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FOUNDATIONS

- CURS 4 -

Foundation movements

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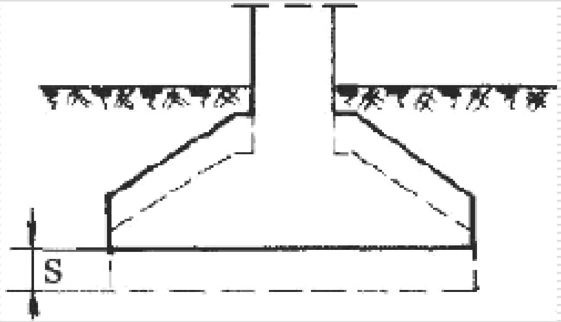
CHAPTER IV – FOUNDATION MOVEMENTS

§ 4.1 Introduction

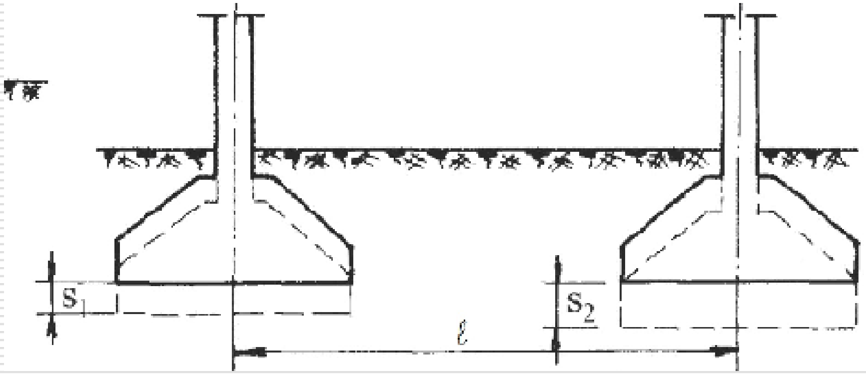
- The structural loads induced in the foundations lead to movements of the footing of the foundation in regard to the initial position (prior loading or prior execution).
- The components of foundation movement, which should be considered include settlement, relative (or differential) settlement, rotation, tilt, relative deflection, relative rotation, horizontal displacement and vibration amplitude (EN 1997-1).
- The vertical displacements of the foundations (and implicitly of the building) is named **settlement**.
- In usual manner, the foundation settlement is denoted by s (NP112-2014 and EN 1997-1).
- Usually the **design settlement** represents the calculated settlement on the basis of soil mechanics rules. This could be different from the **real settlement**, measured on site.

§ 4.2 Types of settlements

- The following types of settlement could be distinguished:
  - **Absolute settlement** *s* – represents the vertical settlement of a point of a foundation or an entire single or continuous foundation.
  - **Average settlement** s_m – computed as the mean of the absolute settlements for at least three individual foundations. Condition for individual settlement: $|s-s_m|<0.5s_m$
  - **Relative settlement** s_{rel} – representing the difference between two adjacent foundations in regard to the distance between them, considering the ULS combination of actions: $s_{rel}=(s_1-s_2)/l$



