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Eurocode 7 – second generation – spread foundations

Eurocode 7 - deuxième génération – fondations superficielles

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ABSTRACT: In the new second generation version of Eurocode 7, Part 3 the limit state design for various geotechnical structures is outlined. Spread foundations are covered in Clause 5 of this part where requirements for the verification of ultimate and serviceability limit states are provided. In comparison to the current version of Eurocode 7 the requirements have been improved first by revising the structure of this clause so that it is now unified and consistent with the other clauses in this part and follows the design-path defined in Part 1. In addition, various aspects addressing the limit state design of spread foundations have been complemented or modified such as the inclusion of the well-known Terzaghi-Buisman method for calculating the bearing resistance in the main text, the explicit consideration of rock mass as well as various calculation models provided in Annex B, e.g. models for punching failure and foundation settlement evaluation. The present paper provides an overview of the design of spread foundations according to the new Eurocode 7. A simple design example illustrates the design procedure.

RÉSUMÉ: Dans la nouvelle version de deuxième génération de l'Eurocode 7, partie 3, la conception des états limites pour diverses structures géotechniques est décrite. Les fondations superficielles sont traitées par la clause 5 de cette partie, où les exigences relatives à la vérification des états limites ultimes et d'aptitude au service sont fournies. Par rapport à la version actuelle de l'Eurocode 7, les exigences ont été améliorées tout d'abord en révisant la structure de cette clause afin qu'elle soit désormais unifiée et cohérente avec les autres clauses de cette partie et qu'elle suive le chemin de conception défini dans la partie 1. En outre, divers aspects relatifs à la conception à l'état limite des fondations superficielles ont été complétés ou modifiés, comme l'inclusion de la méthode bien connue de Terzaghi-Buisman pour le calcul de la résistance à l'appui dans le texte principal, considération explicite des masses rocheuses ainsi que divers modèles de calcul fournis dans l'annexe B, par exemple des modèles pour la rupture par poinçonnement et l'évaluation du tassement de la fondation superficielle. Le présent document donne un aperçu de la conception des fondations superficielle selon le nouvel Eurocode 7. Un exemple simple de conception illustre la procédure de conception.

Keywords: Second generation Eurocode 7; spread foundations; design; ultimate limit state; serviceability limit state.

1 INTRODUCTION

The design of spread foundations is covered in Part 3, Clause 5 of the new second generation Eurocode 7 (prEN 1997-3:2023). Clause 5 is organized with design provisions following the unified structure of all the clauses in Part 3 which reflects the design requirements in Part 1 (prEN 1997-1:2023) as illustrated in Figure 1. Clause 5 also refers to Part 2 (prEN 1997-2:2023) for required derived ground properties.

The scope of Clause 5 is the limit state design of spread foundations, i.e. of pad, strip and raft foundations. Compared to the current version of Eurocode 7 (EN 1997-1:2004 + AC:2009 + A1:2013) the scope has been extended to include unreinforced working platforms.

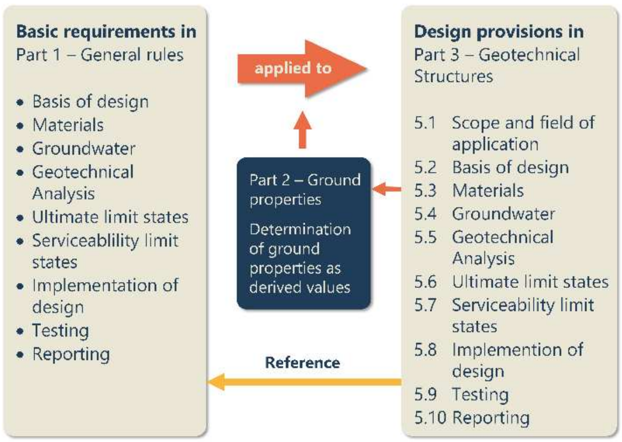

Figure 1. Structure of clause 5 – spread foundations.

While the design of load transfer platforms over rigid inclusions is covered in Clause 11 of Part 3, Clause 5 is applicable to certain aspects as well. Furthermore, it is applicable to deep foundations such as caissons, which behave as spread foundations.

