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Tomorrow's geotechnical toolbox: Design of geotechnical structures to EN 1997:202x La boîte à outils géotechnique de demain: Conception des structures géotechniques selon EN 1997: 202x

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ABSTRACT: This paper shows how three new concepts – ‘Design Cases’ (introduced in prEN 1990), the ‘Geotechnical Design Model’ (prEN 1997-1), and the ‘Ground Model’ (prEN 1997-2) – are combined (in prEN 1997-3) to provide a comprehensive and flexible set of tools for the design of specific geotechnical structures. The paper presents flow charts divided between: a) reliability management, b) ground modelling, c) verification of the design, and d) structure execution, which provide guidelines for navigating prEN 1990 and prEN 1997.

RÉSUMÉ: Cet article montre comment trois nouveaux concepts - "Cas de conception" (introduits dans le prEN 1990), "Modèle de conception géotechnique" (prEN 1997-1) et "Modèle de terrain" (prEN 1997-2) - sont combinés (dans le prEN 1997-3) pour fournir un ensemble complet et flexible d'outils pour la conception de structures géotechniques particulières. Le document présente des organigrammes relatifs: a) a la gestion de la fiabilité, b) a la modélisation du terrain, c) a la vérification de la conception, et d) a l'exécution de la structure.

Keywords: Eurocodes, design, flowchart, geotechnical structures, reliability management

1 INTRODUCTION

In November 2004, the European Committee for Standardization (CEN) published the first Eurocode for geotechnical design, designated EN 1997. Only six years later, in May 2010, the European Commission invited CEN to “initiate

the process of further evolution of the Eurocodes system, incorporating both new and revised Eurocodes”. CEN’s Technical Committee TC250 (which is responsible for the Eurocodes) replied to the Commission in June 2011 with a detailed proposal for a second generation of Eurocodes. In mid-2012, the Commission issued

Mandate 515 instructing CEN to develop a detailed work programme for this work. Finally, at the beginning of 2015, the Commission approved CEN's technical proposal and financial quotation in response to Mandate 515 (M/515).

Phase 1 of M/515 started in earnest in September 2015 with the appointment of Project Teams (PTs), including two which would be responsible of the development of Eurocode 7. Using previously developed drafts, the outcomes of four 'Expert Meetings', and a multitude of discussion, SC7's Project Team 2 delivered a new draft of Eurocode 7 Part 1, designated prEN 1997-1:2018 (hereafter 'prEN 1997'). At the same time, SC10's Project Team 1 delivered a new draft of EN 1990, designated prEN 1990:2018 (hereafter 'prEN 1990'), with the revised title "Basis of structural and geotechnical design". EN 1990 serves as a reference document for all the other Eurocodes.

This paper gives guidelines for navigating prEN 1990 and prEN 1997 and for complying with the requirements and recommendations for safety, serviceability, robustness, and durability of geotechnical structures.

2 DESIGN OF A GEOTECHNICAL STRUCTURE

The design of a geotechnical structure according to prEN1997 comprises four major tasks, as shown in Figure 1:

- Reliability management: a series of classifications that combine to place the

geotechnical structure into a single Geotechnical Category.

- Ground modelling: whose main output is a representation of the ground and groundwater at the site, known as the "Ground Model".
- Design verification: covering all the procedures to verify that no limit states are exceeded in any design situations that the structure encounters during its service life.
- Execution: in which the structure is constructed while meeting the design assumptions and other detailed plans developed during the design phase.

2.1 Task 1: Reliability management

The reliability management system developed in prEN 1997 has a number of components, as shown in Figure 2.

The broad characteristics of the site and the nature of the geotechnical structure are collected in a desk study, by compiling and analysing existing documentation on the site; establishing a preliminary Geotechnical Complexity Class (GCC, shown in Table 1) for the ground; and classifying the consequences of failure of the geotechnical structure into one of the three Consequence Classes (CC) – Lower, Normal or Higher, according to Table 4.2 of prEN1997. Both these tables are designated as "National Determined Parameters" (NDPs), which means they can be changed by individual countries in their corresponding National Annexes to Eurocode 7.

