THE SECOND GENERATION OF EUROCODE 7 – A MODERN BASIS FOR THE DESIGN OF PILED FOUNDATIONS AND GROUND IMPROVEMENT

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ABSTRACT

Eurocode 7 is known as the European standard for geotechnical engineering design and is widely considered as a great success story. The second generation of the standard drafted by CEN/TC250/SC7 was recently published and represents a significant step forward towards further harmonization and efficient guidance for geotechnical design. The revision is performed focusing on the user´s need with the main goals of ease-of-use and harmonization, to meet new demands in geotechnical engineering looking at the coming 20 to 25 years. The second generation covers new basic aspects like numerical methods, probability and reliability-based verification, rock on an equal basis as soil, etc. In addition, geotechnical structures like reinforced fill structures, soil nailing and ground improvement were included for the first time. The paper presents an overview of some of the key revisions compared to the first generation of Eurocode, that will affect the practicing geotechnical engineer and explains the application on example of piled foundations and ground improvement. The paper concludes that the 2nd generation of Eurocode will be a modern standard for all kind of geotechnical structures and a useful tool for engineers in practice.

Keywords: Eurocode 7, piled foundation, ground improvement, standards

INTRODUCTION

In 2012, the European Commission decided on the M515 mandate, giving the responsibility to CEN to further develop the Eurocodes. In 2015 the first project teams were established to start the drafting process of the second generation of all structural Eurocodes. The aim has been that the first parts of new generation will be published in 2022 and the last in 2027, a timeline that still applies to this day.
In this context, also Eurocode 7, the basis for the geotechnical design was transferred from first edition to second generation including fundamental reorganisation and extensions. In its 2nd generation the new Eurocode 7 comprises three parts as illustrated in Figure 1. The contents of the existing Eurocode 7, Part 1 ´General rules´ (EN 1997-1:2004) have been split between EN 1990 ´Basis of structural and geotechnical design´, a revised Part 1 (EN 1997-1:2024) ´General rules´; and a new Part 3 (EN 1997-3:2025) ´Geotechnical structures´. The new Part 3 comprises text from Sections 5-9 and 11-12 of 1st generation´s EN 1997-1 together with new clauses on reinforced fill structures, ground reinforcing elements, ground improvement and groundwater control. The reorganization of the second generation of Eurocode 7 is illustrated in Figure 1.

EUROCODE 7 PART 1 – GENERAL RULES

The scope of part 1 has been reduced since the basis of geotechnical design has been moved to EN 1990 and specific considerations for different geotechnical structures has been moved to part 3. However, the table of content has introduced some new concepts, and the strive to include all common topics in part 1, instead of repeating them in each clause in part 3, has given a part with a similar amount of text as in 1st generation.
The concept of the geotechnical category (GC) has been revised so that it is systematically determined with the consideration of the consequence of failure (CC) and geotechnical complexity (GCC). This revised concept is used as the base of classification to achieve geotechnical reliability (Franzén & van Seters 2022).

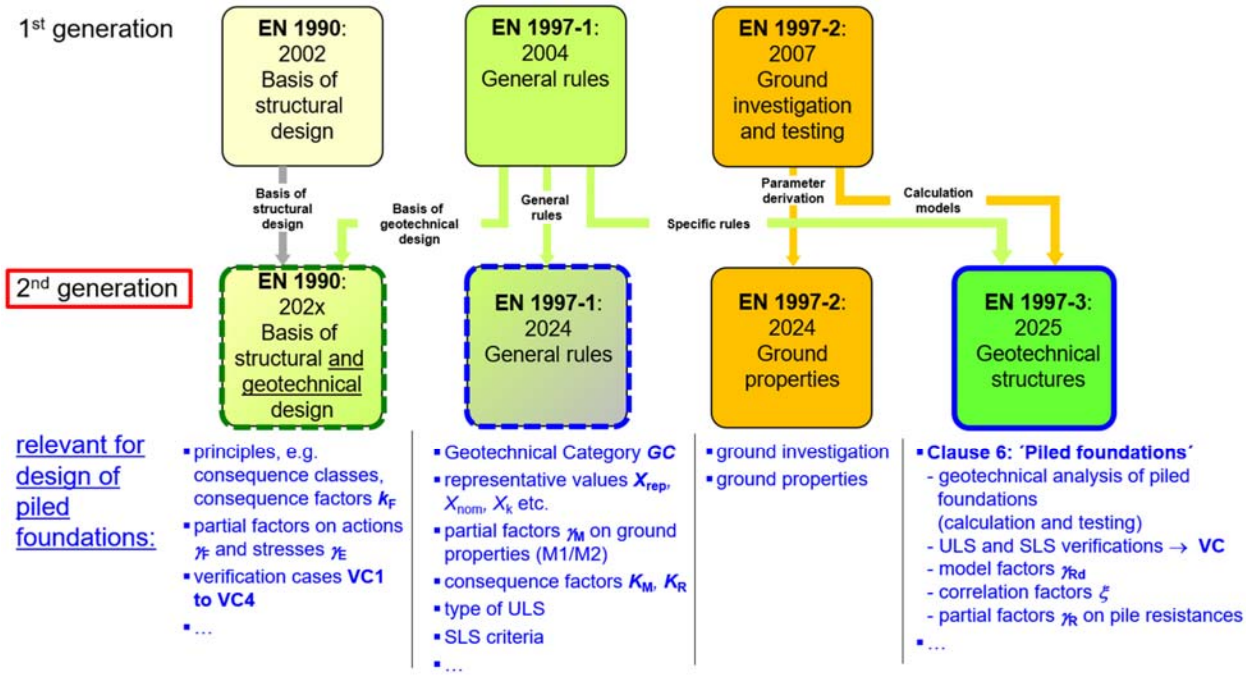


Figure 1. Division and redistribution of the 1st generation of Eurocode 0 and Eurocode 7 into the standards of the second generation (acc. to Bond et al. 2019); at the bottom: contents of these standards being relevant for the design of piled foundations.

The term ´representative value´ is introduced and replace the old characteristic value. The representative value is determined either as a cautious estimate or with a statistical approach.
EN 1997-1:2024 provides further guidance on the four methods for verification of limit states, on the use of numerical methods for design and verification, on the concept of the zone of influence and on the implementation of design during execution and service life focusing on supervision, inspection, monitoring, and maintenance applied to ensure that the design is implemented correctly.

