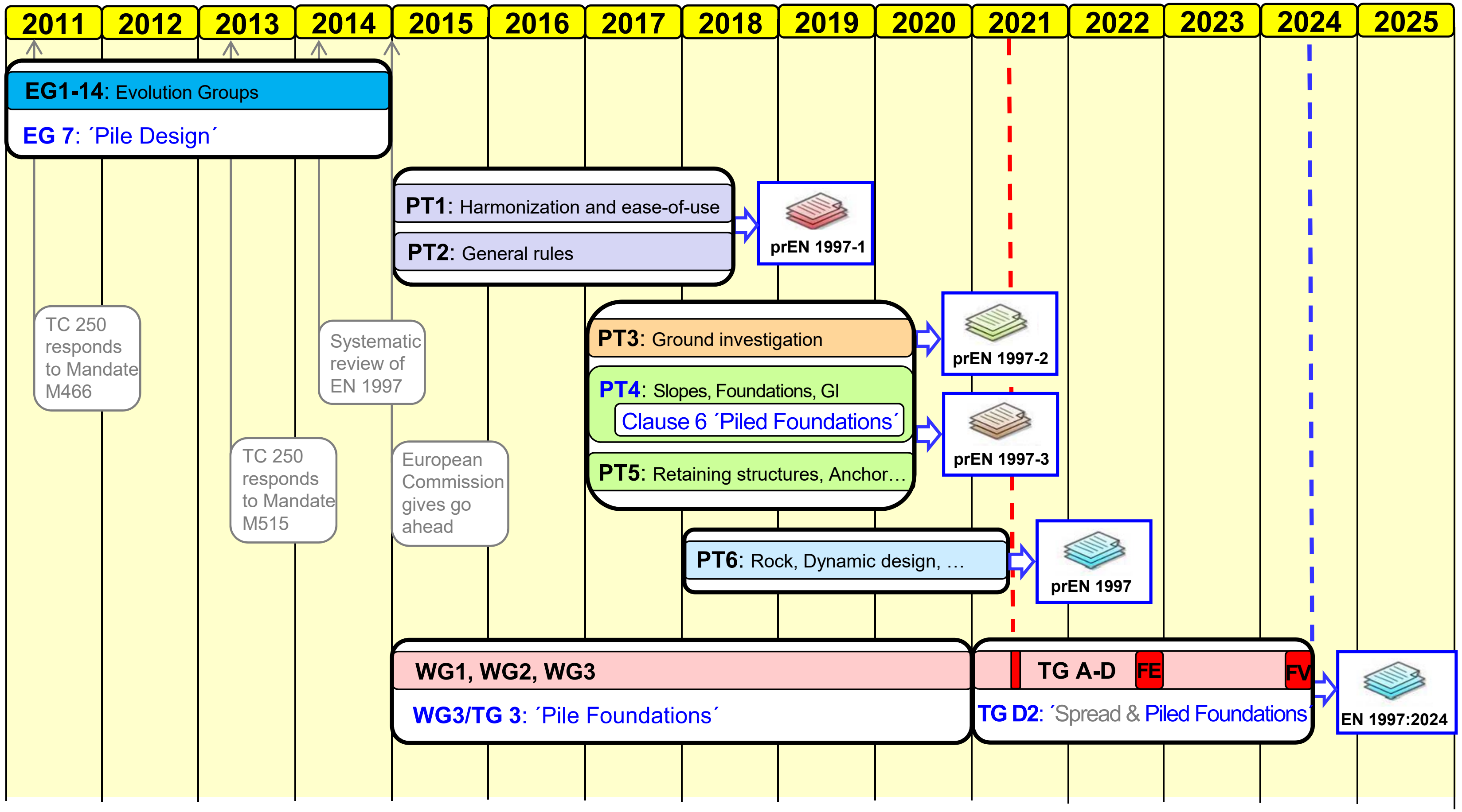
   - 3.4 Splitting of previous correlation factors in correlation & model factors
   - 3.5 Application of numerical methods
4. Conclusions

