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DESIGN OF SHALLOW FOUNDATIONS ACCORDING TO SR EN 1997.

Marius Călin GHERMAN*, Augustin POPA**

* PhD s. eng. , Assistant, Technical University Cluj-Napoca.
**Prof . eng. , Consultant, Technical University Cluj-Napoca.

Corresponding author: Marius Călin GHERMAN, E-mail: marius.gherman@cif.utcluj.ro

Abstract: The paperwork presents the steps required to verify a shallow foundation using European norm SR EN 1997. Some aspects about the verification of the structural elements are mentioned. The objective is to present the main aspects from SR EN 1997 regarding the shallow foundation.

Key words: shallow foundation design, Eurocode 7.

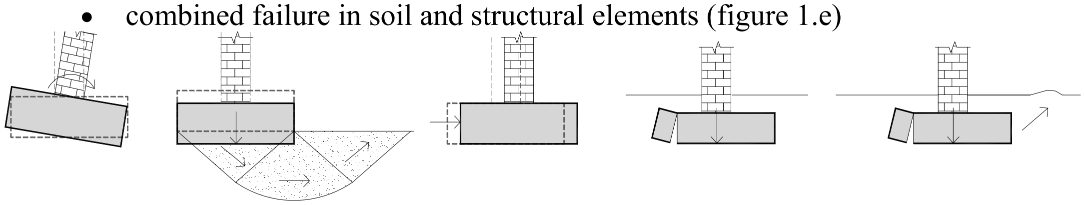
1. INTRODUCTION

Starting with 2010 the codes for geotechnical design and structural concrete design are SR EN 1997 and SR EN 1992. For a better understanding in approaching European design codes the paper will present the general aspects regarding the design of shallow foundation systems. Numerical studies reflect a better view above the European design principles.

2. ULTIMATE LIMIT STATE FOR SHALLOW FOUNDATIONS

When designing shallow foundations the following ultimate limit states should not occur:

- general stability loss (figure 1.a)
- bearing capacity loss (figure 1.b)
- sliding (figure 1.c)
- structural elements failure (figure 1.d)
- combined failure in soil and structural elements (figure 1.e)



a) b) c) d) e)

Fig. 1 a) general stability loss, b) bearing capacity loss, c) sliding, d) structural failure, e) combined failure in soil and structural elements.

3. SAFETY IN DESIGN

The safety factor in design is based on partial safety factor for actions (γ_F), soil parameters (γ_M) and bearing capacity of soil (γ_R) or structural elements.

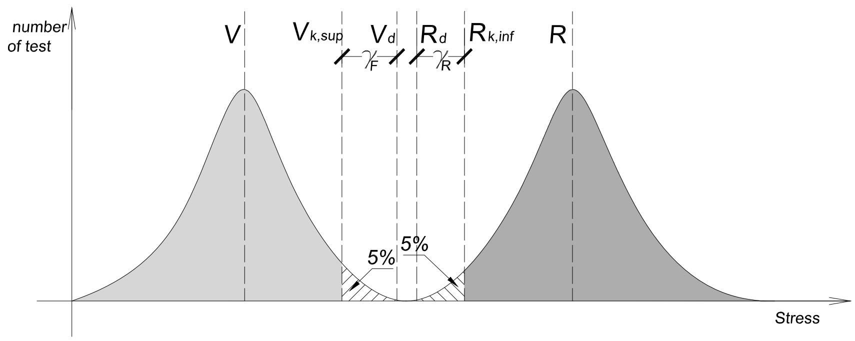


Fig. 2 Design values for actions and bearing capacity from experimental data.

