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Tomorrow's geotechnical toolbox: EN 1990:202x Basis of structural and geotechnical design

La boîte à outils géotechnique de demain: EN 1990: 202x Bases de calcul des structures et géotechnique

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ABSTRACT: This paper presents the background to the revision of the head Eurocode, EN 1990, including the broadening of its scope to cover the basis of geotechnical design. It details the key changes to EN 1990 as far as they affect geotechnical design, including the specification of water actions and Design Cases for different ultimate limit states.

RÉSUMÉ: Ce document présente le contexte de la révision de l'Eurocode de tête, EN 1990, y compris l'élargissement de son champ d'application à la base de la conception géotechnique. Il détaille les principaux changements dans l'EN 1990 dans la mesure où elles affectent la conception géotechnique, y compris la spécification des actions d'eau et les cas de conception pour différents états limites ultimes.

Keywords: Eurocodes; design; effects-of-actions; resistance; non-linear systems; combinations of actions; water actions

1 INTRODUCTION

In 2010, the European Commission started the process of evolving European standards for structural design, by inviting proposals for the development of the second generation of Eurocodes. The technical committee responsible for these codes, CEN/TC 250, prepared an ambitious programme of work, including both new and revised standards, that was accepted by the Commission in 2012 through its Programming Mandate M/515. To date, the Commission has provided funds to the tune of €11.5 M in support of this programme.

The main objectives of this work are to incorporate improvements to the existing Eurocode suite that reflect the state-of-the-art in engineering design and the needs of the civil engineering market; to improve the ease-of-use of the standards; and to harmonize practice between countries by reducing the number of Nationally Determined Parameters and alternative design methods.

Detailed plans for the evolution of Eurocode 7 (EN 1997-1:2004 and EN 1997-2:2007) were prepared by CEN/TC 250/SC 7 and have been reported previously by Bond et. al. (2015).

2 RESTRUCTURING EUROCODE 7

A key part of the work on the second generation of Eurocode 7 has involved re-organizing the structure of the document to provide a clearer distinction between requirements, recommendations, and permissions and easier navigation through the text.

The contents of the existing Eurocode 7 Part 1 *General rules* (EN 1997-1:2004) have been divided into three distinct groups, as illustrated in Figure 1.

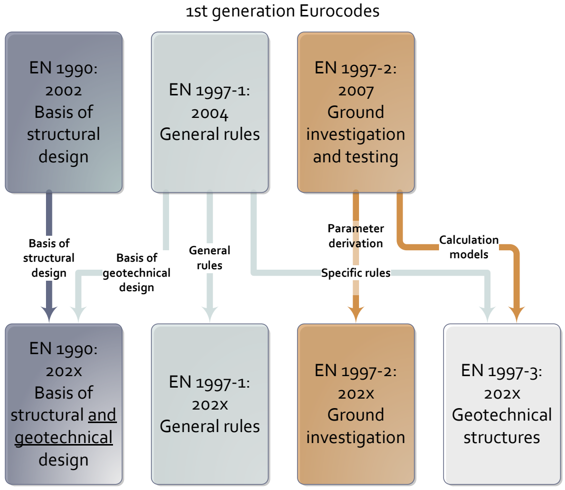

Figure 1 Redistribution of EN 1997-1:2004 and EN 1997-2:2007 into other standards

The basis of geotechnical design has been moved into EN 1990:202x; general rules that affect all geotechnical design remain in EN 1997-1:202x; and specific rules for particular geotechnical structures will form a new standard, EN 1997-3:202x.The contents of the revised Eurocode 7 Part 1 are described in detail in a companion paper by Franzen et al. (2019) and those of the new Part 3 by Bond et al. (2019).

The contents of the existing Eurocode 7 Part 2 *Ground investigation and testing* (EN 1997-2:2007) are also being revised so that it focuses on how to derive parameters for design, rather than on documenting field and laboratory tests and their application. The revision of Eurocode 7 Part 2 is described in detail by Norbury et al. (2019).

Finally, guidelines for navigating through the second generation of EN 1990 and EN 1997 are given in a paper by Estaire et al. (2019).

