SO-Foundation

Version 2.3.8598.1

Scientific Manual

This software is developed by Soil Office Software Group and is aimed at the bearing capacity of shallow footings considering both shear failure criterion and allowable settlement.

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1 Introduction

1-1 Soil Office

“Soil Office” is a developer of geotechnical engineering software since 2013. Our main objective is to develop functional and user friendly software, capable of performing precise calculations. The following software is currently considered:

- SO-Foundation: Bearing capacity of shallow foundations
- SO-Lab: Soil mechanics laboratory tests and boring logs including:
  - SO-Sieve: Sieve analysis, Hydrometer & Atterberg limits
  - SO-Shear: Direct shear
  - SO-Unconfined: Unconfined compression
  - SO-Triaxial: Triaxial compression
  - SO-Consolidation: One-dimensional consolidation
  - SO-Log: Geotechnical engineering boring logs

Feel free to contact us regarding any criticism, recommendation or additional information.

1-2 SO-Foundation

“SO-Foundation” calculates bearing capacity of shallow foundations considering both “shear failure” and “settlement”. Hansen, Meyerhof, Vesic, Terzaghi and Eurocode methods are employed for the determination of shear failure. Elastic and consolidation settlements can be calculated using various options.

Fully detailed reports are also presented that are self-explanatory.

1-3 Software capabilities

Multiple options are available in order to perform calculations in various situations. Some of them are listed below:

1-3-1 General features

- Supports “SI”, “Metric” and “English” units.
- Introduction of up to 20 soil layers.
- User is informed about the common ranges regarding input parameters.
- Pressure isobars are calculated and generated below footings.

– Determination of bearing capacity of shallow footings (Spread, Continuous and Mat) with different dimensions considering both shear failure and settlement (Elastic and Consolidation).
– Calculation of settlement corresponding to the allowable pressure.
– Calculation of modulus of subgrade reaction.
– Calculation and generation of modulus of subgrade reaction contour on the footing surface.
– Presentation of custom load-settlement graphs.
– Exporting results to MS Excel format.
– Presentation of calculation reports with sufficient details.
– Creation of profiles for the desired settings.
– Saving files with a minimal size.

1-3-2 SHEAR FAILURE

– Employment of 5 methods; Eurocode, Hansen, Meyerhof, Terzaghi and Vesic.
– Alteration of general factor of safety.
– Strength reduction factors may be assigned for friction angle and cohesion, separately.
– Water table effect is applied by 2 methods.
– Consideration of large footing effect in calculations.

1-3-3 SETTLEMENT

❖ General

– Alteration of allowable settlement by user's will.
– Effective depth in settlement calculation is determined as the minimum of below:
    - Pressure isobars (according to each of the methods; Boussinesq, Westergaard and Approximate 2V:1H) or a multiple of foundation width.
    - Depth of the rigid layer.

❖ Elastic settlement

– Modulus of elasticity can be determined by 3 methods:
    - Weighted average of layers.
    - Integration is performed on the specified graph (variation of modulus of elasticity by depth) over the effective zone of settlement and the mean value is obtained.
    - Manually specified by the user.

– Excavation effect is considered by 2 methods:
    - By the use of soil stress history (E_r/E_s).
    - Adding a specified percentage of footing overburden pressure to the bearing capacity with settlement criterion.

- Settlement calculations are performed by 2 methods, Steinbrenner and Das.
  2 footing types, flexible and rigid are available.

❖ <u>Consolidation settlement</u>

- Excavation effect may or may not be considered.
- Preconsolidation pressure can be calculated by 3 methods, “Auto” and specified by the user (“P'_c” and “OCR”).
- Stress increase due to footing load is calculated by 3 methods; Boussinesq, Westergaard and Approximate 2V:1H. Mentioned calculations are performed in 2 modes:
  - Middle depth of the layer is considered as the layer’s average.
  - Calculations are performed in top, middle and bottom of the layer and the result is obtained by the use of Simpson’s rule.
- Ability to divide each layer to a maximum of 20 sublayers, in order to increase solution precision.
- A specified fraction of consolidation settlement will be taken into account by user’s will.