Absolute settlement

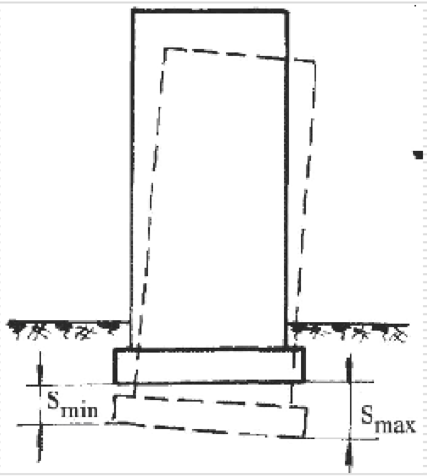


Relative settlement

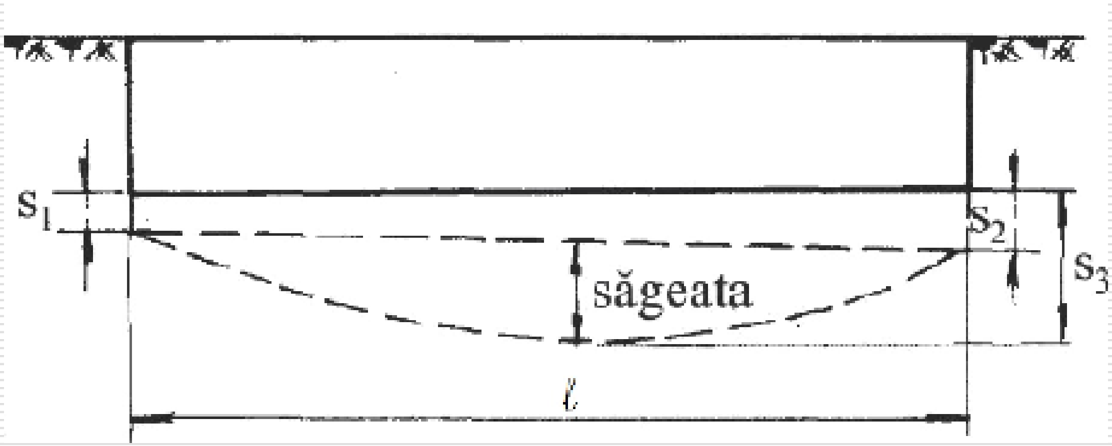
§ 4.2 Types of settlements

- **Foundation inclination** *(tanθ)* – measures the angle of possible differential settlement between the edges of the foundation. This is due to eccentric loading or differences in soil characteristics at foundations edges: $\tan\theta=(s_{max}-s_{min})/l$.
- **Relative bending of the foundations** *f* – represents the ratio between the absolute deflection of long foundations and its length:

$$f = \frac{s_3 - \frac{s_1 + s_2}{2}}{\ell} = \frac{2s_3 - s_1 - s_2}{2\ell}$$



Foundation inclination



Relative bending of the foundations

§ 4.3 Design principles of foundations to settlements

□ In the design of foundations to settlements, the soil is assumed to behave as a linear deformable medium. In consequence, for design the following conditions should be fulfilled:

- For centrically loaded foundations: $p_{ef} \leq p_{pl}$
- For uni-axial eccentrically loaded foundations:

$$p_{ef} \leq p_{pl} \quad \text{and} \quad p_{ef,max} \leq 1.2p_{pl}$$

- For bi-axial eccentrically loaded foundations:

$$p_{ef} \leq p_{pl} \quad \text{and} \quad p_{ef,max} \leq 1.4p_{pl}$$

where:

p_{ef} is the average effective pressure under foundation footing

$p_{ef\,,max}$ is the maximum effective pressure under foundation footing derived from eccentrically applied loads.

§ 4.3 Design principles of foundations to settlements

- The following condition should be fulfilled when checking the foundation deformations:

$$\Delta s \leq \overline{\Delta s}$$

where:

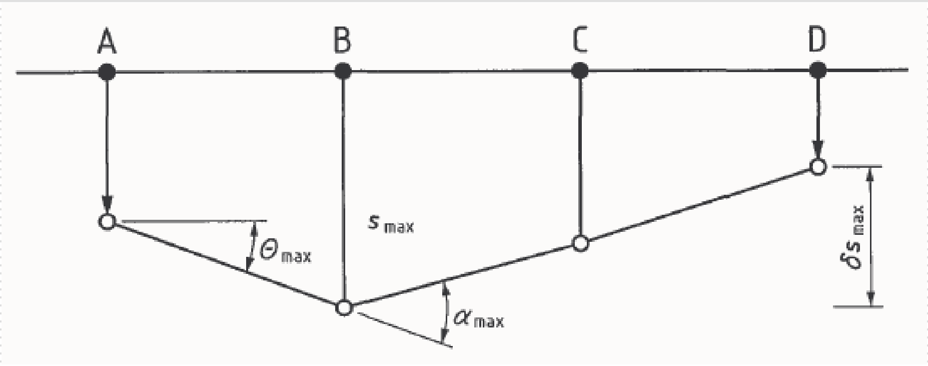
Δs is the design movement, displacement or rotation of the foundation due to foundation settlement

$\overline{\Delta s}$ is the maximum effective pressure under foundation footing derived from eccentrically applied loads.