Introduction: Timeline - Evolution of Clause on Pile Design

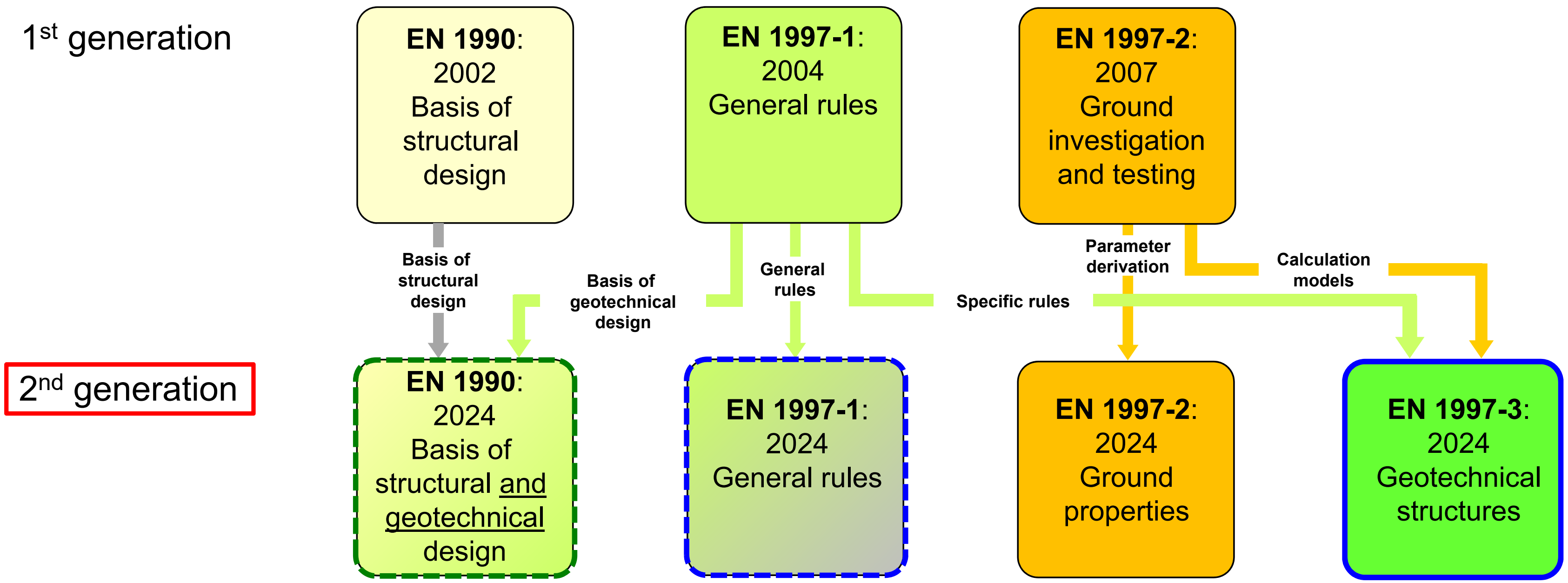


EG Evolution Group
PT: Project Team
WG: Working Group
TG: Task Group

FE: Formal Enquiry
FV: Formal Vote

- **long-term evolution process**
- **many European experts involved**
- **intensive review and commenting (NSBs, …) at regular intervals**

Introduction: Pile Design based on EN 1997:2024



content relevant for pile design:

EN 1990:

- principles, e.g. Consequence Classes, consequence factors K_F
- partial factors on actions γ_F and stresses γ_E
- verification cases VC1 to VC4
- …

EN 1997-1:

- Geotechnical Category *GC*
- representative values X_{rep}, X_{nom}, X_k etc.
- partial factors γ_M on ground properties (M1/M2)
- consequence factors K_M, K_R
- type of ULS
- SLS criteria
- …

EN 1997-2:

- ground investigation
- ground properties

EN 1997-3:

- **Clause 6: ´Piled foundations´**
  - geotechnical analysis of piled foundations (calculation and testing)
  - ULS and SLS verifications
  - model factors γ_{Rd}
  - correlation factors ξ
  - partial factors γ_R on pile resistances
- …

