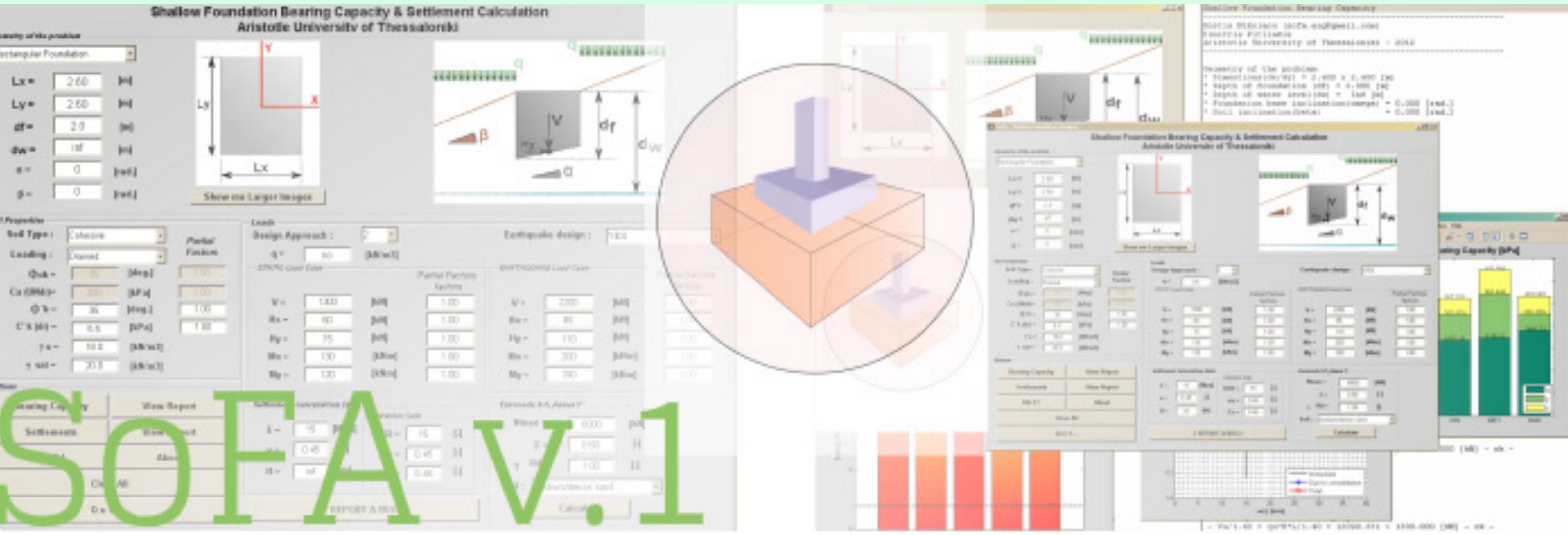
SoFA

version 1.0

Users' Manual

Konstantinos Nikolaou
Dimitris Pitilakis



ShallOw Foundation Analysis Software

Aristotle University of Thessaloniki
Thessaloniki 2012

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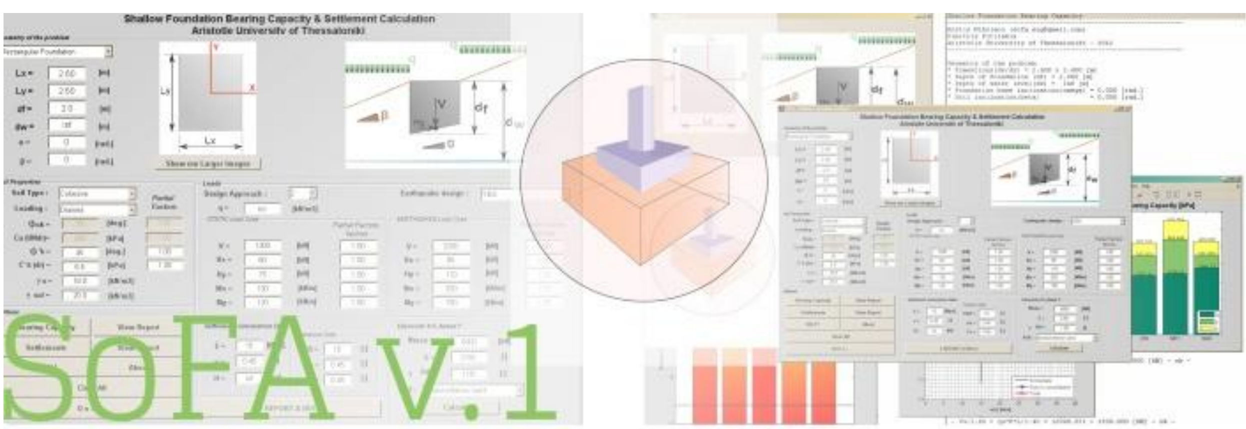

ShallOw Foundation Analysis Software

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Contents

1. Introduction

About this manual

The purpose of the present manual is to provide basic guidelines in the use of SoFAv.1.0 computer program for the design of shallow foundations. A short description of the used algorithms is combined with appropriate theoretical documentation.

About the software

SoFA is a newly-developed stand-alone simple program based on Matlab, for the calculation of bearing capacity and settlements of shallow foundations. Correct calculation of ultimate bearing capacity and foundation settlement is the most crucial step in the design of shallow foundations. Analytical solutions are preferred to numerical methods (i.e. complex finite element models) in engineering practice, mainly because of their inherent simplicity. In SoFA, safety factors are calculated for the ultimate bearing capacity using several well-known formulas from literature. Short-term components of settlements are calculated using the adjusted elasticity method, while confined one-dimensional deformation of the soil is assumed for the consolidation. SoFA provides solutions for all three design approaches implemented in Eurocode 7, as well as in Eurocode 8 for earthquake loading. Cohesive and cohesionless soils, static and dynamic loads, drained and un-drained conditions are examined. Our program has a simple user-friendly graphical interface. It is freely distributed and well documented in order to attract engineers to exploit its capabilities.

About shallow foundations

Foundations are considered shallow if their depth to length ratio is small enough compared to their length. Shallow foundations are used to safely transfer superstructure loads to the ground. The basic checks that a shallow foundation must pass are the following:

- Bearing capacity of underlying soil
- Stability against sliding
- Stability against overturning
- Settlement check
- Yield of structural components check (bending, shear etc)

SoFA can currently perform only bearing capacity and settlement calculations.

Licensing information

2. Static Bearing Capacity of Shallow Foundations

Several methods are used to calculate bearing capacity of a shallow footing, but only the theoretical methods are going to be discussed here. These methods use general soil data i.e. angle of friction φ, cohesion c to assess the ultimate bearing capacity.