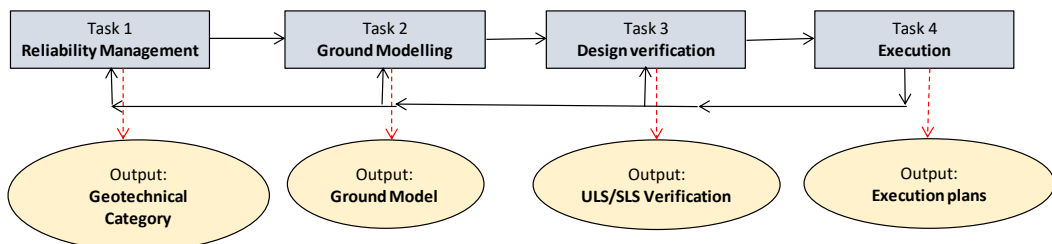


Figure 1. Tasks in the design and execution of a geotechnical structure

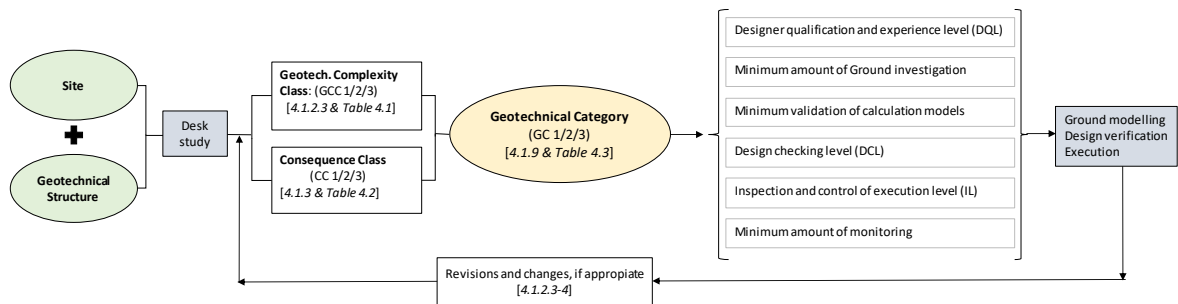


Figure 2. Components of the reliability management system

Table 1. Selection of Geotechnical Complexity Class

Geotechnical Complexity Class	Complexity	General features causing uncertainty
GCC3	Higher	Either considerable uncertainty regarding the ground conditions or any of the following apply: <ul style="list-style-type: none"> • difficult ground conditions • difficult geomorphologies • complex geological conditions • significant sensitivity to groundwater conditions • significant complexity of the ground-structure interaction
GCC2	Normal	Covers everything not contained in the features of GCC 1 and 3
GCC1	Lower	All the following conditions apply: <ul style="list-style-type: none"> • negligible uncertainty regarding the ground conditions • uniform ground conditions • standard construction technique • isolated shallow foundations are systematically applied in the zone • well established design methods • low complexity of the ground-structure-interaction

The next step is to classify the geotechnical structure into a Geotechnical Category (GC) that combines the consequence of failure of the structure (represented by its Consequence Class, CC) and the complexity of the ground (represented by the Geotechnical Complexity Class, GCC), according to Table 2.

Table 2. Relationship between Geotechnical Categories (GCs), Consequences Classes (CCs) and Geotechnical Complexity Classes (GCCs)

Consequence class (CC)	Geotechnical Complexity Class		
	Lower (GCC1)	Normal (GCC2)	Higher (GCC3)
Higher (CC3)	GC2	GC3	GC3
Normal (CC2)	GC2	GC2	GC3
Lower (CC1)	GC1	GC2	GC2

The draft code requires the GCC to be reviewed and, if appropriate, changed at each stage of the design and execution process.

The classification of the geotechnical structure into one Geotechnical Category enables minimum requirements to be specified for subsequent reliability management procedures, as shown in Table 3.