3 INCORPORATING GEOTECHNICAL DESIGN INTO EN 1990

The existing version of EN 1990:2002 was written as a state-of-the-art treatment of the basis of structural design, founded on limit state theory. Reliability of design was provided by a semi-probabilistic method based on partial factors. Applying the same method to geotechnical design proved to be extremely difficult and resulted in three different Design Approaches being presented in EN 1997-1:2004, with countries free to choose which Approach to adopt. The complexity of this arrangement has proved to be a major barrier to understanding Eurocode 7 and is probably its most criticised feature.

The Design Approaches have been removed from the second generation of Eurocode 7 since the methods presented in EN 1990 have been extended to reflect the particular features of geotechnical engineering. These features include non-linear material behaviour; ‘coupling’ between actions and resistances and between material properties and effects-of-actions; two-phase materials; and large uncertainties and variablility in material properties.

The scope of the second generation of EN 1990 has now been extended to include geotechnical design (as reflected in its revised title). This has necessitated generalization of the core principles of EN 1990, particularly with respect to the verification of ultimate limit states.

3.1 Simplification of EQU, STR, and GEO limit states

EN 1990:2002 identifies four ultimate limit states that should be verified as relevant: loss of static equilibrium ('EQU'); internal failure of the structure ('STR'); failure of the ground ('GEO'); and fatigue ('FAT'). EN 1990:2002 provides separate equations for this verification:

$$E_{d,dst} \leq E_{d,stb} \qquad (1)$$

for EQU, where $E_{d,dst}$ denotes destabilizing design effects-of-actions (e.g. oveturning moments) and $E_{d,stb}$ denotes stabilizing design effects (e.g. restoring moments) and:

$$E_d \leq R_d \qquad (2)$$

for STR and GEO, where E_d denotes design effects-of-actions (e.g. bending moments) and R_d denotes resistance (e.g. bending capacity).

Unfortunately, this simple presentation hides considerable complexity that exists in the real world, such as when ground anchors are used to stabilize a structure that would otherwise not be in equilibrium. Although such combined EQU/STR limit states are covered by a note in Table A.1.2(A) of EN 1990:2002, for the second generation of EN 1990 it was decided to generalize the verification of ultimate limit states to avoid 'gaps' in coverage.

EN 1990:202x still requires verification according to equation (2), but in cases of combined limit states this becomes:

$$E_{d,dst} - E_{d,stb} \leq R_d \qquad (3)$$

In addition, when checking ultimate limit states caused by excessive deformation, EN 1990:202x requires additionally that:

$$E_d \leq C_{d,ULS} \qquad (4)$$

where, here, the effect-of-actions is a movement or strain and $C_{d,ULS}$ is the design value of the deformation that causes an ultimate limit state to be exceeded (for example, settlement of a pile by more than 10% of its diameter).

Finally, the abbreviations EQU, STR, GEO, UPL (failure by uplift), HYD (hydraulic failure), and FAT have been removed from the Eurocodes, since they cause more confusion than clarity.

3.2 Design effects-of-actions

EN 1990:2002 was written primarily for linear structural systems. Design effects of actions (E_d) – such as bending moments and shear forces – are determined by applying partial factors (γ_F) to representative actions (F_{rep}) – see 3.2.1 (below) for details.

For linear systems, when a partial factor 1.35 is applied to a permanent load, the corresponding load-effect (e.g. bending moment) increases by 35%. However, when the response of the system is non-linear, this correspondence does not hold. To explain this, it is helpful to classify structural systems as 'over-linear' or 'under-linear', according to Figure 2.

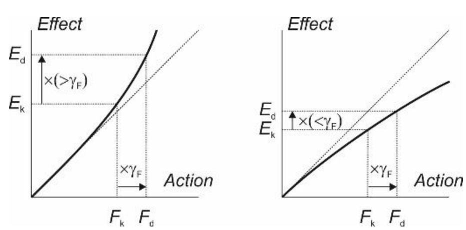

Figure 2 Definition of (left) 'over-linear' and (right) 'under-linear' structural systems (after Gulvanessian et al., 2002)

When an increase in action causes a disproportionally larger increase in effect, the system is denoted 'over-linear'; but when it causes a smaller increase, it is denoted 'under-linear'. Examples in geotechnical engineering include active (under-linear) and passive (over-linear) earth pressures.

The second generation of EN 1990 now explicitely caters for both linear and non-linear structural and geotechnical systems (with the latter being inherently non-linear).