The present paper addresses the most important changes compared to the current version of the code with a focus on the basis of design, the geotechnical analysis and the verification of the ultimate and serviceability limit states. The procedure of design verification is illustrated using a simple design example at the end of this paper.

2 PHILOSOPHY AND DESIGN BASICS

2.1 Design philosophy

The head Eurocode EN 1990 (EN 1990:2023), Basis of structural and geotechnical design, states that the reliability required for structures within the scope of this document shall be achieved by design in accordance with all parts of the Eurocodes. Thus, the overall design goal is achieved if a design follows the requirements provided in Eurocode 7, Parts 1 to 3 together with those in EN 1990.

The new Eurocode 7, Part 1 provides a set of measures to achieve this reliability goal. These measures address not only the representation of design parameters and the accuracy of calculation models used, but also the prevention of errors in design and execution. They are defined at different levels, depending on the Geotechnical Category of the structure. The Geotechnical Category reflects the relationship between the Geotechnical Complexity Class, describing ground and groundwater conditions as well as ground-structure interaction, and the Consequence Class, considering the consequences of failure of the structure or the foundation. The provisions in Clause 5 address these requirements.

2.2 Basis of design

Clause 5, Subclause 5.2 summarizes the basic design information such as the design situations, geometrical properties, actions and environmental influences, limit states and ground investigations, which are spread over several subclauses in the current version of the code. Reliability, as outlined in 2.1, is addressed by reference to Part 1 only, so no specific provisions are given for spread foundations. However, the minimum extent (depth) of ground investigations defined here is one of the measures to achieve the required reliability. Table 1 shows the minimum depth values given for spread foundations. These values reflect the zone of influence of different types of spread foundations and are comparable to the recommendations in Annex B of the current Eurocode 7, Part 2. The width B is either the width of a single foundation or the width of a foundation group, depending on the considered system. The content of the table can be modified in the National Annexes.

Table 1. Minimum depth of ground investigations from Table 5.1 of prEN 1997-1:2023.

Types of spread foundations	Minimum depth
Square or circular footing	d_{min} = max (3B; 6m)
Strip footing	d_{min} = max (5B; 6m)
Raft or structure supported by a group of foundations	d_{min} = max (1.5B; 6m)

2.3 Materials and groundwater

Subclause 5.3 addresses the materials used in design. It mainly refers to Part 2 for the determination of ground properties and to Part 1, Clause 5.5 for concrete foundations. It further points out the use of effective or total stress ground properties, depending on the design situation.

Subclause 5.4 on groundwater demands explicitly the consideration of groundwater levels and pressures, which could affect the bearing behaviour of a spread foundation. Capillary rise inducing possible deterioration of footing material is mentioned as well.

3 GEOTECHNICAL ANALYSIS

The calculation models for verifying the limit states of spread foundations are the content of Subclause 5.5. The main changes compared to the current version of Eurocode 7 are related to the calculation of the bearing resistance. The well-known general Terzaghi-Buisman formulae for the bearing resistance of soils and fills for drained and undrained analysis (Terzaghi, 1943) are now presented in the code text of the new Eurocode 7. The parameters for the bearing resistance formulae are defined in Annex B.4.

The bearing resistance formulae for soil and fill were extended by depth factors and ground inclination factors. For the depth factors the formulae proposed by Brinch Hansen (1970) and adopted by Vesic (1973) and for the ground inclination factors the formulae provided by Vesic (1975) were adopted. More changes include the deletion of the cohesion term in the load inclination factors and a modification of the bearing capacity factor N_γ. For the latter the formulation provided by Caquot & Kérisel (1953) and Vesic (1973) was selected, which is slightly different from the formulae used in Annex D of the current Eurocode 7, i.e. $N_\gamma = 2(N_q + 1)\cdot\tan\varphi'$ instead of $N_\gamma = 2(N_q - 1)\cdot\tan\varphi'$. Figure 2 illustrates the effect of this modification and of the consideration of depth factors on the foundation design width, B for a simplified design situation.