Table 3. Reliability management procedures

Topic	Reference
Designer qualification and experience level (DQL)	Table B1 prEN1990
Minimum amount of ground investigation	Table 4.4 prEN1997
Design check level	Table B2 prEN1990
Minimum validation of geotechnical calculation models	Table 7.1 prEN1997
Inspection and control of execution level (IL)	Table 10.1 prEN1997
Minimum amount of monitoring	Not specified

2.2 Task 2: Ground modelling

The new code requires that ground investigations establish an outline of the disposition of the ground and of the groundwater conditions at, under and around the site (Norbury, 2017). This is termed the “Ground Model”. Figure 3 shows different steps in the modelling process, including ground investigation; compilation of the results of those investigations into a Ground Investigation Report (GIR); and development of the Ground Model according to the principles to be established in prEN 1997-2 (not expected until April 2020).



Figure 3. Ground modelling steps

2.3 Task 3: Design verification

2.3.1 Design situation, Geotechnical Design Model and ULS & SLS verification

As Figure 4 shows, the first step in design verification is the analysis of the Ground Model

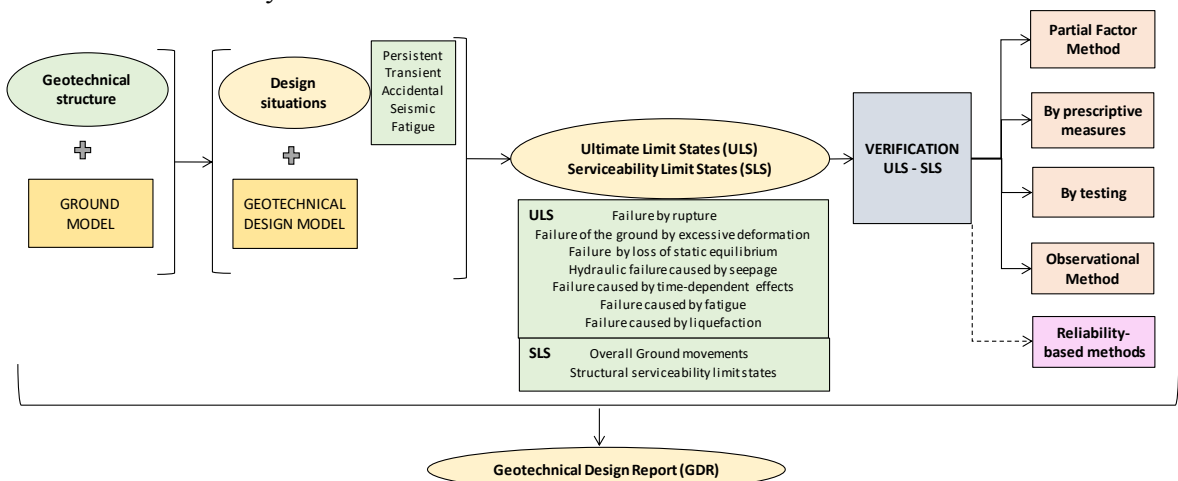


Figure 4. Design verification management

and the conditions under which the structure has to meet its requirements. The aim is: a) to define the design situations in order to describe the physical conditions that could occur during a certain time period; and b) to develop a Geotechnical Design Model.

The design situations (which are classified as persistent, transient, accidental, seismic or fatigue), are associated with a number of relevant ultimate limit states (ULSs) and serviceability limit states (SLSs) that must be verified. The different types of ULS and SLS are shown in Figure 4.

Verification that limit states are not exceeded by geotechnical structures may be achieved by one or more of the following methods: by application of the Partial Factor Method, by using prescriptive measures, directly by testing, or by the application of the Observational Method. In addition, prEN 1997-1 also allows verification of limit states for geotechnical structures via reliability-based methods, as are currently used in rock engineering.

Finally, documentation of the verification and design process of all execution phases and the final design must be compiled into a Geotechnical Design Report (GDR).

2.3.2 ULS verification by the Partial Factor Method

When checking ultimate limit states for a geotechnical structure by the Partial Factor Method, the inequality $E_d \leq R_d$ must be satisfied, where E_d is the design value of the effect of

actions and R_d is the design value of the corresponding resistance.

For each ULS, the characteristic and design values of actions, material properties, and resistances must be identified and determined, as shown in Figure 5.