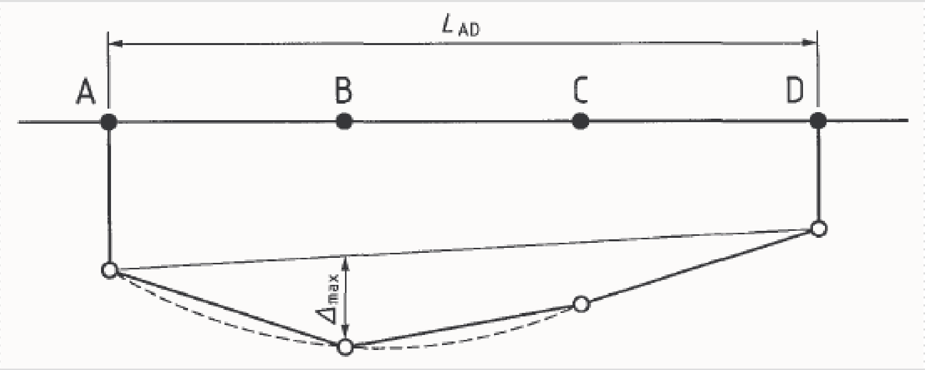
§ 4.3 Design principles of foundations to settlements

EN 1997 limiting values of structural deformations and foundation movement:

- For normal structures with isolated foundations, total settlements up to 50 mm are often acceptable.
- Larger settlements may be acceptable provided the relative rotations remain within acceptable limits and provided the total settlements do not cause problems with the services entering the structure, or cause tilting etc.



definitions of settlement *s*, differential settlement δ_s, rotation θ and angular strain α according to EN 1997-1

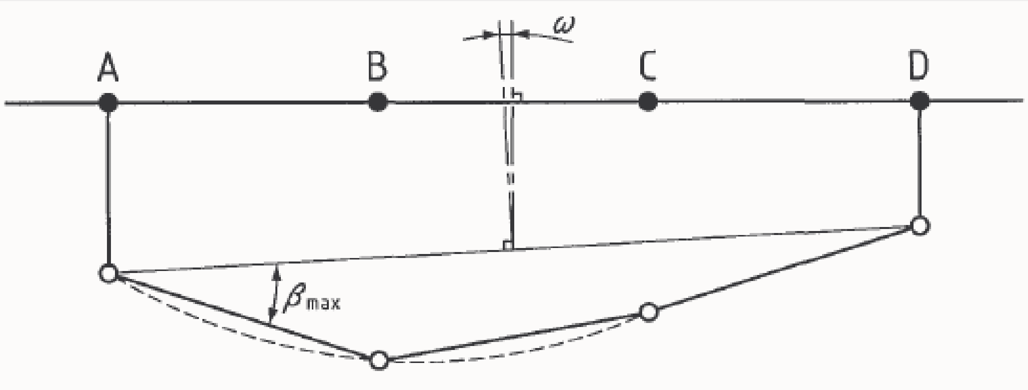


definitions of relative deflection Δ and deflection ratio Δ/L according to EN 1997-1

§ 4.3 Design principles of foundations to settlements

EN 1997 limiting values of structural deformations and foundation movement:

- The maximum acceptable relative rotations for open framed structures, infilled frames and load bearing or continuous brick walls ranging from 1/2000 to 1/300, to prevent the occurrence of a serviceability limit state in the structure.
- A maximum relative rotation of 1/500 is acceptable for many structures. The relative rotation likely to cause an ultimate limit state is about 1/150.



definitions of tilt ω and relative rotation (angular distortion) β according to EN 1997-1

§ 4.3 Design principles of foundations to settlements

NP 112/2014 limiting values of structural deformations and foundation movement:

- The maximum rough values of deformations and displacements of foundations for buildings are given in table below:

Tipul construcției		Deformații		Deplasări (tasări)	
		Tipul deformației	Valoare limită [-]	Tipul deplasării	Valoare limită [mm]
1	Construcții civile și industriale cu structura de rezistență în cadre: a) Cadre din beton armat fără umplutură de zidărie sau panouri	tasare relativă	0,002	tasare absolută maximă, s_{max}	80
	b) Cadre metalice fără umplutură de zidărie sau panouri	tasare relativă	0,004	tasare absolută maximă, s_{max}	120
	c) Cadre din beton armat cu umplutură de zidărie	tasare relativă	0,001	tasare absolută maximă, s_{max}	80
	d) Cadre metalice cu umplutură de zidărie sau panouri	tasare relativă	0,002	tasare absolută maximă, s_{max}	120
2	Construcții în structura cărora nu apar eforturi suplimentare datorită tasărilor neuniforme	tasare relativă	0,006	tasare absolută maximă, s_{max}	150