EUROCODE 7 PART 2 – GROUND PROPERTIES

The contents of the existing Eurocode 7, Part 2 ´Ground investigation and testing´ (EN 1997-2:2007) were also being revised to focus in the new Part 2 ´Ground parameters´ (EN 1997-2:2024) on the derivation of design parameters. Thus, while EN 1997-2 was in 1st generation focusing on ground investigation and testing, for the 2nd generation, this part has been turned 90 degrees and is now focusing on the need of the engineer to derive appropriate ground properties as input to the design instead as previous, on the output from ground investigations.
Calculation models that currently reside in Annexes to EN 1997-2:2007, e.g. on CPT-based calculation of axial pile resistances, have been moved to the new Part 3, as illustrated in Figure 1.

EUROCODE 7 PART 3 – GEOTECHNICAL STRUCTURES

Eurocode 7 part 3 consists of the specific rules for each type of geotechnical structure. General requirements applicable for more than one structure has been moved to part 1. Therefore, the main content for each clause is focused on geotechnical analyses giving the calculation models, ultimate limit state and serviceability limit state.
The chapters known from 1st generation of EN 1997-1. i.e. the clauses on slopes, cuttings and embankments (Clause 4), spread foundations (5), piled foundations (6), retaining structures (7) and anchors (8) were

revised. In addition, the following new clauses have been added: on reinforced fill structures (9), soil nailed structures (10), rock bolts and rock surface support (11), ground improvement (12) and groundwater control measures (13). Thus, the range of geotechnical structures covered by the new EN 1997-3 has been increased significantly.

DESIGN OF PILED FOUNDATIONS ACCORDING TO EN 1997-3:2025

In the following the design of piled foundations according to 2nd generation of EN 1997 is presented and explained in detail.

Introduction

Relevant for the design of piled foundations is predominantly Clause 6 ´of EN 1997-3:2025 which was elaborated on basis of Section 7 ´Pile foundation´ of EN 1997-1:2004 whereby the previous regulations were fundamentally revised, improved and supplemented including new resp. additional rules for pile design. Fundamentally, in the second generation pile groups and piled rafts will be covered equivalently to single piles whereby the regulations of the first generation focused solely on single piles. Detailed guidance is provided to consider actions on piles due to ground displacements like downdrag. Revised sets of correlation, model and partial factors were specified. The design approaches for axially and laterally loaded piled foundations were harmonized.
As each Clause of EN 1997-3 follows a common structure, also Clause 6 comprises the following sub-sections which have the same order as the Clauses in EN 1997-1:2024 and which provide structure-specific rules in addition to the general rules specified in Part 1 of Eurocode 7:

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

These sections of Clause 6 provide specific regulations for the analysis and design of piled foundations. In this context the detailed information documented in Clause 6 includes for example the following aspects:

- requirements on the minimum extent of ground investigations;
- analysis of piled foundations due to structural loads and effects of ground displacements;
- design of piled foundations by testing, calculation, prescriptive measures;
- the specification of ultimate limit state (ULS) and serviceability limit state (SLS) verifications for single piles, pile groups and piled rafts including a definition of the verification cases (VC) being relevant for those verifications;
- the specification of the sets of model factors γ_{Rd}, correlation factors ξ as well as partial factors γ_R for the evaluation of the design value of pile resistances.

Besides the structure-specific regulations documented in Clause 6 of EN 1997-3, information needed for the design of piled foundations are provided also by EN 1990 and EN 1997-1 as illustrated in Figure 1.
EN 1990 specifies the principles of classification of structures according to consequence classes and the consequences factors k_F for actions as well as the principles of limit state design and of the verification by the partial factor method including specification of partial factors on actions γ_F and stresses γ_E. EN 1990 also specifies the ´Verification Cases´ VC1 to VC4 being relevant for different design situations like structural resistance, static equilibrium and geotechnical design and the related sets of partial factors. The partial factors can either be applied on material properties, i.e. the ´Material Factor Approach´ (MFA), or to resistances, i.e. the ´Resistance Factor Approach´ (RFA).
EN 1997-1 as well provides relevant specifications and regulations needed for the design of piled foundations. Besides specifications of the Geotechnical Category (GC) which should be determined by a combination of the Consequence Class (CC) of the structure and the Geotechnical Complexity Class (GCC),

the evaluation of representative values X_{rep} as well as partial factors γ_M on ground properties and consequence factors both on ground properties k_M and resistances k_R are specified in Part 1 of Eurocode 7.
In the following some of the most relevant modifications for the design of piled foundations according to second generation of Eurocode 7 are presented in more detail.

Ground investigations

In addition to EN 1997-2:2024 which includes fundamental requirements on ground investigation and evaluation of ground properties section 6.2 of EN 1997-3 provides additional specific regulations, e.g. specifications on the minimum depth d_{min} of field investigation on piled foundations (Table 1).

Table 1. Minimum depth of ground investigation for piled foundations.

Application	Minimum depth
Single piled foundation	d_{min} = max (5 m; $3 \cdot B_{n,eq}$)
Pile groups or piled rafts in soils and in very weak and weak rock masses	d_{min} = max (5 m; $3 \cdot B_{n,eq}$; p_{group})
Pile groups or piled rafts in strong rock masses	d_{min} = max (3 m; $3 \cdot B_{n,eq}$)

d_{min} is the minimum investigation depth beneath pile base level.
$B_{n,eq}$ is the equivalent size of the pile base, equal to B_b (for square piles), D_b (for circular piles), or p_b/π (for other piles);
B_b is the base width of the pile with the largest base (for square piles);
D_b is the base diameter of the pile with the largest base (for circular piles);
P_{group} is the smaller dimension of a rectangle circumscribing the group of piles forming the foundation, limited to the depth of the zone of influence.