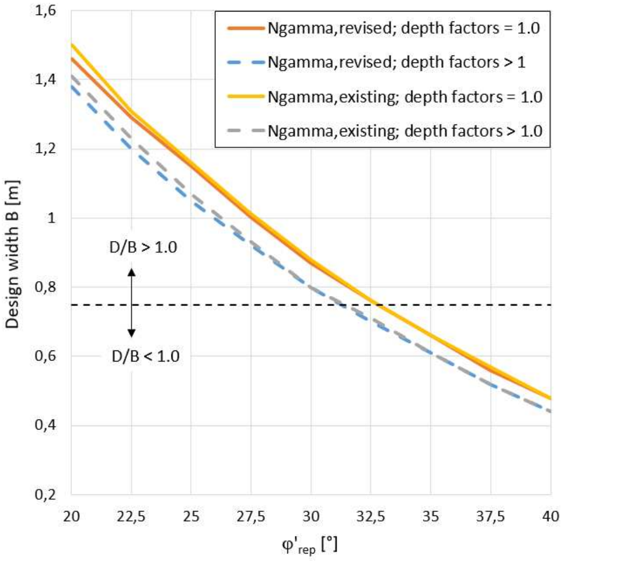

Figure 2. Design width B for a square foundation with 250 kN vertical load calculated using RFA for a dry coarse soil with γ = 18 kN/m³ and an embedment depth of D = 0.75 m (modified from M515/CEN/TC250/SC7/PT4, 2020).

Clearly, the modification of $N_γ$ has negligible effect on B for φ' ≥ 27.5°. For φ' < 27.5° it results in widths B which are slightly smaller than with the existing formulation. No cohesion was considered here, which soils with small friction angles typically exhibit and which would increase the bearing resistance. In view of the scatter generally associated with the factor $N_γ$ (see e.g. Paikowsky et al., 2010) the consequences of using the new $N_γ$ formula are acceptable.

Compared to this, the effect of the depth factors is more significant. However, the depth factors should only be used with great care as the soil within the embedment zone is often disturbed. Consequently, the code states that they should only be used when the strength of the soil or fill in the embedment zone is equal to or greater than the strength of the soil below foundation level.

A further addition is that Subclause 5.5 includes some guidance on how to verify the bearing resistance of rock mass. It also allows the derivation of the bearing resistance from empirical models, provided comparable experience has shown their successful use. Annex B includes additional calculation models, e.g. for punching, a more detailed model for bearing resistance from pressuremeter test results and a model for bearing resistance of rock mass based on wedge equilibrium.

Regarding the calculation of sliding resistance and settlement or heave, no major changes have been made. Annex B provides various calculation models for settlement evaluation, e.g. based on the adjusted elasticity method and on pressuremeter or cone penetration test results.

Subclause 5.5 also includes recommendations for selecting appropriate distributions of bearing pressures for structural analysis.

4 DESIGN VERIFICATION WITH PARTIAL FACTORS

4.1 Limit states

According to Subclause 5.2.5 the design verification shall consider primarily the ultimate limit states (ULS) and serviceability limit states (SLS) shown in Figure 3.

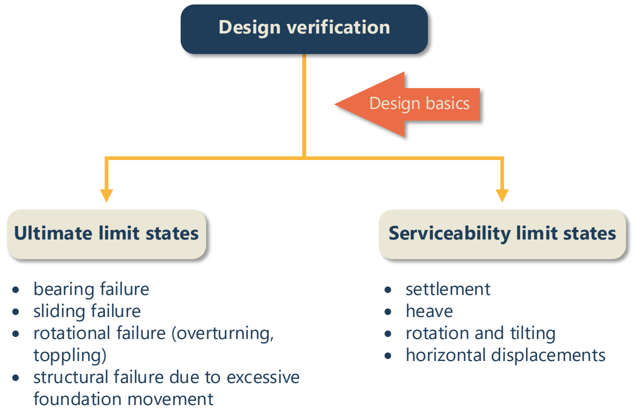

Figure 3. Ultimate and serviceability limit states of spread foundations.

Figure 3 also mentions failure by excessive deformations. However, Clause 5 does not provide recommendations on how to verify this limit state. Instead, this topic is addressed in Part 1.