§ 4.3 Design principles of foundations to settlements

NP 112/2014 limiting values of structural deformations and foundation movement:

3	Construcții multietajate cu ziduri portante din: a) panouri mari	încovoiere relativă, f	0,0007	tasare medie, s_m	100
	b) zidărie din blocuri sau cărămidă, fără armare	încovoiere relativă, f	0,001	tasare medie, s_m	100
	c) zidărie din blocuri sau cărămidă armată	încovoiere relativă, f	0,0012	tasare medie, s_m	150
	d) independent de materialul zidurilor	înclinare transversală $tg\theta_{tr}$	0,005	-	-
4	Construcții înalte, rigide a) Silozuri din beton armat: - turnul elevatoarelor şi grupurile de celule sunt de beton monolit şi reazemă pe acelaşi radier continuu	înclinare longitudinală sau transversală $tg\theta$	0,003	tasare medie, s_m	400
	- turnul elevatoarelor şi grupurile de celule sunt de b.a.p. şi reazemă pe acelaşi radier	înclinare longitudinală sau transversală $tg\theta$	0,003	tasare medie, s_m	300
	-turnul elevatoarelor rezemat pe un radier independent	înclinare transversală $tg\theta_{tr}$	0,003	tasare medie, s_m	250
		înclinare longitudinală $tg\theta_l$	0,004	tasare medie, s_m	250
	- grupuri de celule de beton monolit rezemate pe un radier independent	înclinare longitudinală sau transversală $tg\theta$	0,004	tasare medie, s_m	400
	- grupuri de celule de b.a.p. rezemate pe un radier independent	înclinare longitudinală sau transversală $tg\theta$	0,004	tasare medie, s_m	300
	b) Coşuri de fum cu înălțimea H[m]: H < 100 m	înclinare, $tg\theta$	0,005	tasare medie, s_m	400
	100≤H≤200m	înclinare, $tg\theta$	1 / 2H	tasare medie, s_m	300
	200<H≤300m	înclinare, $tg\theta$		tasare medie, s_m	200
	H > 300 m	înclinare, $tg\theta$		tasare medie, s_m	100
	c) Construcții înalte, rigide, H < 100 m	înclinare, $tg\theta$	0,004	tasare medie, s_m	200

§ 4.4 Evaluation of foundation settlement by summing the sub-soil layer settlements

- Frequently the foundation soil profile is formed from several different sub-soil layers with finite thicknesses and different physic-mechanical characteristics.
- In such cases, starting from the known vertical variation of the vertical stress, the foundation settlement can be estimated as a sum of settlements on sub-layers.
- Considering a foundation of width B, having the footing at the level D_f below the natural ground level.
- The contact pressure transmitted by the foundation p_{ef} is:

$$p_{ef} = \frac{N + G_{f+p}}{A} \text{ [kPa]}$$

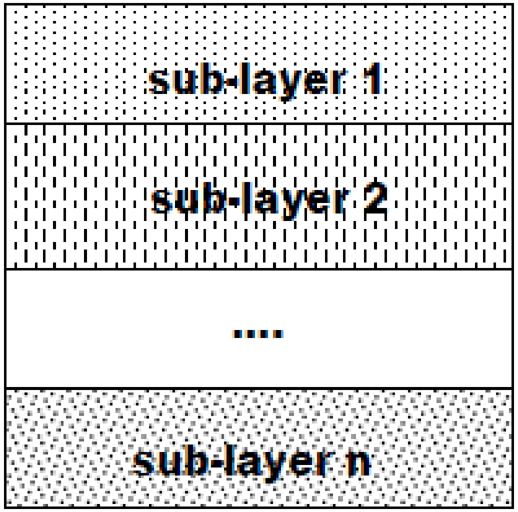
where:

N - the axial load induced by the structure

A – footing area

G_{f+p} – design load of the foundation and soil over the foundation.

Soil profile sub-divided in sub-layers



§ 4.4 Evaluation of foundation settlement by summing the sub-soil layer settlements

- Net pressure is used for the evaluation of the settlement:

$$p_{net} = p_{ef} - \gamma \cdot D_f$$

where:

γ represents the average volume weight of the soil layers above foundation

- The compressible layers within active zone are divided in elementary layers (sub-layers) **considering the lithologic limits soils and a maximum depth of a sub-layer of $h_i \leq 0.4B$** (B-width of the foundation).