Verification of axial resistance of single piles (ULS)

For axially loaded single piles the axial (compression) resistance shall be verified using:

$$F_{cd} \leq R_{cd} \tag{1}$$

Thereby, the verification for axial loaded piles (single piles, pile groups and piled rafts) could be harmonized as solely the Resistance Factor Approach (RFA), where the partial factors are applied on the pile resistance, shall be used in combination with Verification Case VC1, where the partial factors are applied on the actions. Thus, the design value of actions is defined as follows:

$$F_{cd} = 1.35 G_{rep} + 1.5 Q_{rep} \tag{2}$$

with Q_{rep} as characteristic value, combination value, frequent value or quasi-permanent value.
The design value of the axial pile resistance is defined as follows:

$$R_{\mathrm{cd}} = \frac{R_{\mathrm{c,rep}}}{\gamma_{\mathrm{Rc}} \cdot \gamma_{\mathrm{Rd}}} \quad or \quad \left(\frac{R_{\mathrm{b,rep}}}{\gamma_{\mathrm{Rb}} \cdot \gamma_{\mathrm{Rd}}} + \frac{R_{\mathrm{s,rep}}}{\gamma_{\mathrm{Rs}} \cdot \gamma_{\mathrm{Rd}}}\right) \tag{3}$$

where γ_{Rc}, γ_{Rb}, γ_{Rs} are partial factors for pile resistances and γ_{Rd} is a model factor.
The representative values of the pile resistance in axial compression $R_{c,rep}$ resp. of the base and shaft resistance $R_{b,rep}$ and $R_{s,rep}$ can be obtained by testing, by calculation or by prescriptive rules. The use of prescriptive rules is very rare for piles. For the determination of the axial resistances of single piles by calculation either the ´Ground Model Method´ or the ´Model Pile Method´ can be applied. In case of the Ground Model Method the axial resistance of a single pile is calculated based on ground properties determined from both field and laboratory tests, accounting for horizontal variability of the ground in the piled area. The Model Pile Method is a calculation method to determine the axial resistance of a single pile based on individual pile resistance profiles determined from correlations with field test results or ground properties from field or laboratory tests. Methods of calculating base and shaft resistance are included in Annex C of EN 1997-3 for ground parameters as well as for cone penetration methods and for pressuremeter methods. Figure 2 provides an overview about these calculation methods.

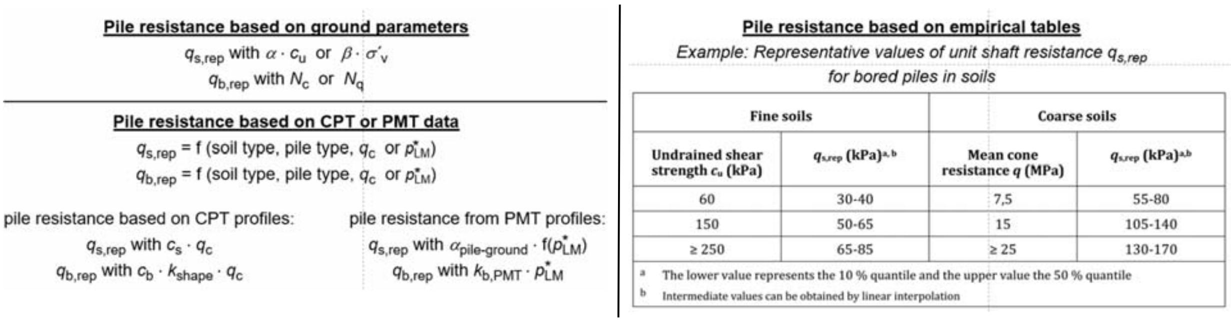


Figure 2. Available calculation methods for evaluation of axial pile resistances.

The axial resistance of a single pile at ultimate and serviceability limit state may be also determined from the results of static load tests. Dynamic impact and rapid load tests may be used to determine the ultimate limit state of a single pile in compression.
Table 2 specifies the evaluation of representative values of axial pile resistances from calculated or measured values.

Table 2. Evaluation of representative axial resistances of single piles based on calculation or testing.

Ground Model Method: R_{calc} from ground parameters (c_u, φ´ and c´, p_{LM}*, q_c, N_{SPT}, etc.)	$R_{rep} = R_{calc}$
Model Pile Method: R_{calc} from N field test profiles (N CPTs, N PMTs, N SPTs, etc.)	$R_{rep} = \min\left\{\frac{R_{calc,mean}}{\xi_{mean}}; \frac{R_{calc,min}}{\xi_{min}}\right\}$
Pile tests: R_{test} from static, dynamic impact or rapid load tests	$R_{rep} = \min\left\{\frac{R_{test,mean}}{\xi_{mean}}; \frac{R_{test,mean}}{\xi_{min}}\right\}$

Figure 3 visualizes the possible procedures to evaluate design values of axial pile resistances from testing and calculation. Tables 3 and 4 document the model factors γ_{Rd} for verification of axial pile resistance assisted by testing and calculations.

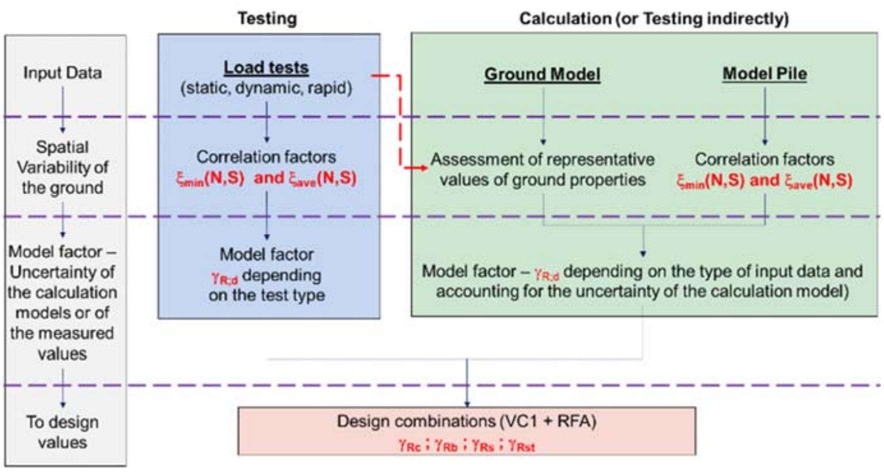


Figure 3. Calculation procedures for piles (acc. to Moormann & Burlon 2024).