Introduction: prEN1997-3 ´Geotechnical Structures´ - Contents

EN 1997-3:2024	EN 1997-1:2004
0 Introduction	
1 Scope	
2 Normative references	
3 Terms, definitions, and symbols	
4 Slopes, cuttings, and embankments	← Chapter 11 ´Overall Stability´ + 12 ´Embankments´
5 Spread foundations	← Chapter 6 ´Spread Foundations´
6 Piled foundations	**← Chapter 7 ´Pile Foundations´**
7 Retaining structures	← Chapter 9 ´Retaining Structures´
8 Anchors	← Chapter 8 ´Anchorages´
9 Reinforced fill structures	← new (section 5.5 ´Ground improvement & reinforcement´)
10 Ground reinforcing elements	← new
11 Ground improvement	← new (section 5.5)
12 Groundwater control	← new (section 5.4 ´Dewatering´)
Annexes A, B, C, D, E, F, G (to Clauses 4, 5, 6, 7, 8, 9 and 11)	
Bibliography	

Introduction: prEN1997-3 ´Geotechnical Structures´ - Contents

EN 1997-3:2024

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4 Slopes, cuttings, and embankments
5 Spread foundations
6 Piled foundations
7 Retaining structures
8 Anchors
9 Reinforced fill structures
10 Ground reinforcing elements
11 Ground improvement
12 Groundwater control

- Annexes A, B, C, D, E, F, G (to Clauses 4, 5, 6, 7, 8, 9 and 11)

Bibliography

uniform structure of Clauses 4 to 11

x.1 Scope and field of application
x.2 Basis of design
x.3 Materials
x.4 Groundwater
x.5 Geotechnical analysis
x.6 Ultimate limit states
x.7 Serviceability limit states
x.8 Implementation of design
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EN 1997-1:2024

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Overview of Clause 6 ´Piled foundations´

EN 1997-3:2024, Clause 6

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

Pile type	Description	Class
Displacement pile	Pile installed in the ground without excavation of material	Full displacement
		Partial displacement
Replacement pile	Pile installed in the ground after the excavation of material	Replacement
Pile not listed above	---	Unclassified

- ↗ Pile class (only) used to determine resistance factors γ_R
- ↗ Annex C.3: Examples of pile types in different classes

Overview of Clause 6 ´Piled foundations´

EN 1997-3:2024, Clause 6

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´

EN 1997-3:2024, Clause 6

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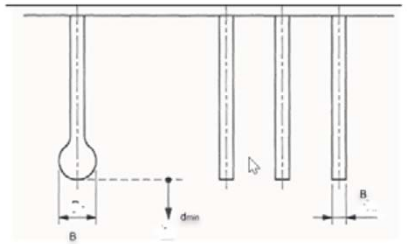
6.2 Basis of design

- 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

Application	Minimum depth	Illustration
Piled foundation	d_{min}=max(3B ; 5 m)	
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: $d_{min} = max(5\text{ m}; 3B_{\text{b,eq}}; p_{\text{group}})$

reduced minimum depths in strong rock masses: $d_{min} = max(3\ m; 3B_{b,eq})$

Overview of Clause 6 ´Piled foundations´

EN 1997-3:2024, Clause 6

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

Overview of Clause 6 ´Piled foundations´

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6.4 Groundwater

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

Overview of Clause 6 ´Piled foundations´

EN 1997-3:2024, Clause 6

6.5 Geotechnical analysis

- Effect of ground displacement:
  - Downdrag
  - Heave
  - Transverse loading

  → *detailed rules for calculation of downdrag for SLS- and ULS- verification*

- Axially loaded single piles:
  - Calculation
  - Testing
  - Prescriptive rules

  → *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).*

  → *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

Overview of Clause 6 ´Piled foundations´

EN 1997-3:2024, Clause 6

6.5 Geotechnical analysis

- Pile groups

$$R_{group} = min\left\{\sum_{i}^{n} R_i \, ; R_{block}\right\}$$

- Piled rafts

$$R_{piled-raft} = \left(\sum_{i}^{n} R_{c,i} + R_{raft}\right)$$

→ *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*

Overview of Clause 6 ´Piled foundations´

EN 1997-3:2024, Clause 6

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 6.2 — (NDP) Minimum quantity of load testing for confirmation of pile design by calculation