4.2 Verification of the ultimate limit state

The new Eurocode 7 allows the material factor approach (MFA) and the resistance factor approach (RFA) to be used for ULS design verification. The partial resistance factors to obtain the RFA design resistances of spread foundations are provided in Subclause 5.6 of Part 3, Table 5.2, whereas the partial material factors to obtain the design MFA ground properties are given in Part 1, Table 4.8. The partial factors on actions and effects of actions are defined for different verification cases (VC) in EN 1990, Table A.1.8. The National Annexes will specify the factoring approach and partial factors to be used. The two approaches result in the combinations (a) to (c) for MFA and (d) and (e) for RFA (see Table 2). However, combination (e) should be used only if the representative load inclination is not larger than 0.2.

Table 2. Partial factors for the ULS verification of spread foundations for persistent and transient design situations (Table 5.2, prEN 1997-3:2023).

Verification of	Partial factor on	Symbol	Material factor approach (MFA), either both combinations (a) and (b) or the single combination (c)			Resistance factor approach (RFA), either combination (d) or (e)[c]	
			(a)	(b)	(c)	(d)	(e)
Overall stability	See Clause 4						
Bearing and sliding resistance	Actions effects-of-actions	γ_F ,γ_E	VC1[a]	VC3[a]	VC1[a]	VC1[a]	VC4
	Ground properties	γ_M	M1[b]	M2[b]	M2[b]	Not factored	
	Bearing resistance	γ_{RN}	Not factored			1,4	
	Sliding resistance	γ_{RT}	Not factored			1,1	
	Passive resistance	$\gamma_{RT,face}$	Not factored			1,4	

[a] Values of the partial factors for Verification Cases (VCs) 1, 3, and 4 are given in prEN 1990:2023 Annex A.
[b] Values of the partial factors for Sets M1 and M2 are given in prEN 1997-1:2023, Table 4.8.
[c] Use combination (d) except where specified otherwise in 5.6.6 (2)

Combinations (a) and (b) correspond to the current DA1 Combination 1 and DA1 Combination 2, (d) corresponds to DA2, (e) to DA2* and (c) to DA3 with VC3 partial factors on structural actions. The new Eurocode 7 offers the possibility of reducing the partial material and partial resistance factors for transient design situations by multiplying them by a reduction factor, k_{tr} provided the products are not less than 1.0 and any constraints on its use are satisfied. It should also be noted that all tables with partial factors are Nationally Determined Parameters (NDPs) and therefore can be adjusted based on national practices and given in National Annexes.

Overall, the verification procedures for undrained and drained bearing and sliding resistances have not changed. Nevertheless, in addition to verification of the undrained sliding resistance in MFA and RFA, it still has to be checked that $R_{tud,base} \leq 0.4 \cdot N_{rep}$ ($R_{tud,base}$: design undrained base resistance; N_{rep}: representative value of the force acting normal to the foundation base (considered as favourable action)). This condition limits the load inclination when there is an irregular bearing surface with poor contact between the base of the foundation and the ground and, thus a reduced contact area, to ensure that simultaneous shearing and bearing failure does not occur. This limit corresponds to a maximum load inclination angle of 21.8° in such a design situation.

In case of eccentrically loaded spread foundations the new Eurocode 7 clearly distinguishes between the limit states of overturning and toppling. Overturning involves failure of the ground caused by rotation of the footing, whereas toppling describes a pure loss of static equilibrium without failure of the ground.

According to Subclause 5.6 the verification against overturning is covered by the bearing resistance verification. It is stated further on that the designer should note the following:

- Reduction of the plan area A to the effective plan area A' should be limited so that rotation does not cause a limit state in the foundation or the overlying structure;
- National Annexes can provide limiting values for the design eccentricity in the ULS;
- Precautions should be taken in the design if the eccentricity exceeds 1/3 of the footing width (or length) or 0.59 times the foundation radius.

It is also indicated that numerical methods can be more appropriate than the conventional bearing resistance formulae if the eccentricity is large.

For verification of the limit state of toppling reference is made to Part 1 and EN 1990. The verification includes a comparison of design stabilizing and destabilizing moments.

Finally, Subclause 5.6 provides guidance on ULS verification by prescriptive rules, testing and the observational method.

4.3 Verification of the serviceability limit state

Not many changes have been made to the verification of the serviceability limit state, which is covered in Subclause 5.7. Nevertheless, a clear distinction is now made between settlement and tilting caused by load eccentricity.