Correlation factors ξ allows to consider the spatial variability of the ground alternatively to the selection of the representative values of the ground parameters which is always related to subjective interpretation. Correlation factors ξ as documented in section 6.2.4 of EN 1997-3 continues to be dependent form number of executed pile tests or ground profiles. The correlation factors given reflect an average uncertainty corresponding to a coefficient of variation of about 12%; other approaches are therefore acceptable if spatial variation is lower or higher.

The correlation factors for the Model Pile Method can be adjusted according to the density of the field test profiles (CPTs, PMTs, etc.) considering the ratio of the average horizontal spacing d_{avg} between the N tests profiles located in the area S to a reference distance $d_{\text{ref}} = 30$ m:

$$\xi_{\text{mean}}(S) = 1 + \frac{d_{\text{avg}}}{d_{\text{ref}}}(\xi_{\text{mean}} - 1) \tag{4}$$

$$\xi_{\text{min}}(S) = 1 + \frac{d_{\text{avg}}}{d_{\text{ref}}}(\xi_{\text{min}} - 1) \tag{5}$$

Table 3. Model factors γ_{Rd} for verification of axial pile resistance assisted by testing.

Verification by		Model factor γ_{Rd} Fine soils	Coarse soils	Rock mass
Static load tests		1.0	1.0	1.0
Rapid load tests (multiple load cycles)		1.4	1.1	1.2
Rapid load tests (single load cycle)		1.4	1.1	1.2
Dynamic impact tests (signal matching)	Shaft bearing	1.5	1.1	1.2
	End bearing	1.4	1.25	1.25
Dynamic impact tests (multiple blow)	Shaft bearing	1.5	1.1	1.2
	End bearing	1.4	1.2	1.2
Dynamic impact tests (closed form solutions)	Shaft bearing	Not permitted	Not permitted	Not permitted
	End bearing	Not permitted	1.3	1.3
Wave equation analysis		Not permitted	1.6	1.5
Pile driving formulae		Not permitted	1.8	1.7

Table 4. Model factors γ_{Rd} for verification of axial pile resistance by calculation.

Verification by	Based on	Model factor γ_{Rd}	
Ground Model Method	Ultimate pile tests	1.15	
	Extensive comparable experience without site-specific control tests	1.3	
	Serviceability pile tests	1.35	
	No pile load tests and limited comparable experience	1.55	
Model Pile Method		Compressive resistance	Tensile resistance
	Pressuremeter test	1.15	1.4
	Cone penetration test	1.1	1.1
	Profiles of ground properties based on field or laboratory tests	1.2	1.2

Verification of axial resistance of pile groups and piled rafts (ULS)

As already mentioned Clause 6 of EN 1997-3:2025 covers not only single piles but equally also pile groups and piled rafts.

Pile group design shall consider that the resistance and load-displacement behaviour of single piles in a group might show significant variation compared to the behaviour of single piles due to pile-pile interaction. Calculation of pile group effects should consider the potential changes in stress and density of the ground resulting from pile installation together with the effects of group behaviour due to the structural loads taking the stiffness of the pile cap and the structure into account. The ultimate vertical resistance of a pile group R_{group} with n piles should be determined from:

$$R_{\text{group}} = \min\{\textstyle\sum_i^n R_{\text{i}}\,; R_{\text{block}}\} \tag{6}$$

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, and where R_{block} is the ultimate vertical resistance of the block of ground bounded by the perimeter of the pile group. The design resistance of a pile group $R_{\text{d,group}}$ shall be verified using

$$F_{\mathrm{d}} \leq R_{\mathrm{d,group}} \tag{7}$$

with

$$R_{\mathrm{d,group}} = \frac{R_{\mathrm{rep,group}}}{\gamma_{\mathrm{R,group}} \cdot \gamma_{\mathrm{Rd,group}}} \tag{8}$$

where $\gamma_{\mathrm{R,group}}$ is a resistance factor and $\gamma_{\mathrm{Rd,group}}$ is a model factor for the pile group.

The design of piled rafts shall consider beside the pile-pile interaction the pile-raft interaction (Fig. 4). Considering the compatibility of the displacements of the piles and the raft, the ultimate compressive resistance $R_{\mathrm{piled\text{-}raft}}$ of a piled raft should be determined as

$$R_{\mathrm{piled-raft}} = \left(\sum_i^n R_{\mathrm{c,i}} + R_{\mathrm{raft}}\right) \tag{9}$$

where Rraft is the additional bearing resistance from the raft. The design resistance of a piled raft $R_{\mathrm{d,piled\text{-}raft}}$ shall be verified using

$$F_{\mathrm{d}} \leq R_{\mathrm{d,piled-raft}} \tag{10}$$

with

$$R_{\mathrm{d,piled-raft}} = \frac{R_{\mathrm{rep,piled-raft}}}{\gamma_{\mathrm{R,piled-raft}} \cdot \gamma_{\mathrm{Rd,piled-raft}}} \tag{11}$$

where $\gamma_{\mathrm{R,piled\text{-}raft}}$ is a resistance factor and $\gamma_{\mathrm{Rd,piled\text{-}raft}}$ is a model factor for the piled raft.

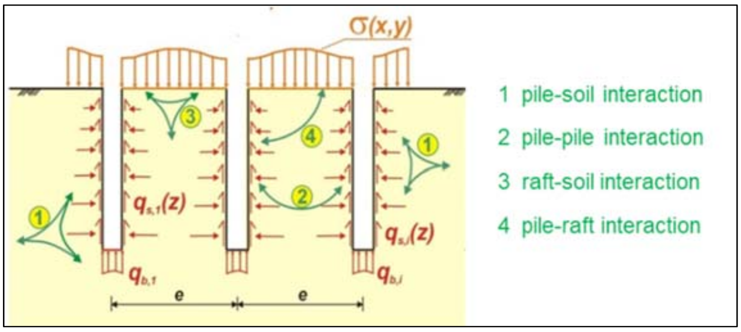


Figure 4. Interaction effects to be considered for the verification of piled rafts according to EN 1997-3, 6.5.6.