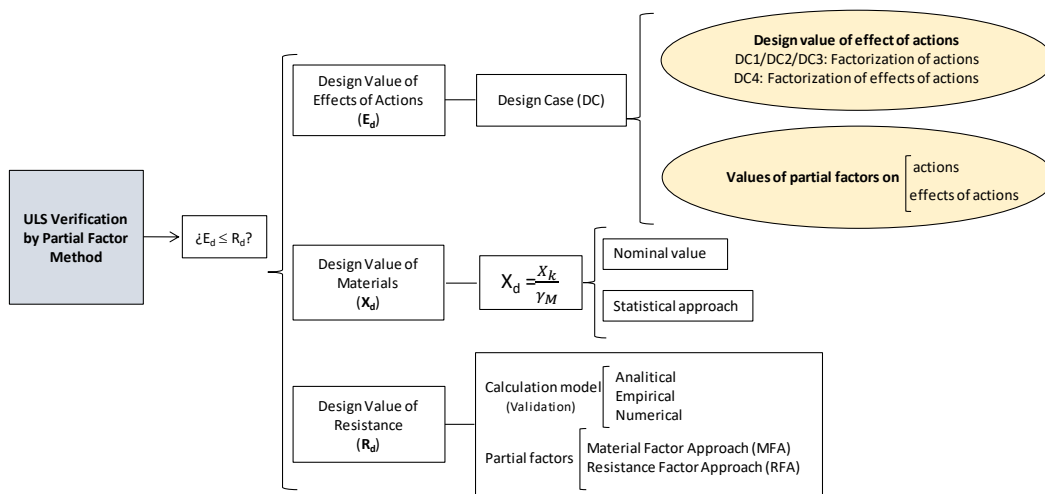


Figure 5: ULS Verification by Partial Factor Method

2.3.3 Design value of effects of actions (Ed)

The first step in determining design values of effects of actions (E_d) is to select the a Design Case (DC) for the limit state being verified, as shown in Table 4.

The Design Case allows us to determine: a) the method of calculating E_d , by factoring either actions or effects-of- actions as shown in Table 5, and b) which set of partial factors to apply, as detailed in Figure 6. The characteristic action that is factored can be a mean value; an upper or lower value; or a nominal value.

Table 4. Selection of Design Cases in geotechnical design as a function of the ULS type

Ultimate limit state	Design Case (and indicative values of partial factors)				
	DC1	DC2		DC3	DC4
	Structural resistance	Static equilibrium and uplift		Geotechnical design	
	$\gamma_Q > \gamma_G > 1.0$	$\gamma_Q > \gamma_G > 1.0$	$\gamma_G = 1.0$ $\gamma_Q > 1.0$	$\gamma_G = 1.0$ $\gamma_Q > 1.0$	$\gamma_E > 1.0$ $\gamma_Q > 1.0$
Rupture or excessive deformation	✓			✓	✓
Loss of rotational equilibrium, loss of vertical equilibrium due to uplift, hydraulic heave, internal erosion, and piping		✓	✓		
Fatigue, time-dependent effects, and liquefaction	✓			✓	✓

Table 5: Determination of the design value of effects-of-actions, depending on the Design Case

Design Case (DC)	Factors applied to	Formula	Expression	prEN 1990 clause
DC1, DC2(a), DC2(b) & DC3	Actions	8.4	$E_d = E \left\{ \sum (\gamma_F \psi F_k); a_d; X_{Rd} \right\}$	8.3.2.2
DC4	Effects of actions	8.5	$E_d = \gamma_E E \left\{ \sum (\psi F_k); a_d; X_{Rd} \right\}$	8.3.2.3

$E\{\dots\}$ denotes the combined effect of the enclosed variables; $\Sigma(\dots)$ denotes the combination of actions; γ_F is a partial factor that takes account of unfavourable deviation of an action from its characteristic value; γ_E is the partial factor corresponding to the effect of actions; ψ is a combination factor (equal to 1,0 for permanent actions or as defined in 6.1.2.3 for variable actions); F_k is the characteristic value of an action; a_d denotes design values of geometrical parameters; X_{Rd} denotes the values of material properties used in the assessment of R_d .