2 Software interface

2-1 General

After running SO-Foundation, the following menus are visible on the top ribbon:

File menu: Contains commands relating to the handling of files, such as creating a new project, save, etc.
Layers: Soil layers along with various calculation settings are defined in this section.
Results: Calculation results are presented through this menu which contains the following sections:

- **Pressure isobars:** Pressure isobars are calculated and generated below footings.
- **Bearing capacity:** Calculation results including allowable bearing capacity, settlement and modulus of subgrade reaction are presented as graphs within this section.
- **Ks contour:** Modulus of subgrade reaction contour is generated across the footing.

Export: Is used to export results (as tables or calculation reports).
Profiles: Program settings and profiles are determined through this menu.
Help: Contains the following:

- **Scientific manual:** Describes functionality of different parts of the software and the theories of the utilized methods.
- **Verification manual:** Some examples chosen from geotechnical engineering references are solved and the results are verified.
- **Index:** Contains indexed help topics.

License: The permit to use the software and information on the client.
About: Contains general information.

- **SO-Foundation:** Brief description about the current software and its version.
- **Soil Office:** Introducing Soil Office Software Group.

Units: Switches between the available unit systems.

2-2 Details on menus

2-2-1 File menu

This menu is consisted of the following:

New: Creation of a new project.
Open: Opens a previously defined project.
Save: Saves project (with *.sof extension).
Save as: Saves project with a different name.
Verified examples: Access to the verified examples from geotechnical engineering references.
Close: Closes project.
Exit: Closes project and exits SO-Foundation.

2-2-2 Layers

Input is mainly defined in this section. Whenever wrong or illogical data is entered, the cell's color is altered and a corresponding message is shown in the bottom ribbon. The utilized colors are described below:

1- **Red:** The cell is empty or of the wrong data type.
2- **Orange:** The entered valued is not acceptable.
3- **Green:** Calculations may be performed, but the cell value seems to be illogical.
Note: Demo version limitations are identified as **pink**.

2-2-2-1 Project information

Basic project information including name, client, location, code and date are entered in this section. A separate field is also dedicated for notes.

2-2-2-2 Soil layers

Soil layers are defined (regardless of the footing depth) from the ground surface. It is advised to avoid redundant layers by the use of engineering judgment. Anyway, number of layers can be extended up to 20. The input parameters are listed below:

USCS: soil group symbol according to USCS. “Rigid” is also among the choices
Thickness: thickness of the layers
Bounds: depth range regarding each of the layers measured from the ground surface
γ: unit weight
ϕ: internal friction angle
c: cohesion
E_s: modulus of elasticity (normally consolidated soils)
v: Poisson’s ratio
Consolidation: determines whether consolidation settlements are calculated or not
C_c: compression index
C_s: swelling index
e_0: initial void ratio
P'_c: effective preconsolidation pressure (if chosen)
OCR: overconsolidation ratio (if chosen)
Sublayers: number of divisions regarding each of the layers

2-2-2-3 General settings and geometry

g: gravitational acceleration
T: footing thickness
D: depth of footing base measured from the ground surface
D_w: depth to water table measured from the ground surface (use “-“ whenever water table is not encountered)
Footing type: Different footing types may be chosen (section 3-1).
B: width of the desired footings
L/B : length to width ratio

A schematic view of a footing and the corresponding parameters is illustrated in Figure 2-1.