3.2.1 Linear systems (factors on actions)

In EN 1990:2002, design effects of actions are determined from:

$$E_d = E\left\{\gamma_{F,i} F_{rep,i}; a_d\right\} \; i \geq 1 \tag{5}$$

where a_d denotes design values of geometrical parameters (e.g. size of the foundation).

This expression, however, is incomplete since it does not recognize the fact that certain actions – such as earth pressure on a retaining wall – also depend on material properties (such as the angle of internal friction of the ground). This is known as 'coupling' between action-effects and material properties.

Note that this phenomenon is not confined to geotechnical engineering – it also applies to force-effects in cables and membrane structures.

The second generation of EN 1990 now caters for this coupling by including an extra term (shown boxed below) in the formula for design effect of actions:

$$E_d = E\left\{\sum\left(\gamma_F F_{rep}\right); a_d; \boxed{X_{Rd}}\right\} \tag{6}$$

where X_{Rd} represents the design values of any material properties used in the assessment of design resistance (R_d) – more on this later.

A simple example using factors on actions is the calculation of axial force in a pile. Representative loads (G_{rep} permanent and Q_{rep} variable) are multiplied by $\gamma_G = 1.35$ and $\gamma_Q = 1.5$ in Design Case 1 (see 3.2.6) to obtain the total design load normal to the pile (N_{Ed}):

$$N_{Ed} = \gamma_G G_{rep} + \gamma_Q Q_{rep}$$
$$\Rightarrow N_{Ed} = 1.35 G_{rep} + 1.5 Q_{rep} \tag{7}$$

3.2.2 Non-linear systems (factors on effects-of-actions)

EN 1990:202x has added a specific formula to determine design effects of actions for non-linear systems, which uses partial factors (γ_E) applied directly to the effects:

$$E_d = \gamma_E E\left\{\sum F_{rep}; a_d; X_{Rd}\right\} \tag{8}$$

A simple example using factors on effects-of-actions is the calculation of bending moments in a retaining wall using a soil-spring model. The calculated bending moment (M_{wall}) is multiplied by $\gamma_E = 1.35$ in Design Case 4 to obtain the design bending moment (M_{Ed}):

$$M_{Ed} = \gamma_E M_{wall} = 1.35 M_{wall} \tag{9}$$

3.2.3 Design resistance

The primary method in EN 1990:2002 for determining the design resistance of a structural element (R_d) involves factoring its characteristic material strength (X_k) by a partial factor (γ_M):

$$R_d = R\left\{\eta_i \frac{X_{k,i}}{\gamma_{M,i}}; a_d\right\} \; i \geq 1 \tag{10}$$

where η is a conversion factor (which is commonly incorporated into γ_M) and a_d denotes design values of geometrical parameters (as before).

However, an alternative method is given which involves factoring characteristic resistance directly:

$$R_d = \frac{R_k}{\gamma_M} \tag{11}$$

where here γ_M is a resistance factor (despite its inconsistent notation).

These expressions, however, are incomplete since they do not recognize the fact that the resistance of an element – such as the bearing resistance of a footing – also depends on the applied actions (such as overburden pressure in the ground). This is 'coupling' between resistance and actions.

Note that this phenomenon is not confined to geotechnical engineering – it also applies to friction beneath the bearing of a bridge.

The second generation of EN 1990 keeps both of these equations but improves on their presentation.

3.2.4 Material factor approach (MFA)

EN 1990:202x caters for coupling between resistance and actions by including an extra term (shown boxed below) in the formula for design resistance:

$$R_d = R\left\{\frac{\eta X_k}{\gamma_M}; a_d; \boxed{\Sigma F_{Ed}}\right\} \qquad (12)$$

where F_{Ed} represents the design values of any actions used in the assessment of design effects-of-actions (E_d) – as discussed earlier.

This formulation of design resistance is called the 'material factor approach' (MFA).

A simple example using MFA is the calulation of bearing resistance of a footing on clay. Bearing capacity theory could be used with characteristic values of undrained strength divided by $\gamma_M = \gamma_{cu} = 1.4$ to obtain the design bearing resistance ($q_{v,Rd}$):

$$q_{v,Rd} = (\pi + 2)\frac{c_{u,k}}{\gamma_{cu}}$$

$$\Rightarrow q_{v,Rd} = (\pi + 2)\frac{c_{u,k}}{1.4} \qquad (13)$$

3.2.5 Resistance factor approach (RFA)

EN 1990:202x provides a more explicit formulation of the 'alternative method' of determing resistance and gives it equal billing with the previous 'primary method':

$$R_d = \frac{R\{\eta X_k; a_d; \Sigma F_{Ed}\}}{\gamma_R} \qquad (14)$$

where the symbol γ_R replaces γ_M as the resistance factor. For symmetry with actions, a new term 'representative' material property (X_{rep}) is defined as:

$$X_{rep} = \eta X_k \qquad (15)$$

although in EN 1997-1:202x we have tentatively set $\eta = 1.0$.