Type of load test	Confirmation of design by Ultimate Control Tests	Confirmation of design by Serviceability Control Tests
Static load test	max (1, 0.5 % *N*)	max (2, 1 % *N*)
Rapid load test	max (3, 1.0 % *N*)	max (6, 5 % *N*)
Dynamic impact load test	max (3, 1.0 % *N*)	max (6, 5 % *N*)
NOTE N = total number of piles in similar ground conditions		

Overview of Clause 6 ´Piled foundations´

EN 1997-3:2024, Clause 6

6.6 Ultimate limit state

- Single piles:
  - Representative values of resistance

→ for design by calculation using the Ground Model Method

$$R_{\text{rep}} = R_{\text{calc}}$$

→ for design by calculation using the Model Pile Method

$$R_{\text{rep}} = min\left\{\frac{R_{\text{calc,mean}}}{\xi_{\text{mean}}};\frac{R_{\text{calc,min}}}{\xi_{\text{min}}}\right\}$$

→ for design by testing

$$R_{\text{rep}} = min\left\{\frac{R_{test,mean}}{\xi_{\text{mean}}};\frac{R_{test,min}}{\xi_{\text{min}}}\right\}$$

with: ξ - correlation factors

Overview of Clause 6 ´Piled foundations´

EN 1997-3:2024, Clause 6

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6.6 Ultimate limit state

- Single piles:
  - Verification of axial compressive resistance

$$F_{cd} \leq R_{cd}$$

$$R_{cd} = \frac{R_{c,rep}}{\gamma_{Rc} \cdot \gamma_{Rd}} \; or \; \left(\frac{R_{b,rep}}{\gamma_{Rb} \cdot \gamma_{Rd}} + \frac{R_{s,rep}}{\gamma_{Rs} \cdot \gamma_{Rd}} \right)$$

with: γ_{Rd} - model factor $\gamma_{Rc}, \gamma_{Rb}, \gamma_{Rs}$ – resistance factors

  - 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

6.6 Ultimate limit state

- Pile Groups:
  - Verification

$$F_d \leq R_{d,group}$$

$$R_{d,group} = \frac{R_{rep,group}}{\gamma_{R,group}\gamma_{Rd,group}}$$

- Piled Rafts:
  - Verification

$$F_d \leq R_{d,piled-raft}$$

$$R_{d,piled-raft} = R_{d,group} + \frac{R_{rep,raft}}{\gamma_{R,raft}}$$

- Model, partial and correlation factors
  for single piles, pile groups and piled rafts

Overview of Clause 6 ´Piled foundations´

EN 1997-3:2024, Clause 6

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

$$F_{\mathrm{cd,SLS}} \leq \kappa_{\mathrm{b,SLS}} R_{\mathrm{b,rep}} + \kappa_{\mathrm{b,SLS}} R_{\mathrm{s,rep}}$$

with $\kappa_{\mathrm{b,SLS}}$ and $\kappa_{\mathrm{s,SLS}}$ 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

Overview of Clause 6 ´Piled foundations´

EN 1997-3:2024, Clause 6

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

Overview of Clause 6 ´Piled foundations´

EN 1997-3:2024, Clause 6

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.

Introduction: Clause 6 ´Piled foundations´

EN 1997-3:2024, Clause 6

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

Annex C ´Piled Foundations´ (informative)

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

(2) 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.

(5) The ultimate vertical resistance of a pile group R_{group} should be determined from Formula 6.8:

$$R_{group} = min\left\{\sum_{i}^{n} R_{i}\,;R_{block}\right\} \quad (6.8)$$

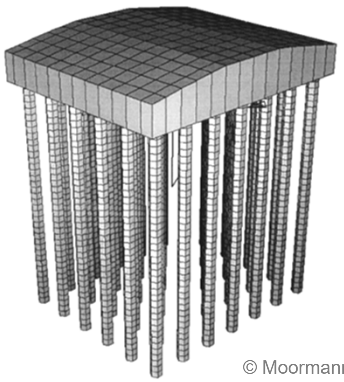
where

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 $R_{piled\text{-}raft}$ should be determined from Formula 6.9 considering the compatibility of the displacements of the piles and the rafts:

$$R_{piled-raft} = \left(\sum_{i}^{n} R_{c,i} + R_{raft}\right) \quad (6.9)$$

where

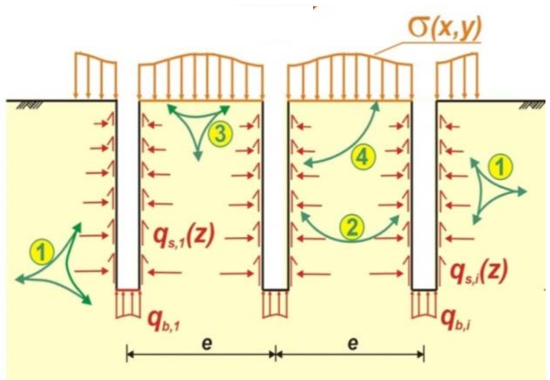
R_{raft} is the ultimate compressive resistance of the raft alone;

$R_{c,i}$ 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.

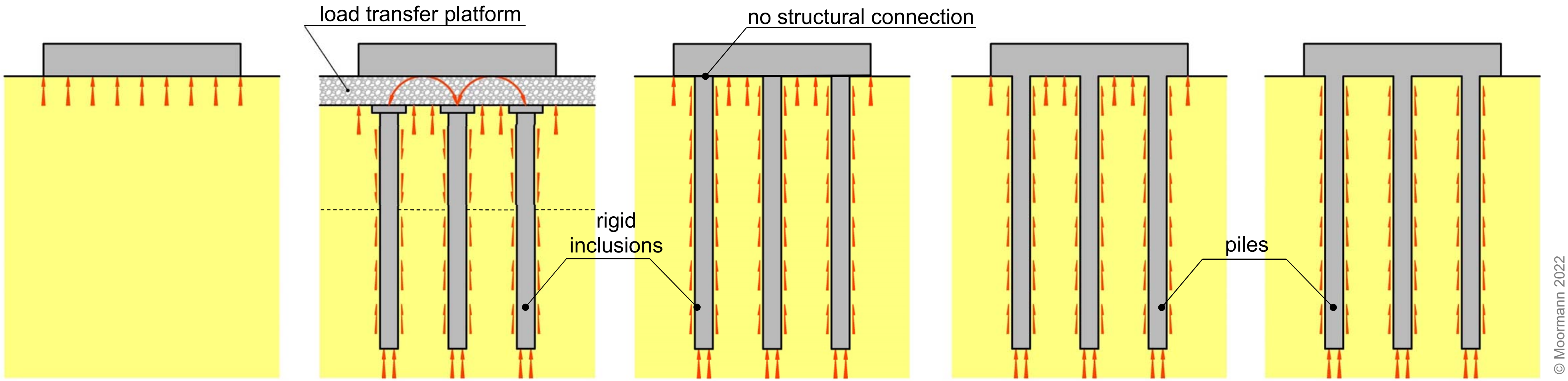
(2) The design of piled rafts should consider the interaction effects shown in Figure 6.1:



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

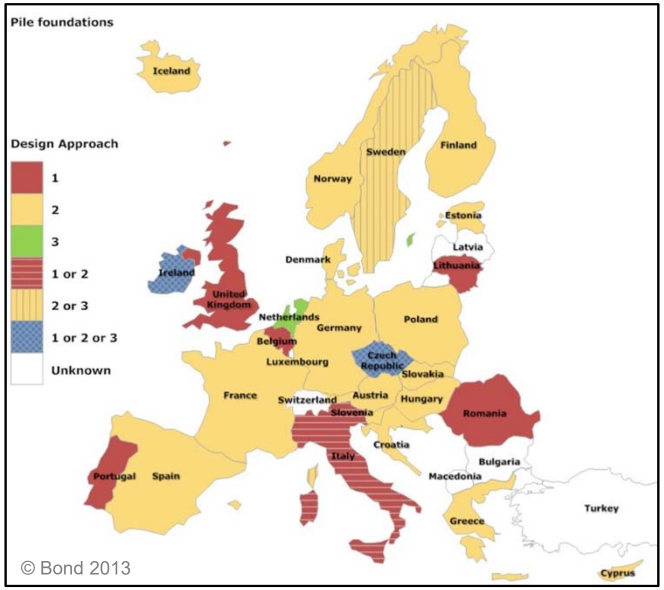


Clause 5	Clause 11		Clause 6	Clause 6
Spread Foundation	**Ground improvement**		**Piled raft**	**Piled foundation**
	with rigid inclusions and LTP	with rigid inclusions w/o LTP		