For the ULS-verification of axially loaded pile groups and piled rafts EN 1997-3 pretends the application of verification case VC1 in combination with RFA and partial factors of $\gamma_{\mathrm{R,group}} = 1.4$ resp. $\gamma_{\mathrm{R,piled\text{-}raft}} = 1.4$ leading to a comparable equivalent global safety level as for spread foundations or single piles. For combined axial and transversal loaded pile groups and piled rafts both approaches, MFA or RFA, might be used for ULS-verifications.
Verification of limit states for pile groups and piled rafts may be carried out by analytical or empirical, but preferentially by numerical calculation methods.

Pile settlements and SLS verifications

Verification of the serviceability limit state for piled foundations should be based on modelling that accounts for non-linear stiffness of the ground, flexural stiffness of the structure, and interaction between the ground, structures, and piles. The non-linearity of the load-displacement curves of axially loaded piles should be considered for the verification of both geotechnical and structural limit states.
The settlement of a single pile may be determined from load tests or calculated using empirical or analytical methods or numerical modelling.

Downdrag (negative skin friction)

The adverse effects of a drag force caused by moving ground shall be included in the verification of serviceability and ultimate limit states of piled foundations when relevant. Thereby the drag force caused by downdrag should be classified as a permanent action. The effects of the downdrag should be modelled by carrying out a ground-pile interaction analysis, to determine the depth of the neutral point L_{dd} corresponding to the point where the pile settlement s_{Pile} equals the ground settlement s_{ground}. This neutral point is different for SLS or ULS conditions as shown in Figure 5 which also illustrates the approach recommended to be used to calculate the neutral point and the dragforce owing to potential downdrag.

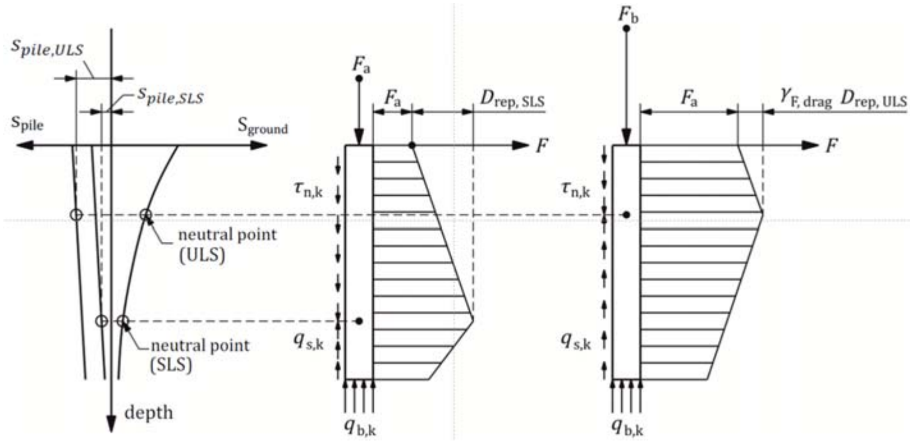


Figure 5. Force distribution for assessment of drag force on a pile subject to downdrag acc. to EN 1997-3, C.9.

The representative drag force D_{rep} should then be determined from

$$D_{\text{rep}} = p \int_0^{L_{\text{dd}}} \tau_{\text{s}} \cdot \text{dz} \qquad (12)$$

where p is the perimeter of the pile and τ_s is the (negative) unit shaft friction causing downdrag at depth z. EN 1997-3 provides in its Annex C a simplified approach for calculating the drag force by adopting a depth to the neutral plane L_{dd} that results in an upper value of the drag force.

Transversal loading

Clause 6 of EN 1997-3 provides also guidance on the verification of single piles, pile groups and piled rafts due to lateral loading. In Annex C.12 calculation models, mainly based on p-y curves from undrained and drained soil properties, are provided to calculate the behaviour of transversely loaded single piles. For the verification of the transverse resistance either the MFA or the RFA can be applied.

Buckling

The buckling resistance of a slender pile under compression should be determined by a validated model, either analytic or numerical, according to second order theory considering the support of the soil and initial transverse deflection due to production imperfections, installation etc. EN 1997-3 provides detailed guidance to evaluate the buckling resistance by analytical methods even though other approaches, e.g. by numerical methods can be applied.

Cyclic effects

Cyclic and dynamic actions can result in reduced ground strength and stiffness leading to additional pile displacements and loss of resistance. Therefore, EN 1997-3 requests to consider the adverse effects of cyclic and dynamic actions on the long-term axial and transverse resistance of piled foundations. In Annex C.14 of EN 1997-3:2025 the concept of ´stability diagram´ based on Poulos (1988) is provided.

Further aspects

Clause 6 of EN 1997-3 provides guidance to many further aspects being relevant for piled foundations including further calculation and design issues but also execution, testing and reporting. Even aspects of sustainability are addressed as the thermal, geotechnical and structural design aspects of thermoactivated deep foundations are mentioned.

DESIGN OF GROUND IMPROVEMENTS ACCORDING TO EN 1997-3:2025

In its current first generation Eurocode 7 does not cover ground improvement. This will change significantly with the second generation of Eurocode 7 which includes a new clause 12 ´Ground Improvement ´for the design of such geotechnical works. One of the main challenges of including ground improvement works in the code was the wide variety of techniques used for this purpose and considering their specific features as some of them involve soil densification or drainage, while others require installation of various inclusions or treatment of the soil in place using binders. Therefore, it was necessary to establish a comprehensive design methodology that aligns with the philosophy of partial factors in Eurocode 7 and accommodates this versatility (Denies et al. 2024).

Classification of ground improvement

As basis for the design considerations a new classification scheme was developed and implemented in EN 1997-3:2025 which does not consider executional aspects and the specific techniques for carrying out the works but focus on the bearing behaviour and the calculation model usually applied. Table 5 shows the classification of ground improvement (GI) according to Clause 12 of EN 1997-3:2025, considering the diffused (Classes AI and AII) or discrete (Classes BI and BII) character of the GI and the possibility to measure the unconfined compressive strength (UCS) of the improved ground.