2.1 General Bearing Capacity Equation

The general bearing capacity equation is:

$$q_u = c' N_c s_c i_c b_c g_c d_c + po' N_q s_q i_q b_q g_q d_q + \frac{1}{2} B' \gamma' N_\gamma s_\gamma i_\gamma b_\gamma g_\gamma d_\gamma$$

Where

- q_u: bearing capacity of the shallow foundation
- c : soil cohesion
- po: loading on foundation depth
- B : width of the foundation
- γ' : weight of the soil under the foundation
- s_c, s_q, s_γ : shape factors
- i_c, i_q, i_γ : load inclination factors
- b_c, b_q, b_γ : base inclination factors
- g_c, g_q, g_γ : soil inclination factors
- d_c, d_q, d_γ : depth factors

2.2 Loading convention in SoFA

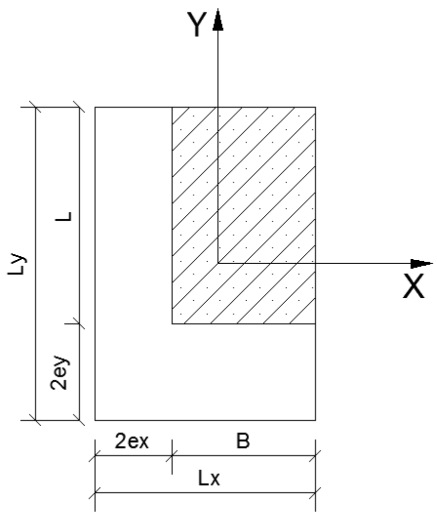
All loads are considered acting at the soil-footing interface, and NOT at the theoretical point of column fixity.

SoFA does not calculate self weight of the footing, the user has to include it in the loading case scenario. All loads are user specified.

2.3 Effective dimensions

Effective dimensions have to be calculated for central loading.

Let effective dimensions be B, L, whereas Lx, Ly are the footing length on X and Y directions, V a vertical load and Mx, My moments about X and Y axes respectively. The effective area of the footing (hatched area) would be



$$A_{eff} = B * L$$

where

$$e_x = \frac{My}{V} \ \ \& \ \ e_y = \frac{M_x}{V}$$

$$B_x' = L_x - 2 * e_x \ \ \& \ \ B_y' = L_y - 2 * e_y$$

$$B = min[B_x', B_y'] \ \ \& \ \ L = max\ [L_x', L_y']$$

2.4. Water level

2.4.1 Water level - undrained loading

Water level changes the total loading on foundation depth (po’) and the effective weight of the soil under the foundation (γˈ)

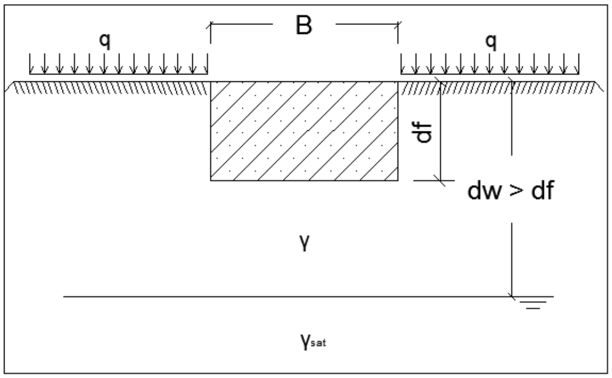
- If the depth of water level (d_w) is larger than the depth of foundation (d_f), as shown in figure A, then:

$$po = \gamma * d_f + q$$

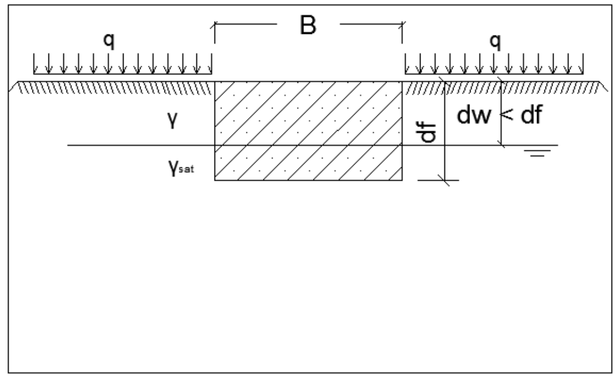
- Else if $d_w < d_f$ as shown in figure B:

$$po = \gamma * d_w + \gamma_{sat} * (d_f - d_w) + q$$

$*$ γ_{sat} is the saturated soil weight



A) dw > df



B) dw < df

2.4.2 Water level - drained loading

For the drained loading case:

- If $\mathbf{d_w} > \mathbf{d_f} + \mathbf{B}$ then

$$po = \gamma * d_f + q$$

  Water level affects bearing capacity only when $d_w < d_f + B$, in which case the weight of the soil under the footing is considered equal to drained soil weight

$$\gamma' = \gamma$$

- If $\mathbf{d_f} < d_\mathbf{w} < \mathbf{d_f} + \mathbf{B}$ then

$$po = \gamma * d_f + q$$

  But γ' is given by

$$\gamma' = \frac{\gamma * (d_w - d_f) + (\gamma_{sat} - \gamma_w) * (d_f + B - d_w)}{B}$$

- If $\mathbf{d_w} < \mathbf{d_f}$ then

$$po = \gamma * d_w + (\gamma_{sat} - \gamma_w) * (d_f - d_w) + q$$

  now γ' is

$$\gamma' = \gamma_{sat} - \gamma_w$$

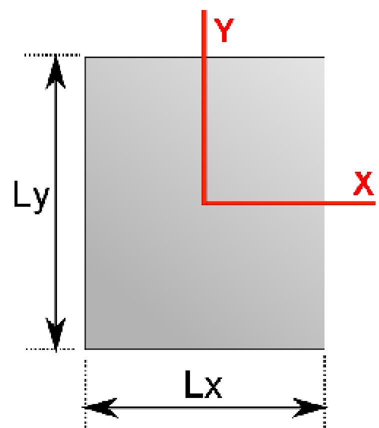
2.5 Code provision formulas

In this section several bearing capacity formulas from code provisions are presented. The following figures contain the general geometry specifications.

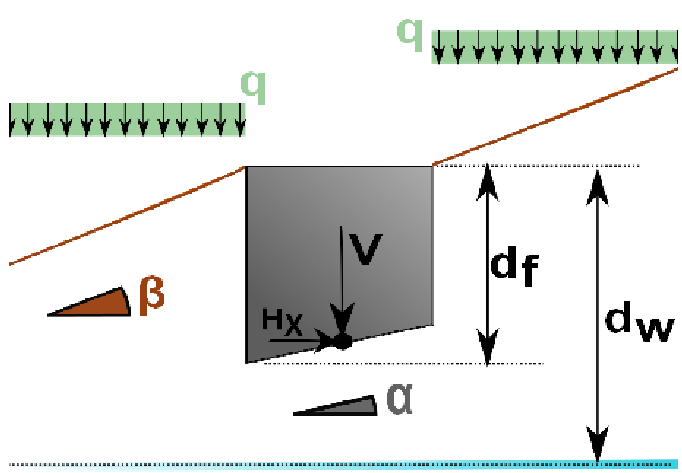
- β is the soil inclination
- α is the foundation base inclination
- θ is the angle of vertical load (V) with Z-axis due to horizontal load (H) $\theta = Arctan(H/V)$

A full list of symbols used can be found in Appendix A at the end of this document.