For eccentrically loaded foundations it shall also be verified that the load eccentricity remains within certain limits to confine the occurence of a physical gap at the edge of the foundation (see Table 3).

Table 3. Limits of the representative load eccentricity in SLS verification (Table 5.3, prEN 1997-3:2023).

Loading effects	Strip foundation	Circular foundation	Rectangular foundation
Permanent action effects only (No tension gap)	$\frac{e_B}{B} \leq \frac{1}{6}$	$\frac{e}{R} \leq \frac{1}{4}$	$\frac{e_L}{L} + \frac{e_B}{B} \leq \frac{1}{6}$
Permanent and variable action effects	$\frac{e_B}{B} \leq \frac{1}{3}$	$\frac{e}{R} \leq 0{,}59$	$\left[\frac{e_L}{L}\right]^2 + \left[\frac{e_B}{B}\right]^2 \leq \frac{1}{9}$

5 DESIGN EXAMPLE

The application of the design procedure outlined above will be illustrated using the example of a spread foundation under combined loading embedded in sand. For this purpose Example A2 prepared by CEN/TC250/SC7TG B2 in the course of analysing the applicability of the new Eurocode 7 (Bogusz, 2022) was selected and slightly modified. Figure 4 shows the design situation. In the following, only the ULS verification is presented.

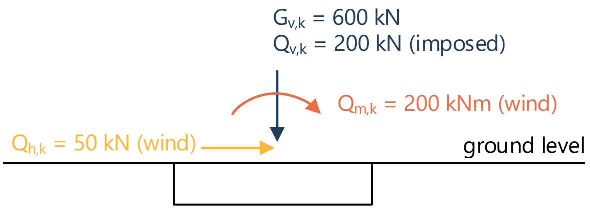

Figure 4. Design situation of a spread foundation on sand according to TG B2 example A2 by Bogusz (2022).

The cast-in-place square footing (weight density 25 kN/m³) has a width of 1.45 m and a thickness of 1.0 m which is equal to the embedment depth. The ground comprises a medium dense silty sand to significant depth and the groundwater level is located at the footing base. The representative weight density of the soil is 19 kN/m³ above and 9 kN/m³, the buoyant weight density, below groundwater level. The peak effective angle of internal friction of the silty sand is 39°. The foundation carries a vertical central permanent load of 600 kN, an imposed central vertical variable load of 200 kN, a horizontal wind load of 50 kN and a moment due to wind of 200 kNm. In the following, the ULS of the foundation is verified for Consequence Class 2 (CC2).

Table 4 summarizes the partial factors adopted in the various MFA and RFA approaches recommended for CC2 (see Section 4.2). In Combination (e) (RFA/VC4) the factor γ_Q results from $\gamma_Q = \gamma_Q/\gamma_E = 1.5/1.35 = 1.11$ (see EN 1990, Table A.1.8).

Table 4. Partial factors for the design example for the different combinations.

	MFA			RFA	
	a	b	c	d	e
	VC1	VC3	VC1	VC1	VC4
γ_G	1.35	1.0	1.35	1.35	1.0
$\gamma_{G,fav}$	1.0	1.0	1.0	1.0	1.0
γ_Q	1.5	1.3	1.5	1.5	1.11
γ_E	1.0	1.0	1.0	1.0	1.35
$\gamma_{\tan\varphi,p}$	1.0	1.25	1.25	1.0	1.0
$\gamma_{\tan\delta}$	1.0	1.25	1.25	1.0	1.0
γ_{RN}	1.0	1.0	1.0	1.4	1.4
γ_{RT}	1.0	1.0	1.0	1.1	1.1

To determine the representative load, combination factors according to Table A.1.7 of EN 1990 need to be considered, which are $\psi_0 = 0.7$ for imposed loads on buildings and $\psi_0 = 0.6$ for wind actions. With that, the following two load combinations were considered here for the bearing resistance verification: LC1 when the imposed load is the leading variable action and LC2 when wind effects are the leading variable actions (horizontal load and moment resulting from the same source). For the sliding resistance, load case LC3 is used with the permanent load assumed to act favourably ($\gamma_{G,fav} = 1.0$ for all combinations). Since only wind effects are considered, the imposed load must be neglected.