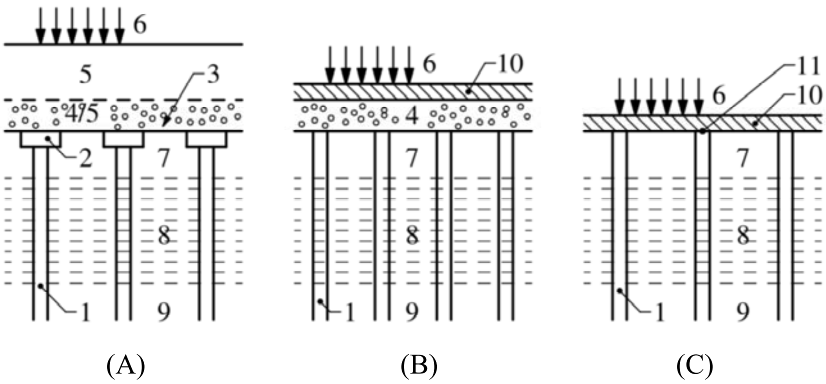
Table 5. Classification of ground improvement according to EN 1997-3:2025, Clause 12.

Class	A - Diffused	B - Discrete
I	**AI – Diffused with no measurable unconfined compressive strength (UCS)** The improved ground has an increased shear strength or stiffness higher than that of the original ground. The improved ground can be modelled as a ground with improved properties.	**BI – Discrete with non-rigid inclusions** Inclusions, installed in the ground, with higher shear capacity and stiffness compared to the surrounding ground. The unconfined compressive strength of the inclusion is not measurable.
II	**AII – Ground improvement zone with measurable unconfined compressive strength** The improved ground is modified from its original natural state, has a measurable unconfined compressive strength and is significantly stiffer than the surrounding ground. Usually, it comprises a composite of a binder and ground.	**BII – Discrete with rigid inclusions** Rigid inclusions, installed in the ground, with unconfined compressive strength and significantly higher stiffness than the surrounding ground. The inclusions can be an engineered material such as timber, concrete/grout or steel or a composite of a binder and ground.

For rigid inclusions (Class BII) which represent structural elements with stiffness and strength both significantly higher than the ground in which they are installed, one of the following conditions should be satisfied in order to clearly distinguish them from conventional piles, as illustrated in Figure 6:

- structural loads are transferred from the slab and spread foundations or embankment through a load transfer platform (LTP) into the improved ground (Fig. 6 and b);
- in absence of a LTP, there is no structural connection between the rigid inclusions and the slab or spread foundation (Fig. 6c).

In the absence of a load transfer platform, additional verifications may be considered according to the design situations; further in this situation a single rigid inclusion used to support the foundation shall comply with Clause 6 (´Piled foundations´), except when it is used for settlement reduction only.



1) rigid inclusions
2) optional caps
3) optional basal reinforcement
4) load transfer platform (LTP)
5) embankment
6) load
7) working platform
8) weak soil
9) load bearing ground
10) slab or spread foundation
11) no structural connection between 1 and 10

Figure 6. Class BII concepts with rigid inclusions: (A) embankment, (B) slab or spread foundation with a load transfer platform (LTP), (C) slab or spread foundation without a LTP.

In the following the focus will be set on GI used for transfer of predominately vertical loads into the ground, especially on rigid inclusions.

Ground investigations

In addition to considerations on geometrical properties taking acceptable deviations from execution tolerances into account, on actions from structures and due to ground displacements, section 12.2 of EN 1997-3 provides additional specifications on the minimum depth $d_{\min}$ of field investigation for ground improvements as documented in Table 6.

Table 6. Minimum depth of ground investigation for ground improvement.

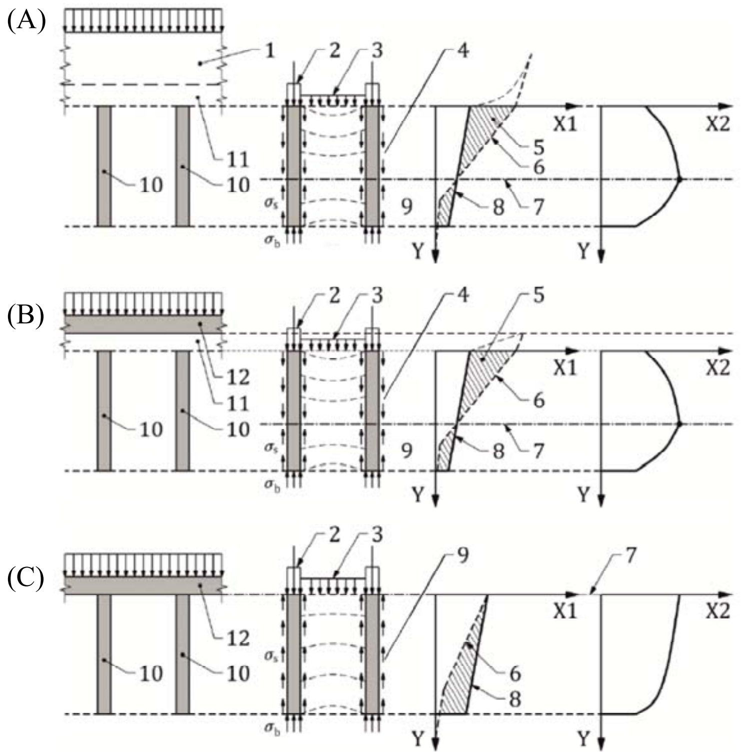
Ground Improvement Class	Minimum depth, $d_{\min}$
AI	treatment depth + 5 m
AII	treatment depth + 5 m
BI	treatment depth + max (5 m; $3 \cdot B_{\mathrm{i}}$)
BII	treatment depth + max (5 m; $3 \cdot B_{\mathrm{ri}}$)

$d_{\min}$ is the minimum depth of field investigation from the ground surface
B_{i} is the equivalent diameter of a non-rigid inclusion (Class BI)
B_{ri} is the equivalent diameter of a rigid inclusion (Class BII)
The equivalent diameter of an inclusion is determined from, $B = 2\sqrt{A/\pi}$, where A is its horizontal cross sectional area.

Geotechnical Analyses and Design Verifications

Analyses of the interaction between a structure, improved ground and ground should be carried out to verify that the ultimate and serviceability limit states (ULS, SLS) are not exceeded, and should take into account the stiffness ratio of discrete inclusions to the surrounding ground. For ground improvement the following ULS shall be verified in particular (Denies et al. 2024):

- failure of the ground improvement inclusion or zone in compression, tension, bending, buckling or shear;
- failure in the ground due to transverse loading of the improved ground zone;
- uplift or insufficient tensile resistance of the ground improvement zone;
- combined failure in the ground and in the ground improvement inclusion or zone;
- bearing resistance failure below the ground improvement inclusion or zone;
- limit states caused by changes in groundwater conditions or groundwater pressure;
- failure at the edges of the improved ground zone.