A simple example using RFA is the calculation of base resistance of a single pile. The calculated resistance (q_b) from piling theory is divided by $\gamma_R = \gamma_b = 1.5$ (say) to obtain the design base resistance ($q_{b,Rd}$):

$$q_{b,Rd} = \frac{q_b}{\gamma_b} = \frac{q_b}{1.5} \qquad (16)$$

3.2.6 Design cases

To assist the engineer in choosing the most appropriate partial factors on actions and effects, EN 1990:202x introduces specific Design Cases for different ultimate limit states.

Design Case 1 is used primarily for verification of structural resistance and is equivalent to the old 'Set B' in EN 1990:2002 – as used in Design Approach 1 Combination 1 and Design Approach 2 and Design Approach 3 of EN 1997-1:2004.

Design Case 2 is used for checking static equilibrium and uplift and is equivalent to the old 'Set A' in EN 1990:2002 (with NOTE 2 of Table A1.2(A) applied).

Design Case 3 is used for geotechnical design and is equivalent to the old 'Set C' in EN 1990:2002, as used in Design Approach 1 Combination 2 of EN 1997-1:2004 and Design Approach 3.

Finally, Design Case 4 is used for geotechnical design, particularly those involving under-linear systems. This Design Case has no equivalent in EN 1990:2002, but is used in the so-called Design Approach 2* commonly employed in Germany.

Table 1 presents the values of the partial factors on actions and effects for buildings and general geotechnical strructures, as specified in Annex A of EN 1990:202x.

Table 1. Partial factors on actions and effects for persistent and transient design situations

Action or effect				Partial factors γ_F and γ_E for Design Cases 1-4				
Type	**Group**	**Symbol**	**Resulting effect**	**DC1**	**DC2**		**DC3**	**DC4**
					a	**b**		
				Structural resistance	**Static equilibrium and uplift[1]**		**Geotechnical design**	
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	not used	1,15	1,0	not used	
	Water	$\gamma_{G,w,stb}$			1,0	1,0		
	All	$\gamma_{G,fav}$	Favourable	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	$\gamma_{Q,1}/\gamma_{G,1}$
	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

[1]Values of γ_F are taken from columns (a) or (b), whichever gives the less favourable outcome.

K_F is a consequence factor, equal to 1.1 for structures in Consequence Class CC3, 1.0 for CC2, and 0.9 for CC1.

4 OTHER IMPROVEMENTS TO EN 1990

4.1 Simplified presentation of combinations of actions

Although of less significance to geotechnical engineers than the changes described above, EN 1990:202x also improves its presentation of combinations of actions for the various design situations.

In EN 1990:2002, two entirely equivalent notations are used to specify combinations, for example, for persistent and transient design situations:

$$E_d = E\{\gamma_{G,j} G_{k,j}; \gamma_P P; \gamma_{Q,1} Q_{k,1}; \gamma_{Q,i} \psi_{0,i} Q_{k,i}\} \quad (17)$$

where the term in brackets is also given by:

$$\sum_{j\geq 1} \gamma_{G,j} G_{k,j} \text{ "+" } \gamma_P P \text{ "+" } \gamma_{Q,1} Q_{k,1} \text{ "+" } \sum_{i>1} \gamma_{Q,i} \psi_{0,i} Q_{k,i} \quad (18)$$

These two expressions have been combined to:

$$\overbrace{\sum F_{\mathrm{d}}}^{actions} = \overbrace{\sum_{\mathrm{i}} \gamma_{\mathrm{G,i}} G_{\mathrm{k,i}}}^{permanent} + \overbrace{\gamma_{\mathrm{Q,1}} Q_{\mathrm{k,1}}}^{leading\ variable}$$
$$+ \underbrace{\sum_{\mathrm{j>1}} \gamma_{\mathrm{Q,j}} \psi_{0,\mathrm{j}} Q_{\mathrm{k,j}}}_{accompanying\ Q} + \underbrace{(\gamma_{\mathrm{P}} P_{\mathrm{k}})}_{pre-stress} \qquad (19)$$

Even simpler, the particular parts of this equation that are used in design situations are summarized as shown in Table 2.