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

Table 6.8 — (NDP) Partial factors for the verification of ultimate resistance of single piles for fundamental (persistent and transient) design situations – Ground Model Method

Verification of	Partial factor on	Symbol	Material factor approach (MFA) – both combinations		Resistance factor approach (RFA)		
			(a)	(b)	Pile class	Ground Model Method	
Axial compressive resistance	Actions;effects- of-actions[a]	γ_F and γ_E	Not Used		All	VC1	
	Drag force due to settling ground	$\gamma_{F,drag}$				1,35	
	Ground properties[b]	γ_M				Not factored	
	Base and shaft resistance in compression	γ_{Rb} | γ_{Rs}				Base	Shaft
					Full displacement	1,2	1,05
					Partial displacement	1,3	1,05
					Replacement	1,4	1,15
					Unclassified	1,5	1,25
	Total resistance in compression	γ_{Rc}			Full displacement	1,1	
					Partial displacement	1,2	
					Replacement	1,3 [d]	
					Unclassified	1,4	
Axial tensile resistance	Actions;effects- of-actions[a]	γ_F ; γ_E	Not Used		All	VC1	
	Ground properties[b]	γ_M				Not factored	
	Shaft resistance in tension	γ_{Rst}			Full displacement	1,2	
					Partial displaceme	1,2	
					Replacement	1,3	
					Unclassified	1,5	
Transverse resistance	Actions and effects-of-actions[a,c]	γ_F; γ_E	VC4 or VC1	VC3		VC1	
	Ground properties[b]	γ_M	M1	M2		Not factored	
	Transverse resistance	γ_{Rtr}	Not factored			1,3	

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 $\rightarrow$ more stringent concept
- **Adjustment of previous correlation factors ξ into**
  - **correlation factors ξ** $\rightarrow$ considering (solely) spatial soil variability
  - **model factors γ_{Rd}** $\rightarrow$ 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

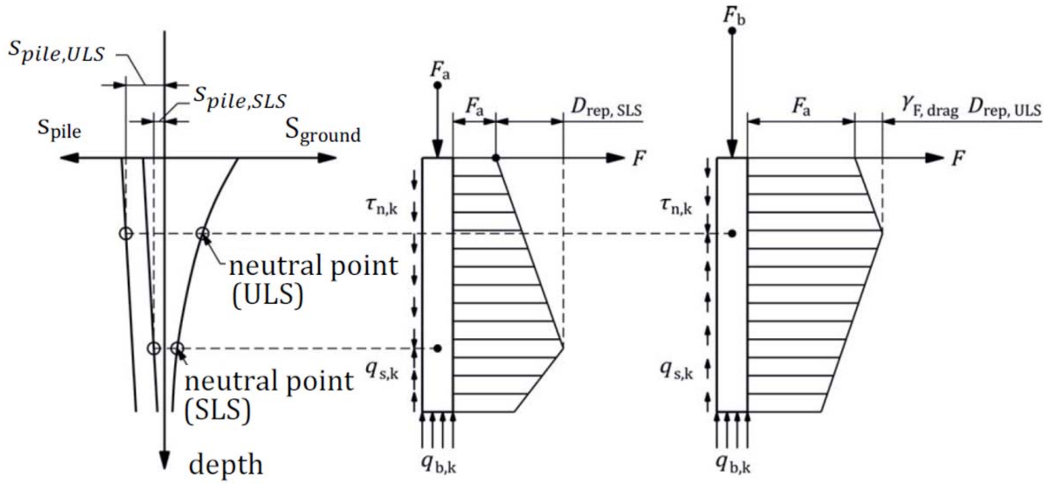
Major modifications: Actions due to ground displacement

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_{dd} 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_{dd} is usually different for serviceability and ultimate limit state conditions.