X-Y plane



X-Z/Y-Z plane



2.5.1 Eurocode 7 (2004)

Undrained loading

$$q_u = 5.14 * cu * s_c * i_c * b_c + po$$

where:

$$s_c = 1 + 0.2 * \frac{B}{L}$$

$$i_c = \frac{1}{2} + \frac{1}{2} * \sqrt{1 - \frac{H}{B * L * cu}}$$

$$b_c = 1 - \frac{2 * \alpha}{\pi + 2}$$

Drained loading

$$q_u = c' * N_c * s_c * i_c * b_c + po' * N_q * s_q * i_q * b_q + \frac{1}{2} * B' * \gamma' * N_\gamma * s_\gamma * i_\gamma * b_\gamma$$

where:

$$N_c = (N_q - 1)/tan\phi'$$

$$s_c = \frac{s_q * N_q - 1}{N_q - 1}$$

$$i_c = \frac{i_q * N_q - 1}{N_q - 1}$$

$$b_c = \frac{b_q * N_q - 1}{N_q - 1}$$

$$N_q = \tan^2\left(\frac{\pi}{4} + \frac{\phi'}{2}\right) * e^{\pi * tan\phi'}$$

$$s_q = 1 + \frac{B}{L} * \sin\phi'$$

$$i_q = \left(1 - \frac{H}{V + B * L * \frac{c'}{tan\phi'}}\right)^m$$

$$b_q = (1 - \alpha * tan\phi')^2$$

$$N_\gamma = 2 * (N_q - 1) * tan\phi'$$

$$s_\gamma = 1 - 0.3 * \frac{B}{L}$$

$$i_\gamma = \left(1 - \frac{H}{V + B * L * \frac{c'}{tan\phi'}}\right)^{m+1}$$

$$b_\gamma = (1 - \alpha * tan\phi')^2$$

$$m = m_L * \cos^2\theta + m_B * \sin^2\theta$$

$m_L = \frac{2+L/B}{1+L/B}$ & $m_B = \frac{2+B/L}{1+B/L}$

* α in [rad.]

2.5.2 DIN 4017 (2006)

Undrained loading

$$q_u = 5.14 * c_u * s_c * i_c * b_c * g_c + po$$

where:

$$s_c = 1 + 0.2 * \frac{B}{L}$$

$$i_c = \frac{1}{2} + \frac{1}{2} * \sqrt{1 - \frac{H}{B * L * cu}}$$

$$b_c = 1 - \frac{2 * a}{\pi + 2}$$

$$g_c = 1 - 0.4 tan\beta$$

Drained loading

$$q_u = c' * N_c * s_c * i_c * b_c * g_c + po' * N_q * s_q * i_q * b_q * g_q + \frac{1}{2} * B' * \gamma' * N_\gamma * s_\gamma * i_\gamma * b_\gamma * g_\gamma$$

where:

$$N_c = (N_q - 1)/tan\phi$$

$$s_c = \frac{s_q * N_q - 1}{N_q - 1}$$

$$i_c = \frac{i_q * N_q - 1}{N_q - 1}$$

$$b_c = e^{-2.58 * a * tan\phi'}$$

$$g_c = \frac{N_q * e^{-2 * \beta * tan} - 1}{N_q - 1}$$

$$N_q = \tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) * e^{\pi * tan\phi}$$

$$s_q = 1 + \frac{B}{L} * \sin$$

$$i_q = (1 - tan\theta)^m$$

$$b_q = e^{-2.58 * a * tan\phi'}$$

$$g_q = (1 - tan\beta)^{1.9}$$

$$N_\gamma = 2 * (N_q - 1) * tan\phi$$

$$s_\gamma = 1 - 0.3 * \frac{B}{L}$$

$$i_\gamma = (1 - tan\theta)^{m+1}$$

$$b_\gamma = e^{-2.58 * a * tan\phi'}$$

$$g_\gamma = (1 - 0.5 * \tan\beta)^6$$

$$m = m_L * \cos^2\theta + m_B * \sin^2\theta$$

$$m_L = \frac{2 + L/B}{1 + L/B} \ \& \ m_B = \frac{2 + B/L}{1 + B/L}$$

*α in [rad.]

2.5.3 EAK (2000)

Undrained loading

$$q_u = 5.14 * cu * s_c * i_c + po$$

where:

$$\mathbf{s_c = 1 + 0.2 * \frac{B}{L}}$$

$$\mathbf{i_c = \frac{1}{2} + \frac{1}{2} * \sqrt{1 - \frac{H}{B * L * cu}}}$$

Drained loading

$$q_u = c' * N_c * s_c * i_c + po' * N_q * s_q * i_q + \frac{1}{2} * B' * \gamma' * N_\gamma * s_\gamma * i_\gamma$$

where:

$$N_c = (N_q - 1)/tan\phi'$$

$$N_q = \tan^2\left(\frac{\pi}{4} + \frac{\phi'}{2}\right) * e^{\pi * tan\phi'}$$

$$N_\gamma = 2 * (N_q - 1) * tan\phi'$$

$$s_c = 1 + \frac{B}{L} * \frac{N_q}{N_c}$$

$$s_q = 1 + \frac{B}{L} * tan\phi'$$

$$s_\gamma = 1 - 0.3 * \frac{B}{L}$$

$$i_c = \frac{i_q * N_q - 1}{N_q - 1}$$

$$i_{qL} = \left(1 - \frac{0.7 * H_B}{V + B * L * c'/tan\varphi'}\right)^3$$

$$i_{qL} = \left(1 - \frac{0.7 * H_B}{V + B * L * c'/tan\varphi'}\right)^3$$

$$i_{\gamma L} = \left(1 - \frac{H_B}{V + B * L * c'/tan\varphi'}\right)^3$$

$$i_{\gamma L} = \left(1 - \frac{H_B}{V + B * L * c'/tan\varphi'}\right)^3$$

!!! Theta is the angle between the horizontal forces

$$\tan\theta = \left(\frac{H_B}{H_L}\right)$$

$$i = i_B * \left(1 - \frac{\theta}{90}\right) + i_L * \left(\frac{\theta}{90}\right)$$

2.6 Literature formulas

2.6.1 Meyerhof (1953, 1963)

Undrained loading

$$q_u = 5.14 * cu * s_c * i_c * d_c + po * s_q * i_q * d_q$$

where:

$$s_c = 1 + 0.2 * \frac{B}{L}$$

$$i_c = \left(1 - \frac{2 * \theta}{\pi}\right)^2$$

$$d_c = 1 + 0.2 * \frac{D}{B}$$

$$s_q = 1$$

$$i_q = \left(1 - \frac{2 * \theta}{\pi}\right)^2$$

$$d_q = 1$$

Drained loading

$$q_u = c' * N_c * s_c * i_c * d_c + po' * N_q * s_q * i_q * d_q + \frac{1}{2} * B' * \gamma' * N_\gamma * s_\gamma * i_\gamma * d_\gamma$$

where:

$$N_c = (N_q - 1)/tan\phi'$$

$$s_c = 1 + 0.2 * \frac{B}{L} \tan^2\left(\frac{\pi}{4} + \frac{\phi'}{2}\right)$$

$$i_c = \left(1 - \frac{2 * \theta}{\pi}\right)^2$$

$$d_c = 1 + 0.2 * \frac{B}{L} \tan^2\left(\frac{\pi}{4} + \frac{\phi'}{2}\right)$$

$$N_q = \tan^2\left(\frac{\pi}{4} + \frac{\phi'}{2}\right) * e^{\pi * tan\phi'}$$