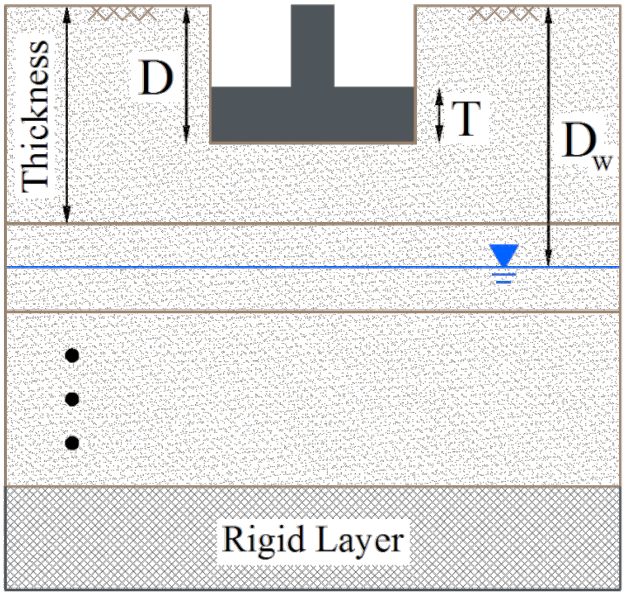

Figure 2-1 A schematic view of the footing, soil layers and the corresponding parameters

2-2-2-4 SHEAR FAILURE SETTINGS

This section contains settings related to the bearing capacity based on shear failure criterion.

Method: Currently five methods are employed; Eurocode, Hansen, Meyerhof, Terzaghi and Vesic.
Failure type: Failure type (General or Local) is determined by the user.
F.S.: Factor of safety. The allowable bearing capacity based on shear failure is obtained by dividing the ultimate bearing capacity by the factor of safety.
RF_ϕ: strength reduction factor – internal friction angle
RF_c: strength reduction factor – cohesion
Water effect: Effect of water table on bearing capacity is applied using methods suggested by Bowles and Das (section 3-2-3).
Large footing effect: By activating this option, large footing effect is applied for footing widths exceeding 2 [m].

2-2-2-5 SETTLEMENT SETTINGS

2-2-2-5-1 BASIC SETTINGS

Allowable settlement: In order to control the settlement of the footing and its superstructure, the allowable settlement (sum of elastic and consolidation settlements) is limited to this value.

Effective stratum depth: Effective depth in settlement calculation is determined by each of the following criteria:

- **Pressure isobars:** The depth at which the increase in stress due to foundation loading is reduced to I [%] of its value, is taken as the effective depth in settlement. This value is assumed 10 [%] by default. The mentioned calculations may be performed using each of the methods; Boussinesq, Westergaard and Approximate 2V:1H (section 3-3-1-1).
- **Multiple of footing width – xB:** Effective stratum depth is considered equal to an optional multiple of footing width.

2-2-2-5-2 ELASTIC SETTLEMENT SETTINGS

E_s method: Modulus of elasticity can be determined by three methods:

- **Weighted average:** The weighted average of modulus of elasticity is calculated in the effective stratum depth.
- **Graph:** This method is most beneficial when variation of modulus of elasticity by depth is available. Integration is performed on the specified graph over the effective zone of settlement and the mean value is obtained.
- **Manual:** Choosing this method, the user can alter the modulus of elasticity in each of the footings; "B"s and "L/B"s. Results achieved by the weighted average method are presented as default.

Excavation effect: In order to account for the excavation effect (especially in deep excavations) two methods can be used (section 3-3-4):

- **E_r/E_s:** The ratio of soil modulus of elasticity while reloading and in normally consolidated state. It is considered 1 by default.
- **U.W.(%):** The specified percentage of footing overburden pressure which is added to the bearing capacity with settlement criterion.

Influence factor: Elastic settlements are calculated by two methods; Steinbrenner and Das (section 3-3-2).

Rigidity: Two footing types, flexible and rigid are available. In rigid footings, settlement is assumed to be constant across the footing base. Flexible footings, on the other hand, are believed to settle more in center than in corners.

2-2-2-5-3 CONSOLIDATION SETTLEMENT SETTINGS

P'_c method: Effective preconsolidation pressure can be calculated by three methods:

- **Auto:** Calculation is automatically performed by the software.
- **P'_c:** Effective preconsolidation pressure is directly specified by the user.
- **OCR:** Effective preconsolidation pressure is obtained by multiplying initial effective overburden pressure (measured from the ground surface) by the OCR.