3.1 Grouping the actions

European code SR EN 1990 sets a combination of loadings by multiplying the characteristic loads with a partial safety factor for common actions and for accidental actions:

Case of common actions:

$$\gamma_{G,i} \cdot \sum_{j=1}^{n} G_{k,j} + \gamma_{Q,1} \cdot Q_{k,l} + \sum_{i=2}^{m} \gamma_{Q,i} \cdot \psi_{0,1} \cdot Q_k \tag{1}$$

Case of accidental actions:

$$\sum_{j=1}^{n} G_{k,j} + \gamma_1 \cdot A_{EK} + \sum_{i=1}^{n} \psi_{2,i} \cdot Q_{k,i} \tag{2}$$

Where:

γ_G, γ_Q partial safety factors for common actions,

G_k, Q_k characteristic value for common action (permanent and variable),

A_{Ek} characteristic value for accidental action,

Partial factors $\psi_{0,1}$ and $\psi_{2,i}$ are discussed in SR EN 1990.

4. BEARING CAPACITY VERIFICATION

4.1 Generalities

Bearing capacity of soil in case of shallow foundation is verified by using ultimate limit state GEO. In this ULS excessive deformation or strain in soil is verified and soil bearing capacity is significant for general strength of the system.(according to SR EN 1997-1 chapter. 2.4.7).

ULS GEO is verified with following relation:

$$E_d \leq R_d \tag{3}$$

Where: E_d design action on footing

R_d design bearing capacity of soil.

4.2 Design approaches

According to SR EN 1997-1 it must be verified if GEO ultimate limit state can occur using partial safety factor according table 1 and 2.

Table 1. Partial safety factors for shallow foundations. Common actions.

DESIGN APPROACH	ACTIONS (γ_F)				SOIL PARAMETERS (γ_M)			BEARING CAPACITY (γ_R)
	Permanent, γ_G		Variable, γ_Q					
	Unfav.	Fav.	Unfav.	Fav.	$\tan\varphi'(\gamma_{\varphi'})$	$c'(\gamma_{c'})$	$c_u(\gamma_{cu})$	γ_R
DA1.Combination 1 -A_1+M_1+R_1	1.35	1.00	1.50	0	1.00	1.00	1.00	1.00
DA1.Combination 2 -A_2+M_2+R_1	1.00	1.00	1.30	0	1.25	1.25	1.40	1.00
DA3 -A_1 or A_2+M_2+R_3	1.35	1.00	1.50	0	1.25	1.25	1.40	1.00

Table 2. Partial safety factors for shallow foundations. Accidental actions

DESIGN APPROACH	ACTIONS(γ_F)						SOIL PARAMETERS (γ_M)				BEARING CAPACITY (γ_R)
	Permanent, γ_G		Variable, γ_Q		Accident	Seismic					
	unfav.	Fav.	unfav.	Fav.			$\tan\varphi'$	c'	c_u	q_u	γ_R
ACCIDENTAL	1.00	1.00	1.00	0	A_d	-	1.25	1.25	1.4	1.4	1
SEISMIC	1.00	1.00	1.00	0	-	γ A_{Ek}/A_{Ed}	1.25	1.25	1.4	1.4	1

For every design approach, actions with characteristic values are multiplied by partial safety factor for actions (ex. $G_d = \gamma_G \cdot G_k$), geotechnical parameters are divided by partial safety factor γ_M (ex. $\tan\varphi_d' = \dfrac{\tan\varphi_k'}{\gamma_{\varphi'}}$) and the soil bearing capacity is divided by partial safety factor γ_R (ex.: $R_d = \dfrac{R_k}{\gamma_{Rv}}$).

4.3 Bearing capacity of soil

According to appendix A from SR EN 1997 the soil pressure is established for:
undrained conditions:

$$R_d / A' = (\pi + 2) \cdot c_u \cdot b_c \cdot s_c \cdot i_c + q \tag{4}$$

Where:

- b footing inclination factor
- s footing shape factor
- i factor for vertical load inclination given by horizontal load

drained conditions:

$$R_d / A' = c' \cdot N_c \cdot b_c \cdot s_c \cdot i_c + q' \cdot N_q \cdot b_q \cdot s_q \cdot i_q + 0.5 \cdot \gamma' \cdot N_\gamma \cdot b_\gamma \cdot s_\gamma \cdot i_\gamma \tag{5}$$

Where:

- b footing inclination factor
- s footing shape factor

i factor for vertical load inclination given by horizontal load

N bearing capacity factor depending on internal friction angle.