- The principal vertical stresses due to net pressure at the separation limits of the sub-layers are found by:

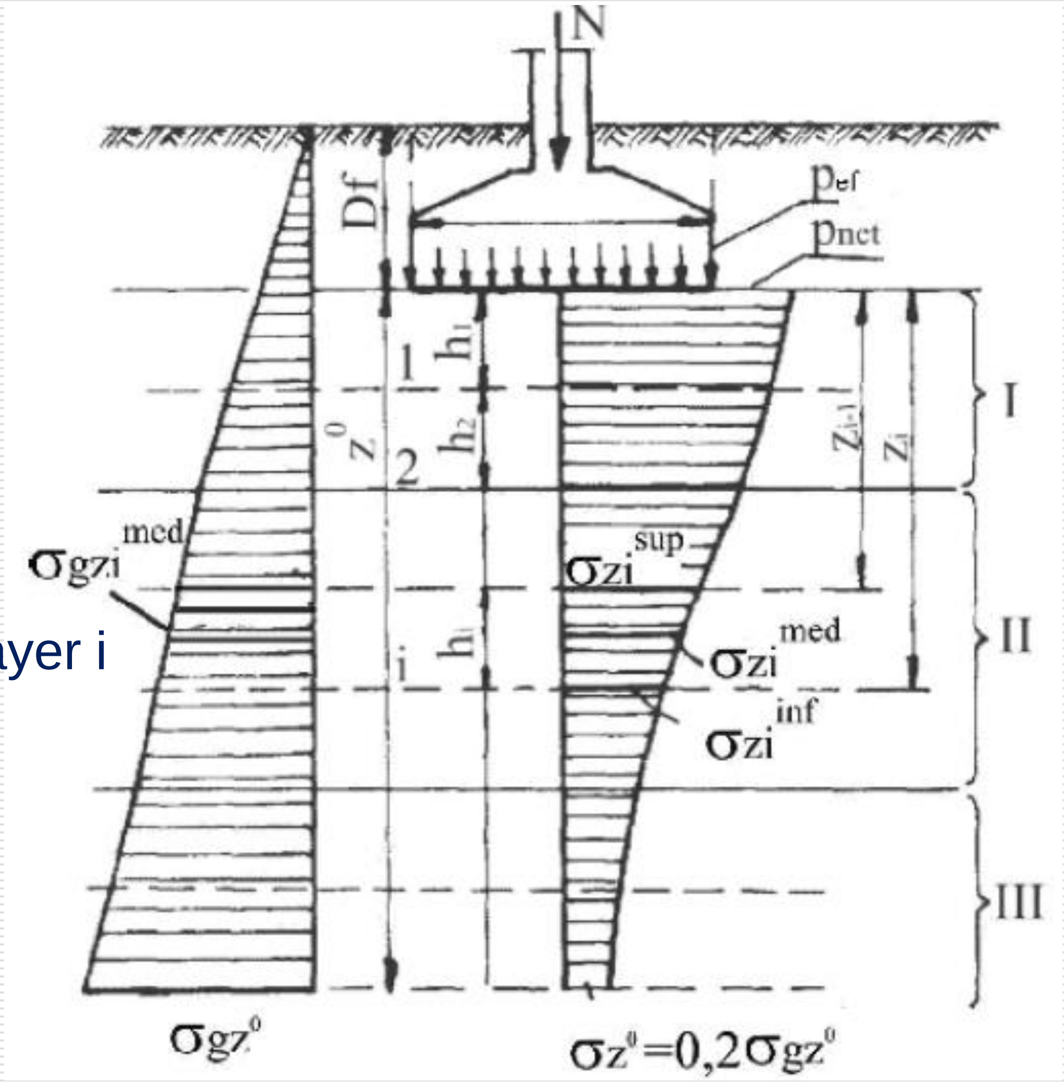
$$\sigma_z = \alpha_0 \, p_{net}$$

where:

σ_z - is the vertical stress at depth z below the footing level structure

α_0 – distribution coefficient of vertical stresses in foundation centre for uniform pressures under foundation.