$$s_q = 1 + 0.1 * \frac{B}{L} \tan^2\left(\frac{\pi}{4} + \frac{\phi'}{2}\right)$$

$$if\ \varphi \leq 10^o \rightarrow s_q = 1$$

$$i_q = \left(1 - \frac{2 * \theta}{\pi}\right)^2$$

$$d_q = 1 + 0.1 * \frac{B}{L} \tan^2\left(\frac{\pi}{4} + \frac{\phi'}{2}\right)$$

$$if\ \varphi \leq 10^o \rightarrow d_q = 1$$

$$N_\gamma = (N_q - 1) * \tan(1.4 * \phi')$$

$$s_\gamma = 1 + 0.1 * \frac{B}{L} \tan^2\left(\frac{\pi}{4} + \frac{\phi'}{2}\right)$$

$$if\ \varphi \leq 10^o \rightarrow s_\gamma = 1$$

$$i_\gamma = \left(1 - \frac{\theta}{\varphi'} * \frac{180}{\pi}\right)^2$$

$$if\ \varphi = 0^o \rightarrow i_\gamma = 0$$

$$d_\gamma = 1 + 0.1 * \frac{B}{L} \tan^2\left(\frac{\pi}{4} + \frac{\phi'}{2}\right)$$

$$if\ \varphi \leq 10^o \rightarrow d_\gamma = 1$$

$$m = m_L * \cos^2\theta + m_B * \sin^2\theta$$

$$m_L = \frac{2 + L/B}{1 + L/B} \ \& \ m_B = \frac{2 + B/L}{1 + B/L}$$

2.6.2 Hansen (1970)

Undrained loading

$$q_u = 5.14 * c_u * \min\left[(1 + s_{cB} + d_{cB} - i_{cB} - b_c - g_c), (1 + s_{cL} + d_{cL} - i_{cL} - b_c - g_c)\right]$$

where:

$$s_{cB} = 0.2 * \frac{B}{L} * i_{cB}$$

$$i_{cB} = \frac{1}{2} - \frac{1}{2} * \sqrt{1 - \frac{H_B}{B * L * cu}}$$

$$d_{cB} = 0.4 * d_f / B$$

$$b_c = \frac{2 * \alpha}{\pi + 2}$$

$$g_c = \frac{2 * \beta}{\pi + 2}$$

$$s_{cL} = 0.2 * \frac{L}{B} * i_{cL}$$

$$i_{cL} = \frac{1}{2} - \frac{1}{2} * \sqrt{1 - \frac{H_L}{B * L * cu}}$$

$$d_{cL} = 0.4 * d_f / L$$

Drained loading

$$q_u = \min\left[q_{uB}, q_{uL}\right]$$

$$q_{uB} = c' * N_c * s_{cB} * i_{cB} * d_{cB} * b_c * g_c + po' * N_q * s_{qB} * i_{qB} * d_{qB} * b_q * g_q + \frac{1}{2} * B' * \gamma' * N_\gamma * s_{\gamma B} * i_{\gamma B} * d_{\gamma B} * b_\gamma * g_\gamma$$

$$q_{uL} = c' * N_c * s_{cL} * i_{cL} * d_{cL} * b_c * g_c + po' * N_q * s_{qL} * i_{qL} * d_{qL} * b_q * g_q + \frac{1}{2} * B' * \gamma' * N_\gamma * s_{\gamma L} * i_{\gamma L} * d_{\gamma L} * b_\gamma * g_\gamma$$

where:

$$N_c = (N_q - 1)/tan\phi'$$

$$s_{cB} * i_{cB} * d_{cB} * b_c * g_c = \frac{N_q * s_{qB} * i_{qB} * d_{qB} * b_q * g_c - 1}{N_q - 1}$$

$$N_q = \tan^2\left(\frac{\pi}{4} + \frac{\phi'}{2}\right) * e^{\pi * tan\phi'}$$

$$s_{qB} = 1 + \frac{B}{L} * i_{qB} * \sin\phi'$$

$$i_{qB} = \left(1 - \frac{0.5 * H_B}{V + B * L * c'/tan\varphi'}\right)^5$$

$$d_{qB} = 1 + \frac{2 * d_f}{B} \tan\varphi'(1 - sin\varphi')^2$$

$$N_\gamma = 1.5 * (N_q - 1) * tan\phi'$$

$$s_{\gamma B} = 1 - 0.4 * \frac{B}{L} * \frac{i_{\gamma B}}{i_{\gamma L}}$$

$$i_{\gamma B} = \left(1 - \frac{0.7 * H_B}{V + B * L * c'/tan\varphi'}\right)^5$$

$$d_{\gamma B} = 1$$

$s_{cL} * i_{cL} * d_{cL} * b_c * g_c = \dfrac{N_q * s_{qL} * i_{qL} * d_{qL} * b_q * g_c - 1}{N_q - 1}$	$s_{qL} = 1 + \dfrac{L}{B} * i_{qL} * \sin\phi'$	$s_{\gamma L} = 1 - 0.4 * \dfrac{L}{B} * \dfrac{i_{\gamma L}}{i_{\gamma B}}$
	$i_{qL} = \left(1 - \dfrac{0.5 * H_L}{V + B * L * c'/tan\varphi'}\right)^5$	$i_{\gamma L} = \left(1 - \dfrac{0.7 * H_L}{V + B * L * c'/tan\varphi'}\right)^5$
	$d_{qL} = 1 + \dfrac{2 * D}{L} \tan\varphi'(1 - sin\varphi')^2$	$d_{\gamma L} = 1$
	$b_q = e^{-2*a*tan\phi'}$	$b_\gamma = e^{-2.7*a*tan\phi'}$
	$g_q = (1 - 0.5 * tan\beta)^5$	$g_\gamma = (1 - 0.5 * \tan\beta)^5$

*ɑ in [rad.]

3. Earthquake Bearing Capacity of Shallow Foundations

3.1 Eurocode 8

According to EN 1998 - part 5 - Annex F, bearing capacity is checked using the following formula:

$$\Phi(\bar{N},\bar{V},\bar{M},\bar{F}) = \frac{(1-e*\bar{F})^{c_T}*(\beta*\bar{V})^{c_T}}{(\bar{N})^{a}*\left[(1-m*\bar{F}^{k})^{k'}-\bar{N}\right]^{b}} + \frac{(1-f*\bar{F})^{c'_M}*(\gamma*\bar{M})^{c_M}}{(\bar{N})^{c}*\left[(1-m*\bar{F}^{k})^{k'}-\bar{N}\right]^{d}} - 1 \le 0$$

where

$\bar{N} = \frac{\gamma_{Rd}*N_{Ed}}{N_{max}}$, $\bar{V} = \frac{\gamma_{Rd}*V_{Ed}}{N_{max}}$, $\bar{M} = \frac{\gamma_{Rd}*M_{Ed}}{B*N_{max}}$

N_{Ed}, V_{Ed}, M_{Ed}: design action effects

N_{max} : is the ultimate bearing capacity of the foundation under a vertical centered load as defined later

B : the foundation width

$\bar{F}$: the dimensionless inertia force as defined later

γ_{Rd} : model partial factor

The other parameters are given in tabular form:

	Cohesive soil	**Cohesionless soil**
a	0.70	0.92
b	1.29	1.25
c	2.14	0.92
d	1.81	1.25
e	0.21	0.41
f	0.44	0.32
m	0.21	0.96
k	1.22	1.00
k'	1.00	0.39
c_T	2.00	1.14
c_M	2.00	1.01
c'_M	1.00	1.01
β	2.57	2.90
γ	1.85	2.80

	Medium dense – dense sand	Loose dry Sand	Loose saturates Sand	Non sensitive clay	Sensitive clay
γ_{Rd}	1.00	1.15	1.50	1.00	1.15

Cohesionless	Cohesive
$N_{max} = \frac{1}{2} * \rho * g * \left(1 \pm \frac{a_v}{g}\right) * B^2 * N_\gamma$	$N_{max} = (\pi + 2) * \frac{c_u}{\gamma_M} * B$
$\bar{F} = \frac{a_g * S}{g * tan\, \varphi'_d}$	$\bar{F} = \frac{\rho * a_g * \gamma_I * S * B}{c_u}$

where:

ρ: the unit mass of the soil

g: the acceleration of gravity

a_g: design ground acceleration on type A ground

a_v: vertical ground acceleration on type A ground(may be taken equal to 0.5*$a_g * S$)

N_γ: is the bearing capacity factor, a function of the design angle of the shearing resistance of soil φ'_d ($\varphi'_d = \tan^{-1}\left(\frac{tan\varphi'}{\gamma_\varphi}\right)$)

c_u: undrained shear strength of soil

γ_I: importance factor

S : soil parameter defined in Eurocode 8- part 1)

Also the following constrains apply for cohesive soils:

$$0 < \bar{N} \leq 1$$

$$|\bar{V}| \leq 1$$

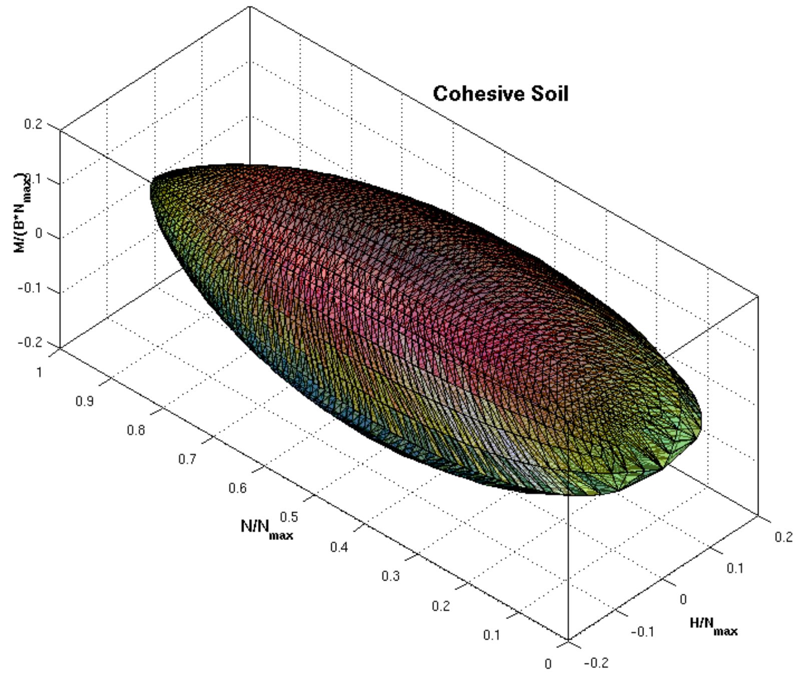
and for cohesionless soils:

$$0 < \bar{N} \leq (1 - m * \bar{F})^{k'}$$

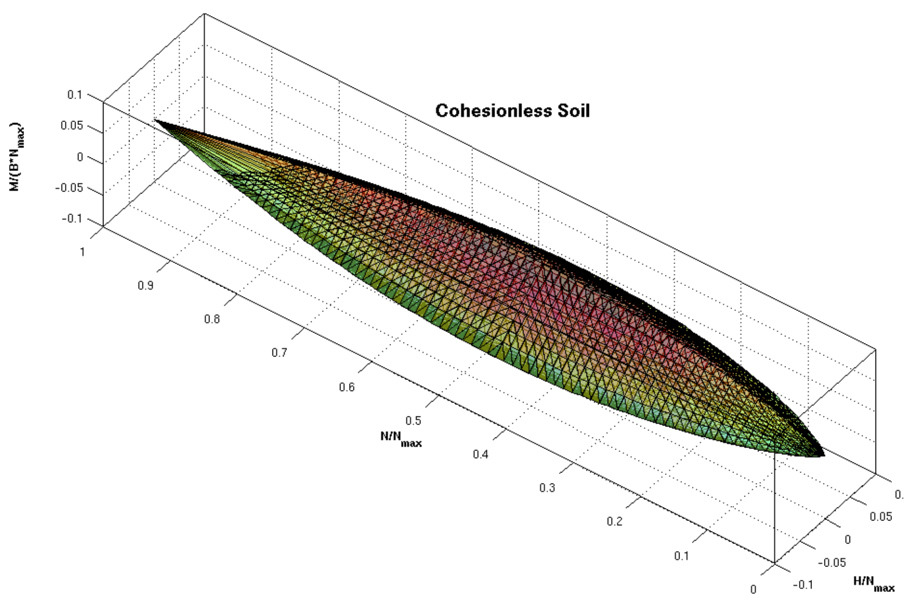
$$|\bar{V}| \leq 1$$

The general formula for a fixed $\bar{F}$ value in the three-dimensional space of $\bar{N}$- $\bar{V}$-$\bar{M}$ can be represented by a surface. Every point lying inside this surface is a safe load combination, while every point outside suggests an unsafe load combination. Depending on the **soil type** and $\bar{F}$ **factor** a different bounding surface is produced.

The following figures depict these yield surfaces for $\bar{F}$ =0 for cohesive and cohesionless soils respectively.

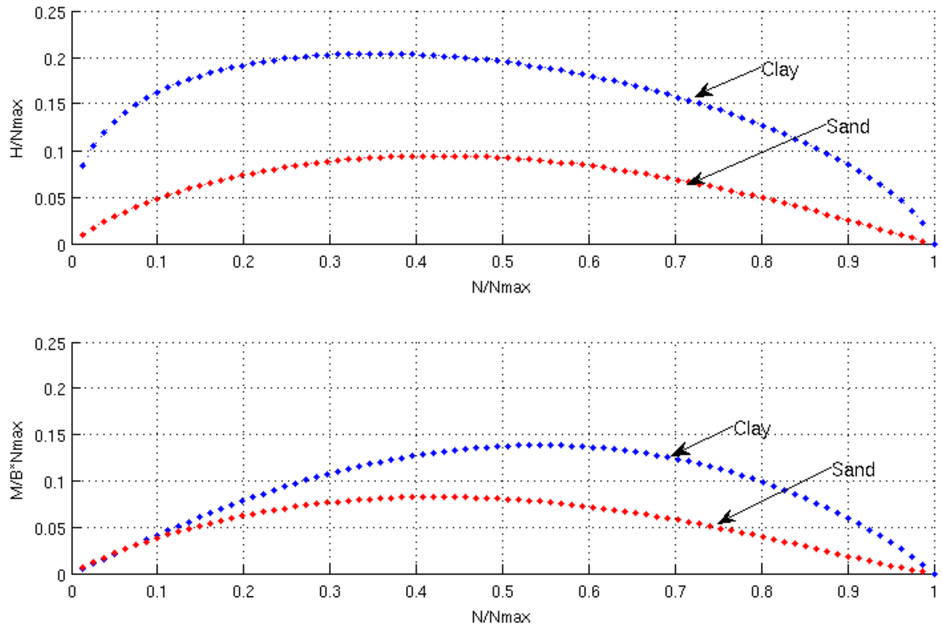


N-M-V Interaction yield criterion for Cohesive Soil ($\bar{F}$=0)