Key:

X1 settlement
X2 inclusion axial force
Y depth
1) embankment
2) load transmitted to the inclusion
3) load transmitted to the ground
4) negative skin friction
5) differential settlement
6) settlement of the ground
7) neutral plane
8) settlement of the inclusion
9) positive skin friction
10) inclusion
11) load transfer platform (LTP)
12) structure (e.g. slab or spread foundation)
σ_s mobilised shaft friction along inclusion
σ_b mobilised tip resistance of the inclusion

Figure 7. Interaction effects of ground improvement with rigid inclusions: (A) embankment, (B) slab or spread foundation with a load transfer platform (LTP), (C) slab or spread foundation without a LTP.

Design of Class A ground improvement is similar to the design of structures without the use of any ground improvement technique, and the resulting improved ground or material properties are used in the verification of limit states for the corresponding geotechnical structure. The behaviour of the improved ground can be conveniently modelled by conventional ground models.
Where Class B ground improvement is used to support or retain a structure, the calculation model shall include:

- the consideration of the interaction effects between the ground, discrete inclusions, and the overlying structure, embankment, or load transfer platform (LTP); and
- for Class BII ground improvement a verification of the structural resistance of the individual inclusions.

Interaction effects for Class BII ground improvement are similar to those relevant for a piled raft, whereby a LTP additionally impacts the load distribution between rigid inclusions and supporting ground, leading to the development of negative skin friction in the upper part of the inclusions (Figure 7: A and B). An appropriate interaction calculation model shall include the derivation of the distribution ratio to determine the proportion of the load applied to individual discrete inclusions and for Class BII ground improvement the derivation of the neutral plane corresponding to the point where the inclusion settlement equals the ground settlement (see Figure 7: A and B).
The design resistance of a Class BI ground improvement $R_{\text{sys,d}}$ may be determined from the representative value of the total resistance of the ground improvement system with inclusions $R_{\text{sys,rep}}$ using a partial factor $\gamma_{\text{R,sys}}$ and a model factor $\gamma_{\text{Rd,sys}}$, i.e.:

$$R_{\text{sys,d}} = \frac{R_{\text{sys,rep}}}{\gamma_{\text{R,sys}} \cdot \gamma_{\text{Rd,sys}}} \tag{13}$$

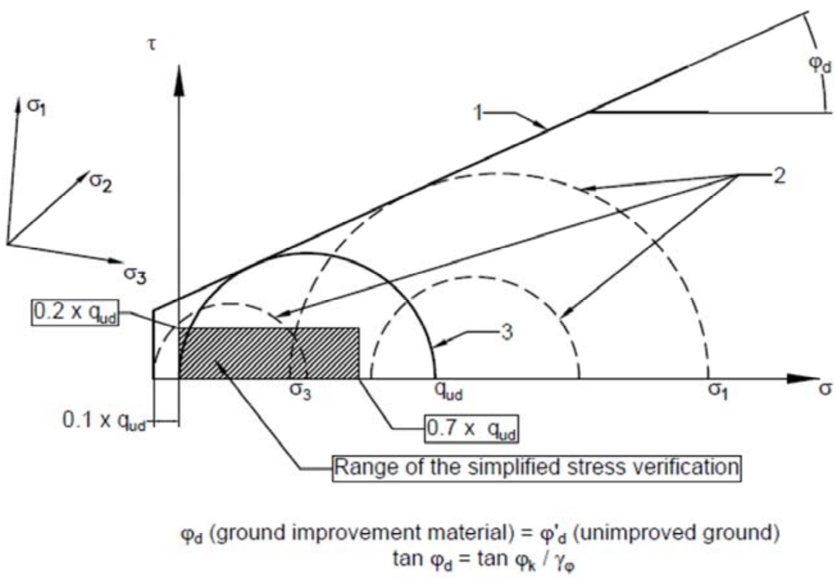
Considering the compatibility of the displacements of the inclusions and the gorund, the design resistance of Class BII ground improvement may be determined as:

$$R_{\mathrm{sys,d}} = \frac{\sum_i^n R_{\mathrm{ri,i}}}{\gamma_{\mathrm{Rd,ri}} \cdot \gamma_{\mathrm{R,ri}}} + \frac{R_{\mathrm{g}}}{\gamma_{\mathrm{Rg}}} \tag{14}$$

considering the following two components:

- the sum of the representative values of the vertical resistance of the *i*-th rigid inclusion $R_{\mathrm{ri,i}}$ with a model factor $\gamma_{\mathrm{Rd,ri}}$ and a partial resistance factor for the rigid inclusion system $\gamma_{\mathrm{R,ri}}$, whereby the values of $\gamma_{\mathrm{Rd,ri}}$ and $\gamma_{\mathrm{R,ri}}$ are equal resp. comparable to the values of $\gamma_{\mathrm{Rd,group}}$ and $\gamma_{\mathrm{R,group}}$ for a pile group; and
- the representative value of the vertical resistance of the ground after installation of inclusions R_g with a partial factor γ_{Rg}.

The representative resistance of a rigid inclusion R_{ri} shall be determined as for piles, depending on the installation technique and taking into account group and further interaction effects, as shown in Figure 7. Consequently, the ultimate geotechnical resistance of a group of rigid inclusions is not the same as the sum of that of the individual inclusions.
The verification of geotechnical limit states for individual inclusions may be omitted provided it is verified that the system is able to redistribute loads without itself exceeding an ultimate or serviceability limit state.
Serviceability limit states of geotechnical structures on improved ground shall be verified according to other relevant clauses of prEN1997-3.
In addition, the structural resistance of rigid inclusions needs to be verificed, whereby this resistance shall be verified according to the relevant standard for the material installed. If no such standard exists, for materials of Class II ground improvement, ultimate limit states shall be verified by demonstrating that design effects of actions do not exceed the stress envelope of the material used (Figure 8). When normal stresses and shear stresses are verified separately, the design value of the normal stresses and of the shear stresses shall not exceed $0.7 \cdot q_{\mathrm{ud}}$ and $0.2 \cdot q_{\mathrm{ud}}$, respectively.