§ 4.4 Evaluation of foundation settlement by summing the sub-soil layer settlements



Soil
Layer 1

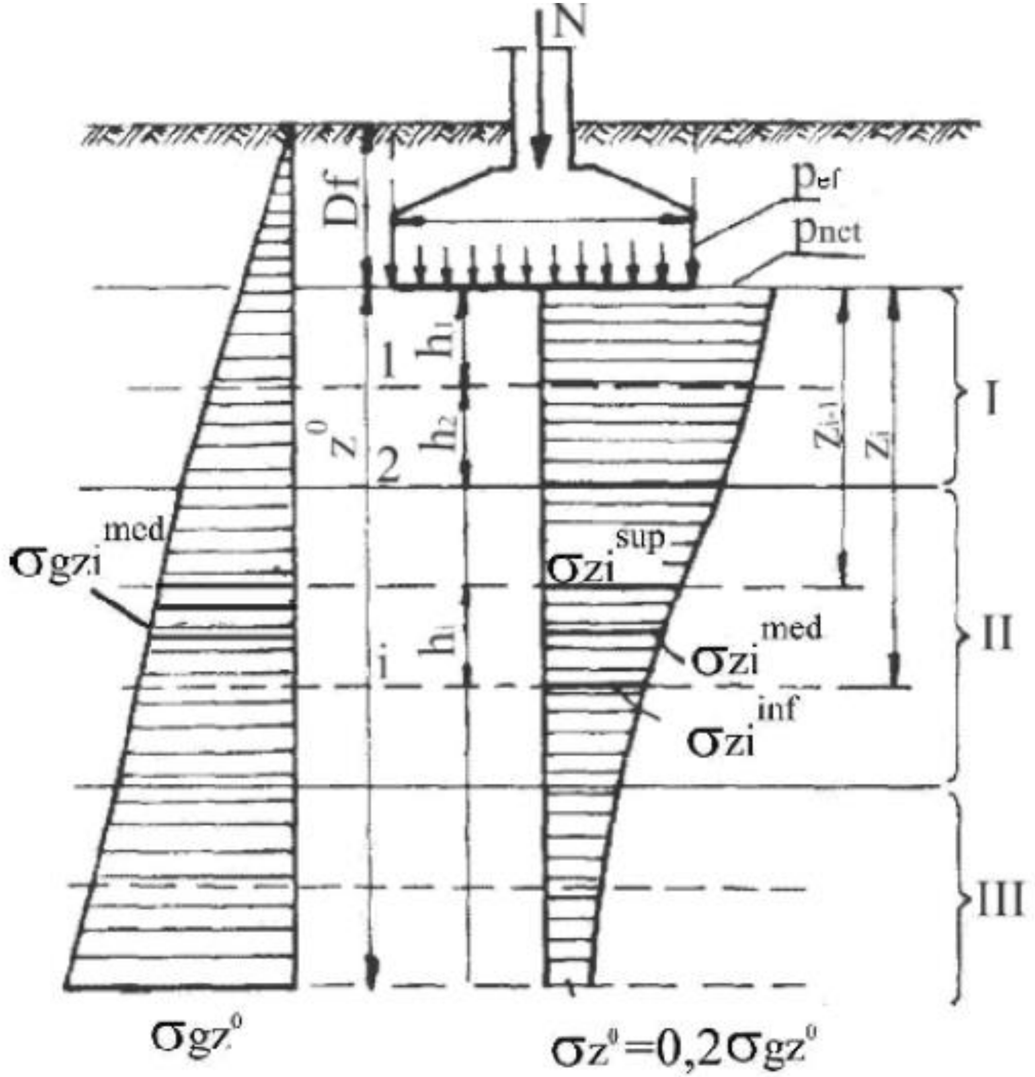
Sub-layer i

Soil
Layer k

Soil
Layer n

§ 4.4 Evaluation of foundation settlement by summing the sub-soil layer settlements

- α_0 is a coefficient, given in tables in function of:
  - The ratio *L/B* between the length (*L*) and the width (*B*) of a rectangular foundation;
  - The ratio *z/B* between the depth of the sub-soil in regard to the footing level and the width (*B*) of a rectangular foundation;



§ 4.4 Evaluation of foundation settlement by summing the sub-soil layer settlements

Values of α_0 coefficient:

z/B	Fundații în formă de:				
	cerc	dreptunghi, cu raportul laturilor L/B			
		1	2	3	≥10
	α_0				
0,0	1,00	1,00	1,00	1,00	1,00
0,2	0,95	0,96	0,96	0,98	0,98
0,4	0,76	0,80	0,87	0,88	0,88
0,6	0,55	0,61	0,73	0,75	0,75
0,8	0,39	0,45	0,53	0,63	0,64
1,0	0,29	0,34	0,48	0,53	0,55
1,2	0,22	0,26	0,39	0,44	0,48
1,4	0,17	0,20	0,32	0,38	0,42
1,6	0,13	0,16	0,27	0,32	0,37
2,0	0,09	0,11	0,19	0,24	0,31
3,0	0,04	0,05	0,10	0,13	0,21
4,0	0,02	0,03	0,06	0,08	0,16
5,0	0,02	0,02	0,04	0,05	0,13
6,0	0,01	0,02	0,03	0,04	0,10