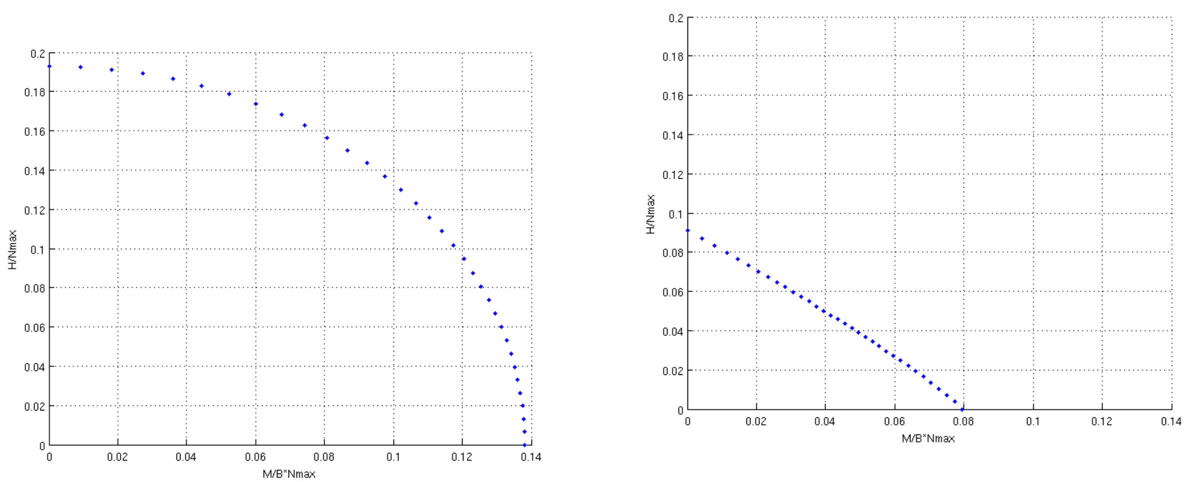


N-M-V Interaction yield criterion for Cohesionless soil ($\bar{F}$=0)

The next figures show some planes of the previous surfaces. All figures are in the same scale, so differences between the surfaces produced can be easily distinguished.

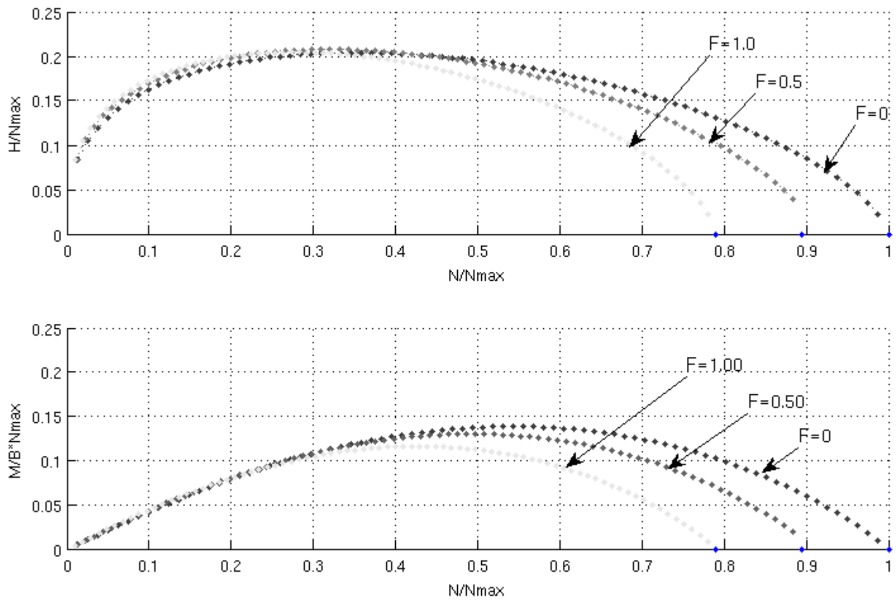


Cohesive and Cohesionless soil failure criteria ($\overline{F}$=0) N-V plane



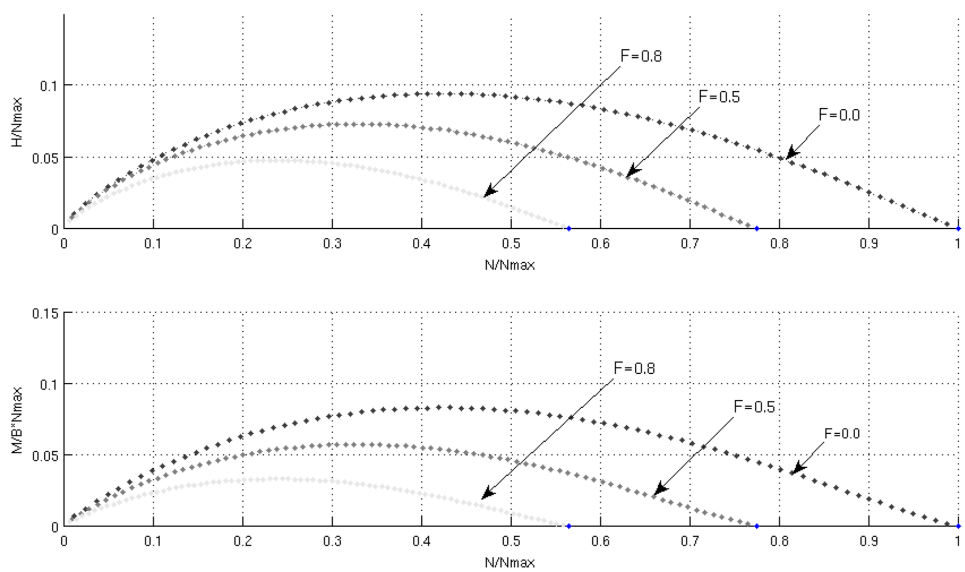
Cohesive and Cohesionless soil failure criteria ($\overline{F}$=0) M-V plane

The same figures are plotted for several values of F, the first figure is for clays



Cohesive soils failure criteria (several F)

and the second for sands.



Cohesionless soils failure criteria (several F)

The aforementioned formula was developed and is valid only for strip footings, but according to the literature the formula can be applied to rectangular footings if the N_{max} value is multiplied by

$$s_c = 1 + 0.32 * \left(1 - \frac{2 * e}{B}\right) * \frac{B}{L}$$

SoFA does not use this formula, but the user is always free to modify N_{max} value calculated by SoFA to get the appropriate results.