Table A.1.8 (NDP) — Partial factors on actions and effects for fundamental (persistent and transient) design situations

Action or effect				Partial factors γ_F and γ_E for Design Cases 1 to 4				
Type	Group	Symbol	Resulting effect	Structural resistance	Static equilibrium and uplift		Geotechnical design	
Design case				DC1 ^a	DC2(a) ^b	DC2(b) ^b	DC3 ^c	DC4 ^d
Formula				(8.4)	(8.4)		(8.4)	(8.5)
Permanent action (G_k)	All ^f	γ_G	unfavourable /destabilizing	$1,35K_F$	$1,35K_F$	1,0	1,0	G_k is not factored
	Water	$\gamma_{G,w}$		$1,2K_F$	$1,2K_F$	1,0	1,0	
	All ^f	$\gamma_{G,stb}$	stabilizing ^g	not used	$1,15^e$	1,0	not used	
	Water	$\gamma_{G,w,stb}$			$1,0^e$	1,0		
	All	$\gamma_{G,fav}$	favourable ^h	1,0	1,0	1,0	1,0	
Variable action (Q_k)	All ^f	γ_Q	unfavourable	$1,5K_F$	$1,5K_F$	$1,5K_F$	1,3	$\gamma_{Q,1}/\gamma_{G,1}^j$
	Water	$\gamma_{Q,w}$		$1,35K_F$	$1,35K_F$	$1,35K_F$	1,15	1,0
	All	$\gamma_{Q,fav}$	favourable	0				
Effects of actions (E)		γ_E	unfavourable	effects are not factored				$1,35K_F$
		$\gamma_{E,fav}$	favourable					1,0

^a Design Case 1 (DC1) is used both for structural and geotechnical design.
^b Design Case 2 (DC2) is used for the combined verification of strength and static equilibrium, when the structure is sensitive to variations in permanent action arising from a single-source. Values of γ_F are taken from columns (a) or (b), whichever gives the less favourable outcome.
^c Design Case 3 (DC3) is typically used for the design of slopes and embankments, spread foundations, and gravity retaining structures. See EN 1997 for details.
^d Design Case 4 (DC4) is typically used for the design of transversally loaded piles and embedded retaining walls and (in some countries) gravity retaining structures. See EN 1997 for details.
^e The values of $\gamma_{G,stb} = 1.15$ and 1.0 are based on $\gamma_{G,inf} = 1,35 \rho$ and $1,2 \rho$ with $\rho = 0.85$.
^f Applied to all actions except water pressures.
^g Applied to the stabilizing component of an action originating from a single source whose overall effect is unfavourable.
^h Applied to actions whose entire effect is favourable and independent of the unfavourable action.
^j $\gamma_{Q,1}$ = corresponding value of γ_Q from DC1 and $\gamma_{G,1}$ = corresponding value of γ_G from DC1

Figure 6: Partial factors on actions and effects of actions [Table A.1.8 of prEN1990]

In addition to permanent (G) and variable (Q) actions, there are other actions that are classified by their variation in time: accidental (A) and

seismic (A_E). For these actions, design values are determined directly, not by the application of partial factors.

2.3.4 Design value of material properties (X_d)

The design value of a material property X_d should be calculated from Equation 1:

$$X_d = \frac{X_{rep}}{\gamma_M} = \frac{\eta X_k}{\gamma_M} \quad (1)$$

where X_{rep} is the representative value of material or product property ($X_{rep}=\eta X_k$); X_k is the characteristic value of material or product property; γ_M is a partial material factor; η is a conversion factor, accounting for scale effects, effects of moisture and temperature, effects of ageing of materials, and any other relevant parameters. For geotechnical structure design, the value of η is 1.0 unless prEN 1997-3 or National Annexes give a different value.

The characteristic value of material or product property X_k may be:

- taken as a nominal value that is fixed on a non-statistical basis; for instance, on acquired experience or on physical conditions. prEN 1997-1 indicates that the nominal value shall be selected as a cautious estimate of the value affecting the occurrence of the limit state,
- determined from Equation (2) when site specific data are available:

$$X_k = X_{av} [1 \mp k_n \Delta_X] \quad (2)$$

where: X_{av} is an estimate of the average value of the ground property; Δ_X is an estimate of uncertainty affecting the ground property; k_n is a coefficient that depends on the number (n) of site-specific data used to estimate X_{av} ; \pm denotes that $k_n \Delta_X$ should be added/subtracted when an upper/lower value of X_k is critical.