Table 5 presents the resultant design loads for bearing and sliding resistance verification. For bearing resistance only the LC2 design loads are provided. The table also indicates which value (representative or design, unfactored or factored) of the soil shear strength (tan φ') and the strength in the footing interface (tan δ) must be considered. Note that the footing is cast-in-place so tan δ = tan φ'.

Table 5. Design loads for bearing resistance (LC2 only) and for sliding resistance (LC3) verification and relevant strength parameters for soil and footing interface (all numbers are rounded).

	MFA			RFA	
	a	b	c	d	e
	VC1	VC3	VC1	VC1	VC4
Design loads for bearing resistance [kN] or [kNm]					
$G_{v,d}$	881	653	881	881	653
$Q_{v,d}$	300	260	300	300	222
$Q_{h,d}$	45	39	45	45	33
$Q_{m,d}$	225	195	225	225	167
Design load for sliding resistance [kN]					
T_d	75	65	75	75	75
Relevant shear strength [-]					
$\tan\varphi'_{rep}$	-	-	-	0.81	0.81
$\tan\varphi_d$	0.81	0.65	0.65	-	-
$\tan\delta_{rep}$	-	-	-	0.81	0.81
$\tan\delta_d$	0.81	0.65	0.65	-	-

Table 6 shows the results of the design verifications for the assumed footing width of 1.45 m. Figure 5 illustrates these results by comparing the utilization achieved by the different combinations (a) to (e). The utilization is defined as the ratio of N_d/R_{Nd} and T_d/R_{Td}.

The results indicate that for this design example the RFA, with combinations (d) and (e), leads to consistent results for both the bearing and sliding resistance verification. For MFA, combination (a), in which the shear strength is not factored, leads to a much lower utilization than combination (b), in which the strength and the variable actions are factored, and so combination (b) controls the design in this case. Combination (c), in which both the strength and all the actions are factored and which can be used alternatively to (a) and (b) (see Table 2), leads to the highest utilization in MFA and hence to more conservative designs.

Table 6. Design values of effects of actions and resistances as well as resultant utilization for bearing resistance and sliding resistance verifications (all numbers are rounded).

	MFA			RFA	
	a	b	c	d	e
	VC1	VC3	VC1	VC1	VC4
Bearing resistance verification					
N_d	1181	913	1181	1181	1181
R_{Nd}	3738	1634	1744	2670	2670
N_d/ R_{Nd}	**0.32**	**0.56**	**0.68**	**0.44**	**0.44**
Sliding resistance verification					
T_d	75	65	75	75	75
R_{Td}	528	423	423	480	480
T_d/ R_{Td}	**0.14**	**0.15**	**0.18**	**0.16**	**0.16**

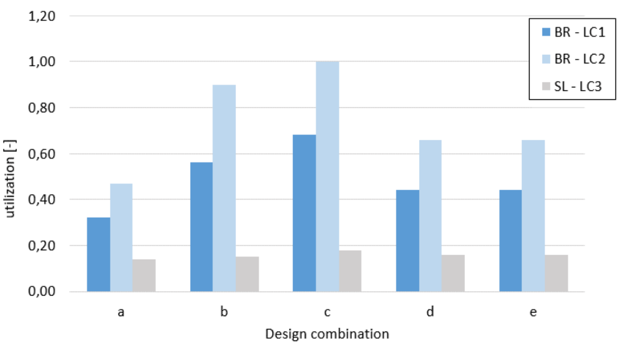

Figure 5. Comparison of the utilization achieved for the different combinations of partial factors for bearing resistance (BR) and sliding resistance (SR).

6 CONCLUSIONS

This paper addresses the design of spread foundations according to the new Eurocode 7. Overall, it can be stated that the design methodology has not changed in comparison to the current version of the code. On the other hand, improvements have been reached e.g. by a clear and unified structure of the code, by an increased harmonization in regard to the calculation of the bearing resistance, by the explicit distinction between soil/fill and rock and by a significantly extended informative Annex B including more calculation models.

Also the new code allows sufficient flexibility to accommodate national design practices and traditions through modification of existing or inclusion of additional tables with NDP values. However, the design example showed that the different alternatives of combining the partial factors lead to significant differences in the design results. So, these factors need to be defined with great care reflecting national design requirements and experiences.

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