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

$$D_{rep} = p \int_0^{L_{dd}} \tau_s \cdot dz \qquad (6.3)$$

where

- p is the perimeter of the pile;
- τ_s is the unit shaft friction causing downdrag at depth z;
- L_{dd} is the depth to the neutral plane.

Major modifications: Numerical calculation of piled foundations

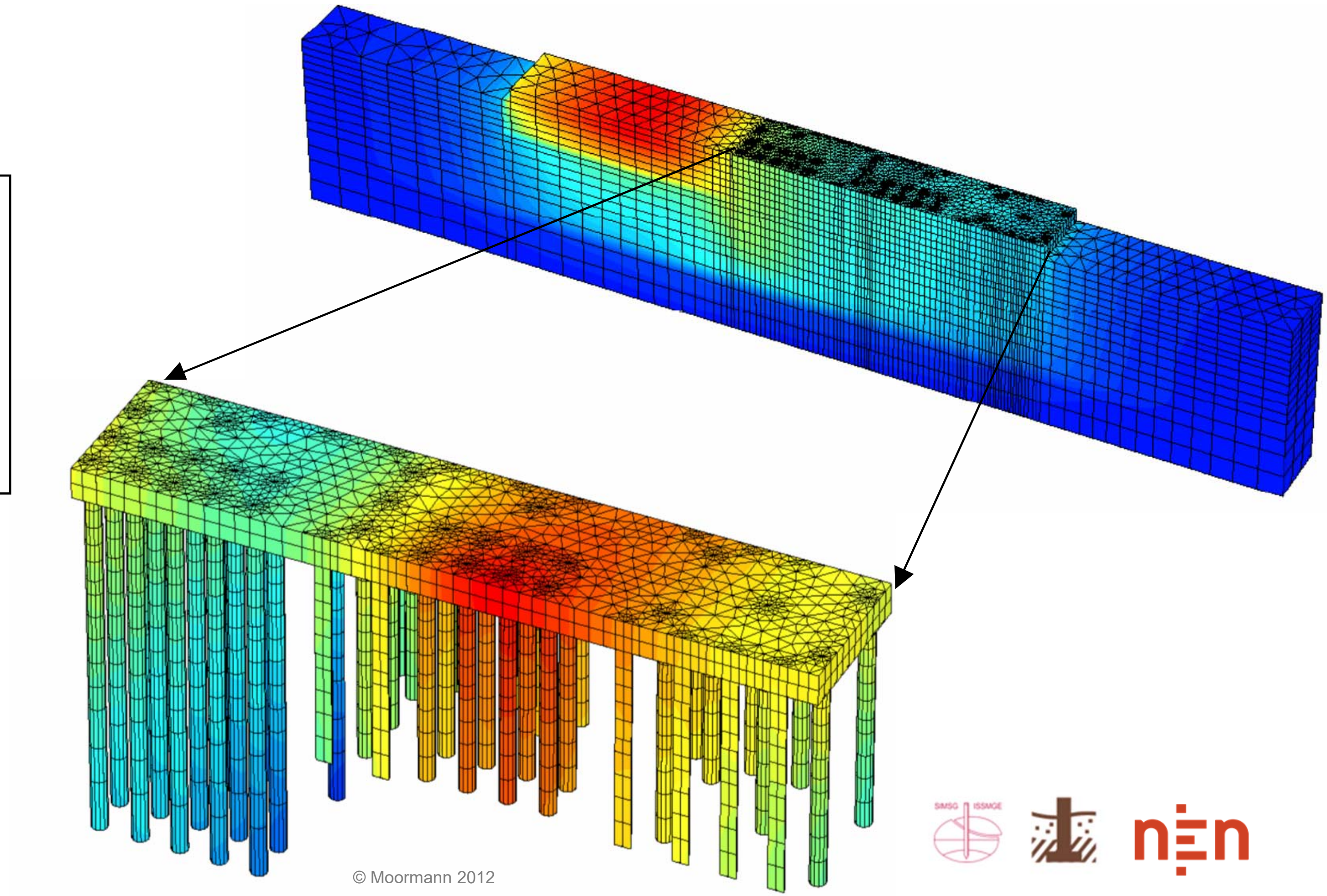
Numerical calculations established for piled foundations in addition to analytical or empirical methods

→ 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