Examples of procedures to evaluate the different terms in Equation (2) are given in Annex B of prEN 1997-1.

Values of the partial material factors (γ_M) are given in Table 6 for persistent, transient, and accidental design situations. Note that the values of γ_M for accidental design situations are about 15% smaller (1,25/1,10 and 1,40/1,20) than the corresponding values for persistent and transient

design situations. In addition, the values of γ_M may be adjusted according to consequences of failure, using the consequence factor K_M given in Table 7.

Table 6: γ_M values for persistent, transient and accidental design situations

Parameter	Persistent / Transient Design situations			Accidental Design situations		
	M1	M2	M3	M1	M2	M3
	τ_s	1,0	1,25	1,25	1,0	1,1
$\tan \phi$	1,0	1,25	1,25 K_M	1,0	1,1	1,1 K_M
$\tan \delta$	1,0	1,0	---	1,0	1,0	---
c_u	1,0	1,4	1,4 K_M	1,0	1,2	1,2 K_M
q_u	1,0	1,4	1,4 K_M	1,0	1,2	1,2 K_M

(1): M1, M2 and M3 are three independent sets of material factors whose use will be specified in EN1997-3 .

Table 7: Values of the consequence factor, depending on Consequence Class

Consequence class	Description of consequences	K_M
CC3	Higher	1,1
CC2	Normal	1,0
CC1	Lower	0,9

2.3.5 Design value of resistance (R_d)

Design value of geotechnical resistance R_d should be calculated using either an empirical or analytical calculation model that is given in prEN 1997-3. These models shall be validated using a procedure chosen according to the Geotechnical Category. prEN 1997 allows the use of numerical models to verify limit states, although calculation procedures for these models differ from the ones described in this paper.

The use of the calculation models should be performed either by the ‘‘Material Factor Approach’’ (MFA), which applies partial factors to material properties, or the ‘‘Resistance Factor Approach’’ (RFA), which applies partial factors to resistances, as shown in Table 8. The partial factors on resistances (γ_R) will be given in prEN 1997-3 for each geotechnical structure.

Table 8: Determination of the design value of resistance dependent on the calculation approach

Material Factor Approach (MFA)	Resistance Factor Approach (RFA)
Partial factors applied to materials properties	Partial factors applied to geotechnical resistances
$R_d = R \left\{ \frac{\eta X_k}{\gamma_M}; a_d; F_{Ed} \right\}$	$R_d = \frac{R \{ \eta X_k; a_d; \sum F_{Ed} \}}{\gamma_R}$
<p><i>R</i>{...} denotes the output of the resistance calculation model; η is a conversion factor [8.3.4.1 of prEN1990]; X_k is the characteristic value of material or product property; γ_M is a partial material factor; a_d denotes design values of geometrical parameters; F_{Ed} denotes design values of actions used in the assessment of E_d; γ_R is a partial resistance factor.</p>	

2.4 Task 4: Measures to be undertaken during execution of the works

To ensure the safety and quality of geotechnical structures, measures shall be undertaken during execution of the works according to the:

- Supervision Plan: to check the validity of design assumptions and to verify the ground and groundwater conditions.
- Inspection Plan: to check the execution is carried out according to the design. This plan should be related to the Inspection Level assigned, based on the GC.
- Monitoring Plan: to check the validity of the Geotechnical Design Model and of performance predictions made during design and to ensure the structure will continue to perform as required after completion.
- Maintenance Plan: to describe any maintenance that is required to ensure the safety and serviceability of the structure after execution.

The level and amount of supervision and inspection and the quantity of field measurements and testing is related to the Geotechnical Category of the structure.

3 CONCLUSIONS

This paper provides guidelines for meeting the requirements and recommendations for safety, serviceability, robustness, and durability of geotechnical structures, as specified in prEN 1990:2018 and prEN 1997-1:2018.

The flowcharts herein help to explain how to establish Geotechnical Categories, develop the Ground Model, and verify ultimate and serviceability limit states.

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