§ 4.4 Evaluation of foundation settlement by summing the sub-soil layer settlements

- The depth of the active zone z^0 (depth used in the evaluation of settlements) is determined by consecutive checks of the vertical stresses due to net pressure σ_{zi} and comparison with the vertical stresses generated by the geological pressure - σ_{gzi}.
- The inferior limit of the active zone is considered the level at which the following condition is achieved: $\sigma_z^0 < 0{,}2 \cdot \sigma_{gz}^0$

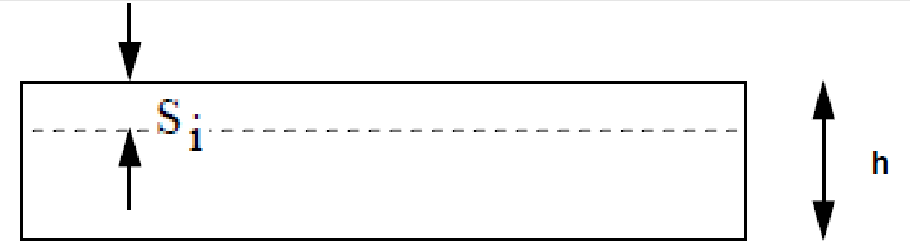
Obs: If at bottom of the active zone there is a soil layer having a deformation modulus $E \leq 5000\ kPa$, the depth z^0 is extended up to a sub-layer satisfying: $\sigma_z^0 < 0{,}1 \cdot \sigma_{gz}^0$

Obs: If on the active zone there is an incompressible soil layer having a deformation modulus E >100 000 kPa, then the depth z^0 is limited to the upper surface of the incompressible layer.

§ 4.4 Evaluation of foundation settlement by summing the sub-soil layer settlements

- The settlement of an sub-layer considered linear deformable environment is computed on the Hooke's law basis:

$$\frac{\sigma_{zi}^{med} \cdot h_i}{E_{si}}$$



where:

σ^{med}_{zi} - vertical average stress:

$$\sigma_{zi}^{med} = \frac{\sigma_{zi}^{sup} + \sigma_{zi}^{inf}}{2}$$

E_{si} is the modulus of linear deformation of the soil layer *i*

σ^{sup}_{zi} , σ^{inf}_{zi} vertical stress at superior and respectively inferior borders of sub-layer *i*

- The absolute settlement of the foundation is computed by:

$$s = 10^3 \cdot \beta \cdot \sum_{1}^{n} \frac{\sigma_{zi}^{med} \cdot h_i}{E_{si}} \ [mm]$$

with: *n* - the number of sub-layers within the active zone

β – correction coefficient: *β=0.8*

§ 4.4 Evaluation of foundation settlement by summing the sub-soil layer settlements

Usual values of the linear deformation modulus of soils (*E*):

Caracterizarea pământurilor			Indicele porilor e						
Origi-nea	Compoziție granulometrică	I_c	0,45	0,55	0,65	0,75	0,85	0,95	1,05
			Valori de calcul ale modulului E, kPa						
Nisipuri cu pietriș			50000	40000	30000				
Nisipuri fine			48000	38000	28000	18000			
Nisipuri prăfoase			39000	28000	18000	11000			
Aluviale, deluviale, lacustre	Praf nisipos	0,25…1	32000	24000	16000	10000	7000		
	Praf, praf argilos, argilă prăfoasă, argilă nisipoasă	0,75…1	34000	27000	22000	17000	14000	11000	
		0,5..0,75	32000	25000	19000	14000	11000	8000	
	Argilă, argilă grasă	0,75…1	-	28000	24000	21000	18000	15000	12000
		0,5..0,75	-	-	21000	18000	15000	12000	9000
Fluvio - glaciare	Praf nisipos	0,25…1	33000	24000	17000	11000	7000		
	Praf, praf argilos, argilă prăfoasă, argilă nisipoasă	0,75…1	40000	33000	27000	21000			
		0,5..0,75	35000	28000	22000	17000	14000		

§ 4.4 Evaluation of foundation settlement by summing the sub-soil layer settlements

- **The supplementary settlement** due to the influence of adjacent foundations or due to the soil overloading in the proximity of the foundation could be found by using the *corner points* method.