More details in section 3-3-3-1.

Loading effects: Options regarding the calculation of stress increase due to the footing load are determined.

- **Method:** Three methods are available; Boussinesq, Westergaard and Approximate 2V:1H.
- **Mode:** Mentioned calculations are performed in two modes.

a- Middle depth of the layer is considered as the layer’s average.

$$\Delta q = \Delta q_{middle}$$

b- Calculations are performed in top, middle and bottom of the layer and the result is obtained by the use of Simpson’s rule.

$$\Delta q = {}^{1}/_{6}\left(\Delta q_{top} + 4\Delta q_{middle} + \Delta q_{bottom}\right)$$

α_{cons}: The specified fraction of consolidation settlement which will be taken into account by user’s will.

Excavation effect: This option is related to the consideration of excavation effect and is enabled by default. Although this effect has been ignored in some references, it leads to more accurate results and is highly recommended to be used.

2-2-3 Results

As mentioned before, this menu presents the calculation results and is consisted of three sections:

2-2-3-1 Pressure isobars

Pressure isobars of a rectangular footing of dimensions $B \times L$, along and beneath line "a" (as in Figure 2-2) can be generated. As a result, the design engineer can easily determine the layers affecting the calculations.

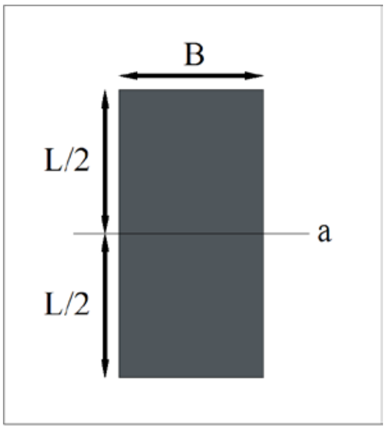

Figure 2-2 Location of pressure isobars beneath a footing

Method: Each of the methods; Boussinesq, Westergaard and Approximate 2V:1H, may be used.
B & L/B: Footing dimensions are determined.
Extension from sides: The magnitude of extension from sides (based on a multiple of the footing width) can be set.
Meshing: In order to control the precision of the pressure isobars, meshes may be finer or coarser. Finer meshes are more precise and of course more time-consuming.

By clicking on any arbitrary point within the generated shadings, the corresponding coordinates and the stress increase due to footing load (I [%]) are presented.

Note: In the Approximate 2V:1H method, Pressure isobars are limited to the points beneath the footing and are not extended from sides.

2-2-3-2 BEARING CAPACITY

The output graphs of the software are illustrated in this section. Variation of the following parameters are presented for various “B”s and “L/B”s defined by the user.

q_{all}: bearing capacity considering both shear failure and settlement
S_{q-all}: settlement due to the allowable bearing capacity
k_s: modulus of subgrade reaction

- In flexible footings, k_s is presented in center, corner and as an average across the footing. The average modulus of subgrade reaction is calculated as:

  $$k_{s-average} = \frac{4 \times k_{s-center} + k_{s-corner}}{5}$$

- k_s is constant across rigid footings.

Shear failure & Settlement: This tab is similar to q_{all} except that results obtained by each of the shear failure or settlement criteria can be presented and compared. Results may also be filtered by length to width ratio (L / B) so as to ease comparison.
Load-Settlement: Custom load-settlement graphs. By user’s will, a constant value for “q_{user}”, “B” or “L/B” is considered and the calculations are performed for all footings.

2-2-3-3 KS CONTOUR

Modulus of subgrade reaction contour is presented in this section and is available only when distinctions are made in the calculation of elastic and consolidation settlement, between all of the points across the footing. In other words, this section is disabled under the following circumstances:

- Footing is rigid.
- Das influence factor is used for elastic settlement calculation.
- Approximate 2V:1H method is used for the calculation of loading effects (*Δq*) in consolidation settlement.

B & L/B: Footing dimensions are determined.
Meshing: Meshing sizes can be set. Finer meshes are more precise and of course more time-consuming.