Table 2. Combinations of actions for ultimate limit states

Design situation	**Persistent/ transient**	**Accidental**	**Seismic**	**Fatigue**
Permanent ($G_{\mathrm{d,i}}$)	$\gamma_{\mathrm{G,i}} G_{\mathrm{k,i}}$	$G_{\mathrm{k,i}}$	$G_{\mathrm{k,i}}$	$G_{\mathrm{k,i}}$
Leading variable ($Q_{\mathrm{d,1}}$)	$\gamma_{\mathrm{Q,1}} Q_{\mathrm{k,1}}$	$\psi_{1,1} Q_{\mathrm{k,1}}$ or $\psi_{2,1} Q_{\mathrm{k,1}}$	$\psi_{2,\mathrm{j}} Q_{\mathrm{k,j}}$	$\psi_{1,1} Q_{\mathrm{k,1}}$
Accompanying variable ($Q_{\mathrm{d,j}}$)	$\gamma_{\mathrm{Q,j}} \psi_{0,\mathrm{j}} Q_{\mathrm{k,j}}$	$\psi_{2,\mathrm{j}} Q_{\mathrm{k,j}}$		$\psi_{2,\mathrm{j}} Q_{\mathrm{k,j}}$
Prestress (P_{d})	$\gamma_{\mathrm{P}} P_{\mathrm{k}}$	P_{k}	P_{k}	P_{k}
Accidental (A_{d})	-	A_{d}	-	-
Seismic (A_{Ed})	-	-	$A_{\mathrm{Ed,ULS}}$	-
Fatigue (Q_{fat})	-	-	-	Q_{fat}

4.2 Better specification of water actions

Something that affects all geotechnical design is the specification of water actions. Even before EN 1997-1:2004 was published, there has been a debate whether water pressures should be factored or not. Notwithstanding strong arguments either way, the answer is of course "it depends…". For any definitive statement to be made on this question, it is important that the needs of civil and structural engineers in several diverse industries are catered for: maritime engineers, coastal and river engineers, liquid containment tank designers, and, of course, geotechnical engineers.

The second generation of EN 1990 recommends that water actions "should be classified as permanent, variable, or accidental *according to the probability that the magnitude of the action will be exceeded*".

The representative value of any permanent water action ($G_{\mathrm{w,rep}}$) should be selected as follows:

- when the uncertainty in the water action is not significant, $G_{\mathrm{w,rep}}$ is taken as a single characteristic value ($G_{\mathrm{w,k}}$) equal to its mean ($G_{\mathrm{w,mean}}$)
- when there is significant uncertainty in the water action, $G_{\mathrm{w,rep}}$ is taken as the more onerous of its upper and lower characteristic values ($G_{\mathrm{w,k,sup}}$ or $G_{\mathrm{w,k,sup}}$)
- when little or no data is available, $G_{\mathrm{w,rep}}$ is taken as a nominal value ($G_{\mathrm{w,nom}}$)

Variable water actions should be represented by two components: one permanent ($G_{\mathrm{w,rep}}$), as defined above; and one variable ($Q_{\mathrm{w,rep}}$), based on a specified probability of exceedence, as detailed in Table 3.

Table 3. Specification of water actions

Value of variable water action	Symbol	Probability of exceedance	Return period (years)
Characteristic	$Q_{w,k}$	2%*	50
Combination	$Q_{w,comb}$	5%*	20
Frequent	$Q_{w,freq}$	1%**	-
Quasi-permanent	$Q_{w,qper}$	50%**	-
*annual probability of exceedance **during design service life			

5 CONCLUSIONS

When published, the second generation of EN 1990, *Basis of structural and geotechnical design*, and Eurocode 7, *Geotechnical design*, will deliver significant improvements in ease-of-use and harmonization of practice between countries, reflecting the state-of-the-art in engineering design and the needs of the ground engineering market.

Eurocode 7 itself will be re-organized into three parts, providing clearer general rules (Part 1), more practical guidance on ground investigation (Part 2), and more detailed rules for specific geotechnical structures (Part 3).

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