Table 3. Nondimensional factor for soil bearing capacity.

Undrained conditions:			
Nondimensional factor	Notation	Relation	
		Rectangular shape	Circular shape
Footing inclination	b_c	$1-2\alpha/(\pi+2)$	
Footing shape	s_c	$1+0{,}2(B'/L')$	1,2
vertical load inclination given by horizontal load	i_c	$\frac{1}{2}\cdot\left[1+\sqrt{1-H/(A'\cdot c_u)}\right]$	
Drained conditions:			
Bearing capacity	N_q	$e^{\pi\cdot\tan\varphi'}\cdot\tan^2(45°+\varphi'/2)$	
	N_c	$(N_q-1)\cdot\frac{1}{\tan\varphi'}$	
	N_γ	$2\cdot(N_q-1)\cdot\tan\varphi'$ si $\delta\geq\varphi'/2$	
Footing inclination	$b_q=b_\gamma$	$(1-\alpha\cdot\tan\varphi')^2$	
	b_c	$b_q-(1-b_q)/(N_c\cdot\tan\varphi')$	
Footing shape	s_q	$1+(B'/L')\cdot\sin\varphi'$	$1+\sin\varphi'$
	s_γ	$1-0{,}3\cdot(B'/L')$	0,7
	s_c	$(s_q\cdot N_q-1)/(N_q-1)$	
vertical load inclination given by horizontal load	i_q	$[1-H/(V+A'\cdot c'\cdot\cot\varphi')]^m$	
	i_γ	$[1-H/(V+A'\cdot c'\cdot\cot\varphi')]^{m+1}$	
	i_c	$i_q-(1-i_q)/(N_c\cdot\tan\varphi')$	
$m=m_B=[2+(B'/L')]/[1+(B'/L')]$			if *H* acting on *B'* direction
$m=m_L=[2+(L'/B')]/[1+(L'/B')]$			if *H* acting on *L'* direction
$m=m_\theta=m_L\cdot\cos^2\theta+m_B\cdot\sin^2\theta$			*H* acting with an angle θ on *L'* direction

Notes:

1. Both situations, undrained and drained conditions, must be verified for GEO ultimate limit state to establish which situation is most unfavourable.
2. Eccentricity should not exceed the central pit (ellipse shape) which limits the maximum pressure to a value that is not exceeding the soil bearing capacity.

The eccentricities are verified using following relations:

- for rectangular shapes:

$$\left(\frac{e_L}{L}\right)^2+\left(\frac{e_B}{B}\right)^2\leq\frac{1}{9} \tag{6}$$

- for circular shapes:

$$\frac{e}{R}\leq 0{,}59 \tag{7}$$

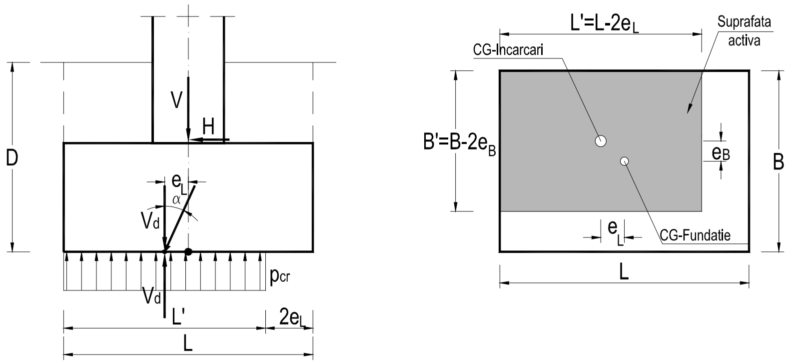


Fig. 3 Shallow foundation with oblique load due to horizontal load.

4.4 Overall factor of safety

In order to have a general perspective of the safety in the design method applied the overall factor of safety can be evaluated as:

$$OFS = \frac{R_k}{V_k} \tag{8}$$

Where:

R_k characteristic value for soil bearing capacity using $\gamma_M = 1$ and $\gamma_R = 1$

V_k characteristic value of vertical loads using $\gamma_F = 1$.