3.2 EAK 2000 (Greek Code)

EAK 2000 suggests using the same formulas with the static bearing capacity but with a different safety factor and a reduced angle of friction (for saturated soils), in order to approximately take into account the pore-overpressure due to the earthquake. SoFA does not modify the angle of friction for the earthquake load case, but the user is free to change the parameter at will.

4. Settlement calculations

4.1 Immediate Settlements

Immediate settlements of a footing are calculated by:

$$\Delta H_{\mathrm{im}} = I * p * B * \frac{1 - v^2}{E}$$

where

I : shape and rigidity factor, value from the following tables

$p = \frac{\mathrm{N}}{\mathrm{B} * \mathrm{L}}$: vertical footing pressure

v :Poisson's ratio

E : Equivalent modulus of elasticity

Soil layer of Infinite Depth	
L/B	**I**
1	0.56
1.5	0.68
2	0.77
5	1.05
10	1.26
100	1.69

Soil layer of finite Depth (=H)		
v = 0.50		
L/B	**H/B**	**I**
1	0	0
	0.5	0.05
	1.0	0.15
	1.5	0.23
	2.0	0.29
	3.0	0.36
	5.0	0.44
	10	0.48
2	0	0
	0.5	0.04
	1.0	0.12
	1.5	0.22
	2.0	0.29
	3.0	0.40
	5.0	0.52
	10	0.64
5	0	0
	0.5	0.04
	1.0	0.10
	1.5	0.18
	2.0	0.27
	3.0	0.39
	5.0	0.55
	10	0.76
10	0	0
	0.5	0.05
	1.0	0.15
	1.5	0.23
	2.0	0.29
	3.0	0.36
	5.0	0.44
	10	0.48
∞	0	0
	0.5	0.04
	1.0	0.10
	1.5	0.18
	2.0	0.26
	3.0	0.37
	5.0	0.52
	10	0.73

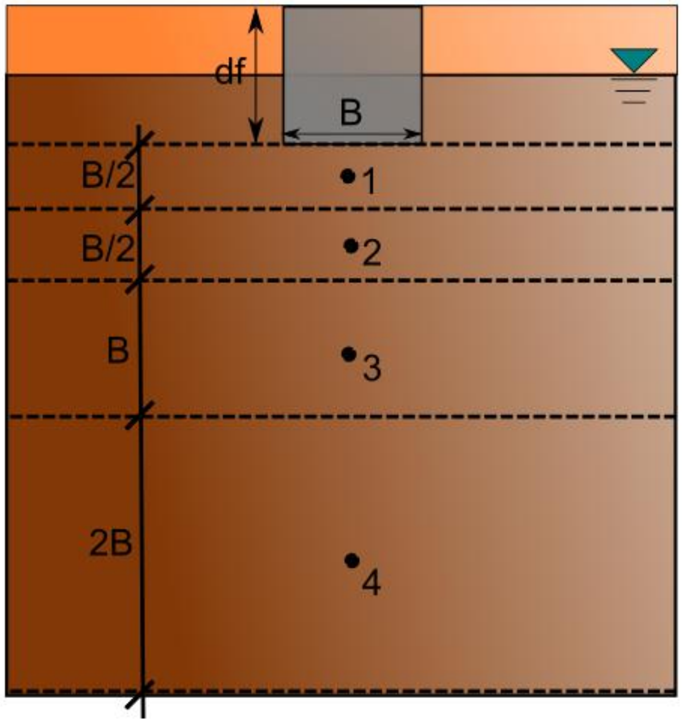
Soil layer of finite Depth (=H)

v = 0.33

L/B	H/B	I
1	0	0
	0.5	0.09
	1.0	0.19
	1.5	0.27
	2.0	0.32
	3.0	0.38
	5.0	0.46
	10	0.49
2	0	0
	0.5	0.08
	1.0	0.18
	1.5	0.28
	2.0	0.34
	3.0	0.44
	5.0	0.56
	10	0.66
5	0	0
	0.5	0.08
	1.0	0.16
	1.5	0.25
	2.0	0.34
	3.0	0.46
	5.0	0.60
	10	0.80
10	0	0
	0.5	0.08
	1.0	0.16
	1.5	0.25
	2.0	0.34
	3.0	0.45
	5.0	0.61
	10	0.81
∞	0	0
	0.5	0.08
	1.0	0.16
	1.5	0.25
	2.0	0.34
	3.0	0.45
	5.0	0.61
	10	0.81

4.2 Due to Consolidation

To calculate the settlements due to consolidation, we define four sub-layers, a characteristic point is selected for each layer, as shown in the following figure, and the soil stresses are computed for the initial state and due to the load case.



Load stresses and I_s factor are calculated using the formulas described in Bowles [6], chapter 5. Integrating Boussinesq equation over a rectangle of dimensions *B*-by-*L* (Newmark 1935 [15]) produces:

$$q_v = q_0 * I_s$$

$$I_s = \frac{1}{4\pi}\left[\frac{2*M*N*\sqrt{V}}{V+V_1}\frac{V+1}{V} + tan^{-1}\left(2*M*N*\frac{\sqrt{V}}{V-V_1}\right)\right]$$

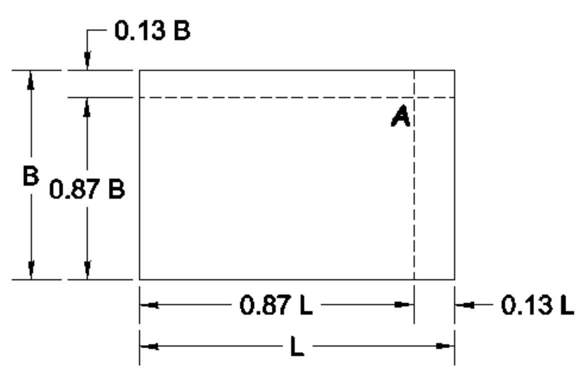
where:

$M = \frac{B}{z}$ & $N = \frac{L}{z}$ ($I_s = 1\ for\ z = 0$ m)

$V = M^2 + N^2 + 1$

$V_1 = (M*N)^2$

I_s is calcutated for point A, as the sum of I_s factors calculated for the four rectangulars defined by A.



Settlements due to consolidation are then calculated:

If $\sigma'_{\mathrm{tot}} > \sigma'_{\mathrm{OCR}}$ by

$$\Delta H_{\mathrm{i}} = H_{\mathrm{i}} * \frac{0.1 * C_{\mathrm{C}}}{1 + e_0} * \log\left(\frac{\sigma'_{\mathrm{OCR}}}{\sigma'_{\mathrm{init}}}\right) + H_{\mathrm{i}} * \frac{C_{\mathrm{C}}}{1 + e_0} * \log\left(\frac{\sigma'_{\mathrm{tot}}}{\sigma'_{\mathrm{OCR}}}\right)$$

If $\sigma'_{\mathrm{tot}} < \sigma'_{\mathrm{OCR}}$ by

$$\Delta H_{\mathrm{i}} = H_{\mathrm{i}} * \frac{0.1 * C_{\mathrm{C}}}{1 + e_0} * \log\left(\frac{\sigma'_{\mathrm{tot}}}{\sigma'_{\mathrm{init}}}\right)$$

Total settlements are the sum of the settlements for each layer.