Key:

1) envelope for allowed states of stress
2) examples for allowed states of stress σ_1, σ_3
3) state of stress in uniaxial compression test: $\sigma_3 = 0$, $\sigma_1 = q_{\mathrm{ud}}$

Figure 8. Allowable stresses in Class II ground improved material with unconfined compressive strength acc. to Annex I of EN 1997-3:2025.

The buckling resistance subject to compression shall be verified. When one of the following conditions is met, verification of buckling of Class BII inclusions may be omitted:

- inclusion diameter $B_{\mathrm{ri}} > B_{\mathrm{ref}}$;
- thickness of the soft layers, where $c_{\mathrm{u}} < c_{\mathrm{u,ref}}$, is smaller than h_{ref}.

The reference values are: $B_{\mathrm{ref}} = 0.3$ m, $c_{\mathrm{u,ref}} = 15$ kPa and $h_{\mathrm{ref}} = 1.0$ m, unless a National Annex gives different values.

The load transfer platform (LTP) and the possible reinforcing elements should be designed to transfer the load from the structure or the embankment to the improved ground. For load transfer platforms over discret inclusion acknowledged calculations methods are the Hewlett & Randolph method (documented in BS 8006-1), the EBGEO method, the Concentric Arches method (details in CUR 226) and the ASIRI method.
ULS verification may be omitted for a LTP where it can be demonstrated that the loads can be redistributed within the confined system, provided that the load transfer platform does not fail at its edges. A confined system can be assumed inside a grid of inclusions in a ground improvement zone (Bohn, 2016).
For reinforced load transfer platforms, the tensile resistance of the reinforcements should be verified according to Clause 9 of EN 1997-3.
In the absence of a LTP, additional verifications may be considered during the design, such as verifications of the stress concentrations at the top of the inclusions and internal forces within the slab or spread foundation.

Testing

Ground improvement should be usually accompanied by testing conducted before or at the beginning of execution. The types of testing should be determined according to the GI technique. The minimum frequency and type of control test should be given by the relevant execution standard or, when no relevant execution standard is available, by the relevant authority or, where not specified, as agreed by the relevant parties for a specific project.
Typical control tests may include for class B ground improvment according to EN 1997-3:

- for Class BI: field testing inside and/or in between inclusions, dummy foundation test on improved ground (individual inclusion and surrounding ground), zone load test on a group of inclusions (group of inclusions and surrounding ground);
- for Class BII: load test on isolated rigid inclusions, zone load test on a group of inclusions (group of rigid inclusions and surrounding ground,) UCS tests of inclusion material.

Clause 12 also provides recommendations on the testing frequency.

CONCLUSION

The second generation of Eurocode 7 is a modern geotechnical standard developed as useful tool for the coming decades. Hence the standard tries to include concepts that are foreseen to be important for the future such as sustainability, robustness, impacts within the zone of influence and climate change. The new structure with a clear division between general rules in part 1, ground properties in part 2 and specific rules for different geotechnical structures in part 3, opens the possibility to add on additional specific clauses, e.g. on tunnels or underground structures, existing geotechnical structures or similar, if ever needed.

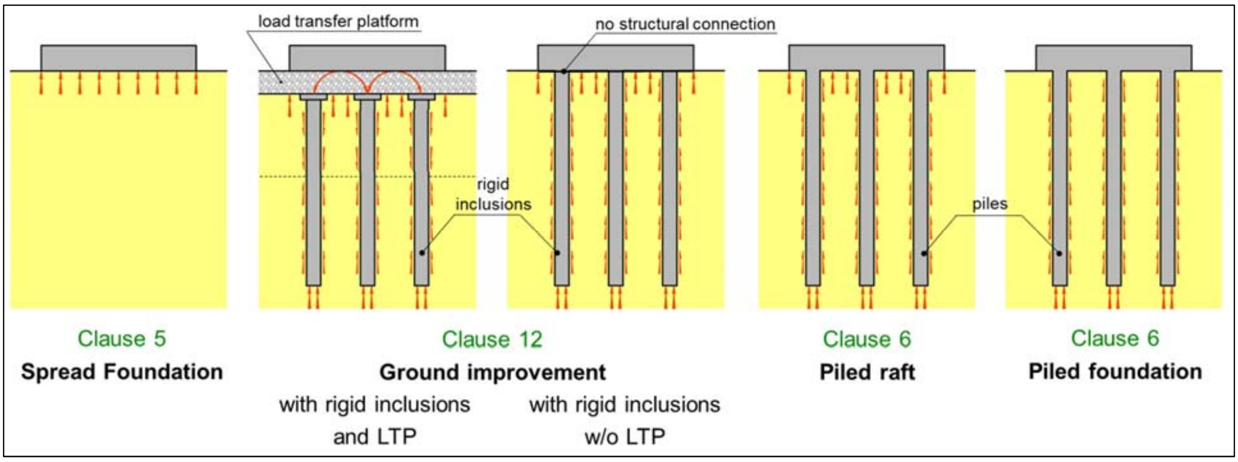


Figure 9. Stringent foundation design and verification concept for all types of foundation acc. to EN 1997-3:2025.

The new Eurocode 7 will serve as the commonly agreed standard for the future functioning as a toolbox that fulfil the needs of geotechnical engineers worldwide. Hereby the standard can be easily adopted to national experience as not only all relevant factors like specification of verification cases, partial safety factors, model factors etc. but also basic specifications of geotechnical categories, minimum extent of ground investigation etc. are ´Nationally Determined Parameters´ (NDP) which can be adjusted according to national experiences and standards.
For the design of piled foundations and ground improvement the second generation of Eurocode 7 provides ´state of the art´-guidance including many new design aspects being relevant engineering practice and allows to cover even sophisticated structures. It has to be highlighted that the regulations provided by EN 1997-3:2025 provide a stringent foundation design and verification concept for all types of foundation allowing a smooth transition from spread foundations via ground improvement with and without rigid inclusions and with or without load transfer platforms to piled rafts and piled foundations with comparable equivalent global safety level (see Figure 9).

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