Note: In practical design OFS is usually greater than 1,4.

5. SERVICEABILITY LIMIT STATE

Serviceability limit state usually refers to settlements. The settlements given by design actions must be lower or equal to allowed settlements

$$s_{Ed} \le s_{Cd} \tag{9}$$

The settlement given by design action has following main evaluations:

- s_0 instantaneum settlement due to shearing at constant volume in saturated cohsive soil or partially saturated soil with volume changes
- s_1 settlement due to soil hardening
- s_2 settlement due to soil flow

$$s_{Ed} = s_0 + s_1 + s_2 \tag{10}$$

Usually for the evaluation of settlements at serviceability limit state the partial safety factors are taken equal to 1.

The settlement evaluation must be made for the entire structure and differential settlements should also be evaluated for short term and for long term due to hardening and flowing of soil.

The settlement evaluation can be made using elasticity methods: finite layer method and elementary layer method or by using methods based on field testing.

6. STRUCTURAL DESIGN. CONCRETE ELEMENTS

Structural elements must be verified using ultimate limit state STR. In this ultimate limit state, internal failure and excessive deflections in structure or structural materials are verified, where strength of materials is significant for general strength (according to SR EN 1997 chapter. 2.4.7.)

The partial safety factors for actions (γ_F) are identical for ultimate limit state STR and GEO. This two ULS, GEO and STR are evaluated at one time for each design approach according to chapter 4.2.

7. NUMERICAL EXAMPLE

An isolated foundation was designed for both situations, undrained and drained conditions, according to SR EN 1997. The structural loads are grouped for design of shallow foundation at ultimate limit state GEO and STR according to table 1.

7.1 Data

The shallow foundation design is made using general relation (1) and partial safety factors from table 1. Footing dimensions are established for two design approaches used for common shallow foundations.

The geotechnical parameters used for design foundation must take into account the undrained and drained conditions. As a general rule, on short term evaluation, undrained shear strength (total stress) can be considered for clays with degree of permeability lower than 10^{-8} cm/s, otherwise shear strength and internal friction angle in drained conditions (effective stress) can be considered.

Further actions should be taken into account like a sand layer which can drain the area on a long term, future excavations, new buildings in the area etc. The long term conditions for soil are drained conditions if the water table is not rising.

7.2 Footing with centric loads(P_k and Q_k)

Shallow foundation with vertical loads:

$$P_k = 400kN;$$
$$Q_k = 100kN.$$

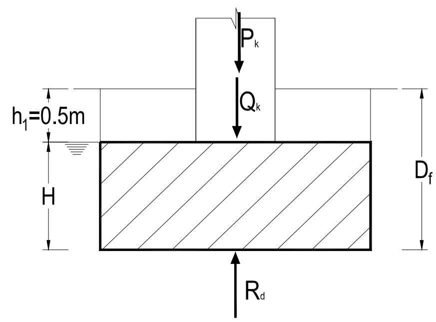


Fig. 4 Footing with centric loads.

Soil characteristics: $\gamma_k = 18kN/m^2$; $\varphi_k' = 15°$; $c_k' = 10kPa$; $c_{uk} = 25kPa$; $\gamma_k' = 10kN/m^3$

Concrete characteristics $\gamma_k = 25kPa$; $\gamma_k' = 15kN/m^3$.

Self weight of footing:

$$G_{p,k} = \left(\gamma_{G,net} \cdot H_2 \cdot \gamma_k + \gamma_{G,net} \cdot \gamma_{G,net} \cdot \gamma_b \cdot h_1\right) \cdot A \tag{11}$$

If the footing is under the water table, for undrained conditions self weight is:

$$G_{p,k}' = \left(\gamma_{G,net} \cdot H_2 \cdot \gamma_k' + \gamma_{G,net} \cdot \gamma_{G,net} \cdot \gamma_b' \cdot h_1\right) \cdot A \tag{12}$$

The evaluation was made according to chapter 4.2 for undrained and drained conditions. The results in undrained conditions are presented in table 4.