- According to this method, the total vertical stress σ_z located on the vertical axis of a corner point of a foundation is computed by: $\sigma_z = \alpha_C \, p_{net}$

With α_C – coefficient of distribution of vertical stresses at the foundation corner, given in tables in function of ratios *L/B* and *z/B*.

Interpolation is possible for other values.

z/B	Fundații în formă de dreptunghi cu raportul laturilor L/B			
	1	2	3	≥10
	α_C			
0,0	0,2500	0,2500	0,2500	0,2500
0,2	0,2486	0,2491	0,2492	0,2492
0,4	0,2401	0,2439	0,2442	0,2443
0,6	0,2229	0,2329	0,2339	0,2342
0,8	0,1999	0,2176	0,2196	0,2202
1,0	0,1752	0,1999	0,2034	0,2046
1,2	0,1516	0,1818	0,1870	0,1888
1,4	0,1308	0,1644	0,1712	0,1740
1,6	0,1123	0,1482	0,1567	0,1604
2,0	0,0840	0,1202	0,1314	0,1374
3,0	0,0447	0,0732	0,0870	0,0987
4,0	0,0270	0,0474	0,0603	0,0758
5,0	0,0179	0,0328	0,0435	0,0610
6,0	0,0127	0,0238	0,0325	0,0506

§ 4.4 Evaluation of foundation settlement by summing the sub-soil layer settlements

- By superposing the effects, the total vertical stress σ_z on the vertical axis of a point *P* under a foundation located at a certain distance from another rectangular foundation *ABCD*, loaded by an uniform net pressure p_{net}, could be determined as follows:

$$\sigma_z = p_{net}(\alpha_{C1} + \alpha_{C2} - \alpha_{C3} - \alpha_{C4})$$

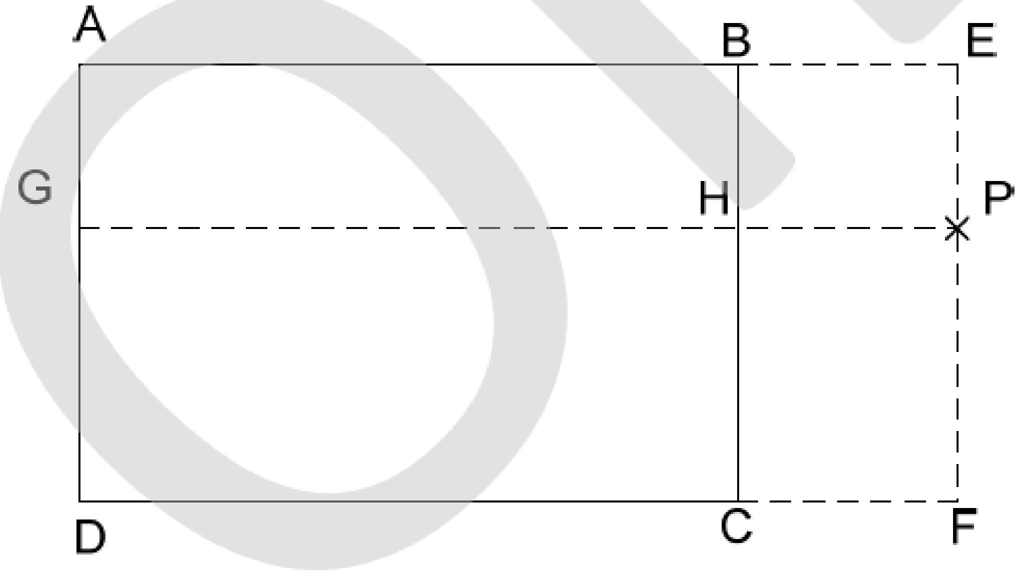
where:

α_{C1} - the distribution coefficient of stresses for the rectangle AEPG

α_{C2} - identical, for rectangle GPFD

α_{C3} - identical, for rectangle BEPH

α_{C4} - identical, for rectangle HPFC



Obs: Special foundation forms are approximated by admitting the foundation form as a sum of rectangular shapes and computing σ_z by multiple superposition.