2-2-4 EXPORT

This tab is dedicated to the software outputs consisted of:

Detailed report: Fully detailed calculation reports with sufficient descriptions are generated and presented in PDF format.
Summary of results: Complete problem input and the calculation results including tables and graphs are exported to MS Excel format.

2-2-5 PROFILES

Software settings and profiles are defined in two tabs within this menu:

Settings: Software settings including active profile, user guides on parameters, etc., are accessible through this section.
Profiles: Contains commands relating to profiles, such as save, save as and delete.

Note: Descriptions regarding “Help”, “License”, “About” and “Units” are previously presented in section 2-1.

3 CALCULATION THEORIES

The lowest part of a structure that transmits its weight to the underlying soil or rock is the foundation. Foundations can be classified into two major categories - shallow foundations and deep foundations. Terzaghi (1943) defined a shallow foundation as one in which the depth is less than or equal to the width. However, research studies conducted since then have shown that in most shallow foundations, the depth can be as large as three to four times the width of the foundation. In the current manual, shallow foundations are referred to as foundations [1].

Foundations must be capable of carrying the loads from any engineered structure placed upon them without a shear failure in the underlying soil and with the resulting settlements being tolerable for that structure. **SO-Foundation does not take into account the footing self-weight in the calculations.**

3-1 Footing types

Footing types in the current software are spread, continuous and mat:

- **Spread footings:** Assuming the general shear failure to occur, failure surface extends to a height of T or D above the footing base, whichever is smaller.
- **Continuous footings:** These footings are spread across the whole structure and therefore, assuming the general shear failure to occur, failure surface extends to the ground surface. Footings supporting walls and embankments are categorized as continuous.
- **Mat footings:** A mat footing is a large footing, usually supporting walls as well as several columns in two or more rows. Failure surface in mat footings, similar to continuous footings, is assumed to extend to the ground surface.

A schematic view of the mentioned footing types is presented in Figure 3-1.