Table 4. Results for footing in undrained conditions.

Value	Design approaches					
	DA1.1		DA1.2		DA3	
	V [kN]	**R** [kN]	**V** [kN]	**R** [kN]	**V** [kN]	**R** [kN]
Footing dimensions LxB [m*m]	2,30x2,30		2,30x2,30		2,80x2,80	
Load						
Characteristic (Vk, Rk)	636,48	915,42	636,48	915,42	731,67	1372,37
Design (Vd, Rd)	874,25	915,42	666,48	682,28	1002,75	1026,86
OFS	1,438		1,438		1,876	

In drained conditions the results are presented in table 5.

Table 4. Results for footing in drained conditions.

Value	Design approaches					
	DA1.1		DA1.2		DA3	
	V [kN]	**R** [kN]	**V** [kN]	**R** [kN]	**V** [kN]	**R** [kN]
Footing dimensions LxB [m*m]	2,30x2,30		2,35x2,35		2,90x2,90	
Load						
Characteristic (Vk, Rk)	689,60	988,04	701,10	1041,20	829,67	1603,32
Design (Vd, Rd)	945,60	988,04	731,10	758,80	1135,06	1170,26
OFS	1,433		1,485		1,932	

7.3 Footing with eccentric loads (P_k and Q_k)

A footing with vertical loads and bending moments:

$P_k = 600kN$; $Q_k = 300kN$;

$M_{xxp} = 18kNm$; $M_{xxq} = 9kNm$;

$M_{yyp} = 18kNm$; $M_{yyq} = 9kNm$;

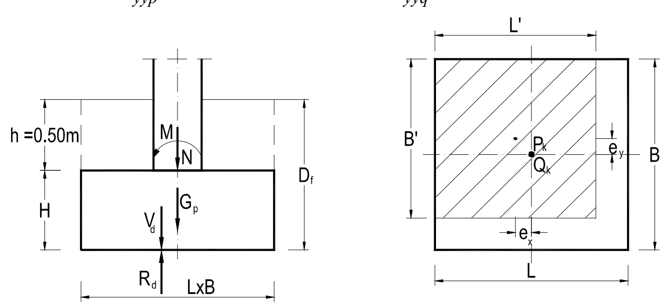


Fig. 5 Footing with eccentric loads.

The results for undrained conditions are presented in table 6.

Table 6. Results for footing in undrained conditions.

Value	**Cazuri de proiectare**					
	DA1.1		**DA1.2**		**DA3**	
	V [kN]	**R** [kN]	**V** [kN]	**R** [kN]	**V** [kN]	**R** [kN]
Footing dimensions LxB [m*m]	3,20x3,20		3,25x3,25		4,00x4,00	
Load						
Characteristic (Vk, Rk)	1233,30	1759,71	1247,70	1818,54	1516,80	2826,60
Design (Vd, Rd)	1709,90	1759,24	1337,70	1364,40	2092,68	2133,40
OFS	1,427		1,458		1,864	

In drained conditions the results are presented in table 7.

Table 7. Results for footing in drained conditions.

Value	**Cazuri de proiectare**					
	DA1.1		**DA1.2**		**DA3**	
	V [kN]	**R** [kN]	**V** [kN]	**R** [kN]	**V** [kN]	**R** [kN]
Footing dimensions LxB [m*m]	3,00x3,00		3,05x3,05		3,70x3,70	
Load						
Characteristic (Vk, Rk)	1320,24	1934,74	1320,24	1934,74	1574,56	2962,72
Design (Vd, Rd)	1410,24	1428,50	1410,24	1428,50	2170,67	2194,32
OFS	1,465		1,465		1,882	

8. CONCLUSIONS

As presented in tables 4-7 the footing dimensions varies for undrained/drained conditions and for design approaches from SR EN 1997.

For drained and undrained conditions the bigger values are obtained from DA3. These footing dimensions are different for drained and undrained conditions.

The OFS from SR EN 1997 offers a good perspective over the safety in design of foundations.

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