5. Feedback

Feel free to contact us for any comments, regarding SoFA. You can directly contact us by email (sofa.eng@gmail.com) or use our comment form in our website.

If you discover a bug, please report it here. Please try to include all SoFA reports.

References

Greek

[1] Αναγνωστόπουλος Χ., Χατζηγώγος Θ., Αναστασιάδης Α., Πιτιλάκης Δ.(2012).” Θεμελιώσεις, αντιστηρίξεις και γεωτεχνικά έργα”. Εκδόσεις Αϊβάζη, Θεσσαλονίκη

[2] Γεωργιάδης Κ., Γεωργιάδης Μ. (2009), "Στοιχεία Εδαφομηχανικής", εκδόσεις ΖΗΤΗ, Θεσσαλονίκη

[3] ΕΑΚ 2000 (2000), “Ελληνικός Αντισεισμικός Κανονισμός”

[4] Πιτιλάκης Κ., Γεωργιάδης Μ., Μπαντής Σ., Χατζηγώγος Θ., Αναγνωστόπουλος Χ., Τίκα Θ. (1999), "Αντισεισμικός Σχεδιασμός Θεμελιώσεων, Αντιστηρίξεων και Γεωκατασκευών", Α.Π.Θ. Πανεπιστημιακές Σημειώσεις ΑΣΤΕ, Θεσσαλονίκη

[5] Τσότσος Στ. (1991), "Εδαφομηχανική: Θεωρία - Μέθοδοι - Εφαρμογές", Αριστοτέλειο Πανεπιστήμιο Θεσσαλονίκης

English

[6] Bowles J.E. (1997), "Foundation Analysis and Design", 5th edition, McGrow-Hill, New York

[7] Bond A. (2008), "Decoding Eurocode 7", Taylor & Francis

[8] CE de Normalisation (1998), “Eurocode 7 – Eurocode 7: Geotechnical design – Part 1: General rules”

[9] CE de Normalisation (1998), “Eurocode 8 – Design of Structures for earthquake resistance– Part 1: General rules, seismic actions and rules for buildings”

[10] Deutsche Norm (2006), “DIN 4017 Soil: Calculation of design bearing capacity of soil beneath shallow foundations”

[11] Frank R., Bauduin C., Driscoll R., Kavvadas M., Krebs Ovesen N., Orr T. and Schuppener B. (2004) ,“ Designers' Guide to EN 1997-1 Eurocode 7: Geotechnical Design - General Rules”, Thomas Telford

[12] Hansen J. B. (1970), “A Revised and Extended Formula for Bearing Capacity” Danish Geotechnical Institute, Copenhagen, bulletin No. 28.

[13] Meyerhof G. G. (1963), “Some recent research on the bearing capacity of foundations” Canadian Geo-technical Journal,No. 1, 16±26.

[14] Meyerhof G. G. (1953), “The bearing capacity of foundations under eccentric or inclined loads” 3rd Int. Conf. on Soil Mech. and Found., Zurich,,Vol.1,pp.440-445

[15] Naval Facilities Eng. Command – NAVFAC (1986), ”Foundations and earth structures Design manual 7.2 ”

[16] Newmark, N.M., (1935) “Simplified computation of vertical stress below foundations.”,Univ. of Illinois Engineering Experiment Station, Circular 24, Urbana, Illinois, 19 p. (as referenced by Holtz and Kovacs, 1981).

[17] Paolucci, R., & Pecker, A. (1997), "Soil inertia effects on the bearing capacity of rectangular foundations on cohesive soils", Engineering structures, 19(8), 637-643.

[18] Pecker, A. (1997)., "Analytical formulae for the seismic bearing capacity of shallow strip foundations", Seismic Behavior of Ground and Geotechnical Structures, 261-268.

[19] Pecker, A., & Pender, M. J. (2000)., "Earthquake resistant design of foundations: new construction.", GeoEng2000, 1, 313-332.

[20] Pender, M. (2007)., "Seismic design and performance of surface foundations", Earthquake geotechnical engineering, 217-243.

[21] Smith I. (2006), "Smith's Elements of Soil Mechanics", Wiley

[22] Terzaghi K., Peck P.B. (1967), “Soil Mechanics in Engineering practice”, John Wiley and Sons, New York

Appendix A - List of Symbols

Latin letters

a_v	design ground acceleration in the vertical direction
a_g	design ground acceleration on type A ground
A_{eff}	effective area of the footing
b_i	the design values of the factors for the inclination of the base, with subscripts c for cohesion , q for surcharge and γ for weight density
B	the foundation width
B'	the effective foundation width
c	soil cohesion
c'	cohesion of soil in terms of effective stress
c_u	undrained shear strength of soil
c'_k	cohesion (for drained loading)
Cc	compression index
d_i	the design values of the factors for the depth of foundation, with subscripts c for cohesion , q for surcharge and γ for weight density
d_f	depth of foundation
d_w	depth of water level
eo	gap percentage
e	the eccentricity of the resultant action
E	Young's modulus of elasticity
F	seismic inertia force (dimensionless)
FS	factor of safety
g_i	the design values of the factors for the soil inclination, with subscripts c for cohesion , q for surcharge and γ for weight density
H	stratum thickness
H_x	horizontal force in x direction

H_y horizontal force in y direction

i_i the inclination factor of the load, with subscripts c for cohesion , q for surcharge and γ for weight density

I_s influence factor

L the foundation length

L' the effective foundation length

m exponent in formulas for the inclination factor i

M_x moment about xx axis

M_y moment about yy axis

N the bearing capacity factors, with subscripts cohesion c, surcharge q and weight density γ

N_{max} ultimate bearing capacity of the foundation under a vertical load

q overburden or surcharge pressure at the level of the foundation base

q' the design effective overburden pressure at the level of the foundation base

q_u bearing capacity of the shallow foundation

s_i the shape factors of the foundation base, with subscripts c for cohesion , q for surcharge and γ for weight density

S soil factor as defined in EN 1998-1

V the vertical load

V_u ultimate vertical load

p actual soil pressure

po loading on foundation depth

po' effective overburden pressure

z vertical distance (depth)

Greek letters

α the inclination of the foundation base to the horizontal

ß soil inclination according to DIN 4017

γ	weight of the soil under the foundation
γ'	the design effective weight of the soil below the foundation level
γ_I	importance factor
γ_s	dry soil unit weight
γ_{sat}	saturated soil unit weight
ΔH	the settlement of the corner of a rectangular base
v	Poisson's ratio
Φ	angle of internal friction
Φ'_k	effective angle of internal friction
Φ_{uk}	friction angle for undrained cohesive soils
σ'_{init}	initial stress
σ'_{OCR}	OCR stress
σ'_{tot}	total stress

Abbreviations

OCR over-consolidation ratio

For calculations, the following units (or multiples) are recommended:

force	[kN]
mass	[kg]
mass density	[kg/m^3]
moment	[kNm]
pressure	[kPa]
stiffness	[kPa]
strength	[kPa]
stress	[kPa]
weight density	[kN/m^3]

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We thank Prof. Christos Anagnostopoulos from the Dept. of Civil Engineering of AUTH for the scientific guidance. We thank Ivan Kraus (University of Osijek) for his comments and for the contribution of the symbols list.

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