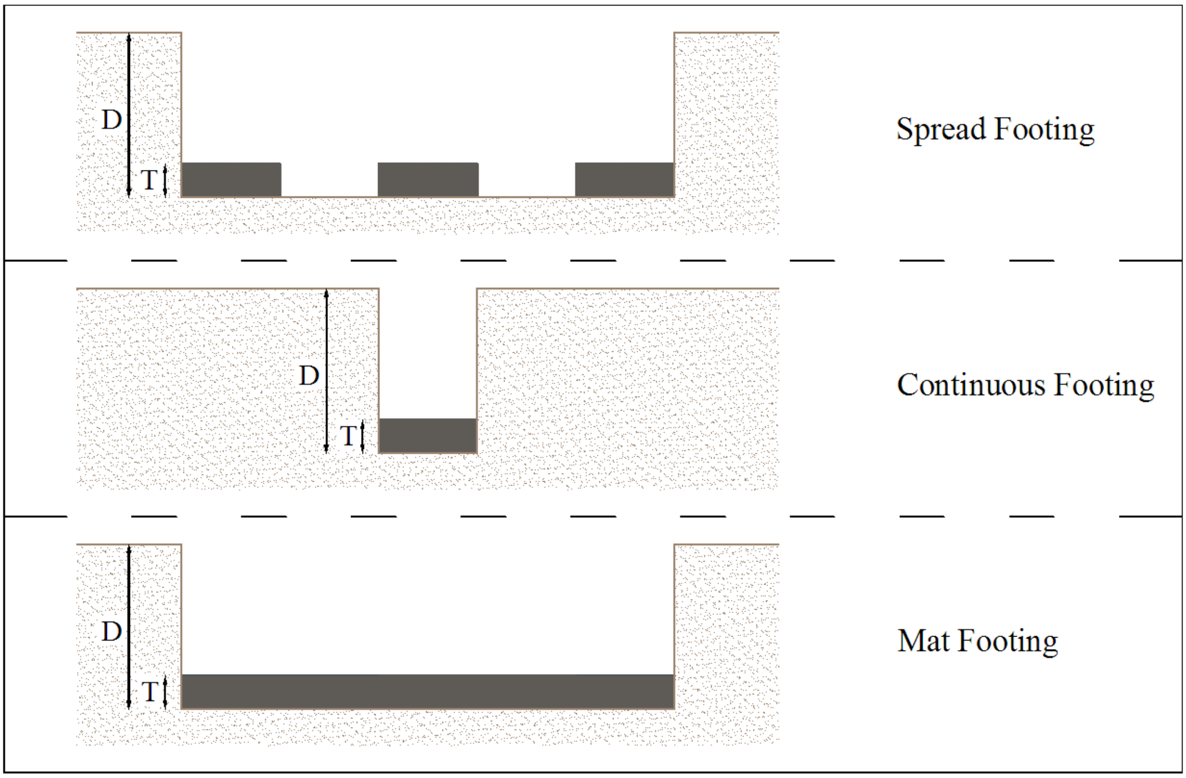

Figure 3-1 Schematic view of spread, continuous and mat footings

3-2 Shear failure criterion

3-2-1 Wedge zone and equivalent parameters

The first step in the calculation of shear failure is to determine the height of the wedge zone and afterwards, equivalent parameters. The initial wedge zone height equals:

$$H = 0.5B \times tan\left({}^{\pi}/_{4} + {}^{\phi}/_{2}\right)$$

Where ϕ, is the friction angle of the first underlying soil layer.

Calculating the weighted average of ϕ within the initial wedge zone height (H), results in a modified value for ϕ [2].

$$\phi = tan^{-1}\left(\frac{\sum_{i=1}^{n} H_i tan\phi_i}{\sum_{i=1}^{n} H_i}\right)$$

After multiple iterations, H and ϕ are obtained, which from now on are considered as the equivalent values. c and γ are then calculated as below:

$$c = \frac{\sum_{i=1}^{n} H_i c_i}{\sum_{i=1}^{n} H_i}$$

$$\gamma = \frac{\sum_{i=1}^{n} H_i \gamma_i}{\sum_{i=1}^{n} H_i}$$

3-2-2 Effect of failure type

Three types of failure may take place in the underlying soil; general shear failure, local shear failure and punching shear failure. Available equations and the current software calculations are valid for the first two.

The methods to apply factor of safety and strength reduction factors are explained in the following sections.

3-2-2-1 FACTOR OF SAFETY

Whenever general shear failure is assumed to occur, factor of safety is used.

$$q_{all-sh} = \frac{q_{ult-sh}}{F.S.}$$

Where:

q_{all-sh}: allowable bearing capacity considering shear failure criterion
q_{ult-sh}: ultimate bearing capacity considering shear failure criterion
$F.S.$: factor of safety

3-2-2-2 STRENGTH REDUCTION FACTORS

Whenever local shear failure is assumed to occur, strength reduction factors may be applied to the soil parameters (cohesion (c) and internal friction angle (ϕ)). The reduced values of c and ϕ are obtained by the following equations:

$$\phi = tan^{-1}\left(RF_{\phi}\,.\,tan\phi_{average}\right)$$
$$c = RF_{c}\,.\,c_{average}$$

Depending on engineering judgment, project importance and the acceptable risk, various combinations of factor of safety and strength reduction factors may be used. Therefore they can be easily defined and altered.

3-2-3 EFFECT OF WATER TABLE

The effective soil unit weight is used in the bearing capacity equations. If the water table is close to the foundation base, some modifications of the bearing capacity equations will be necessary. On this basis, Bowles and Das have separately assigned an effective water table depth. If the water table is located below this depth, it has no effect on the bearing capacity and vice versa.

Note: SO-Foundation does not allow the calculation of problems where the water table is above the footing base. Such situations cause construction problems and are rarely encountered. If desired, the user may assign the water table equal to the footing base and manually replace soil unit weight with the submerged unit weight, for the soil layers located above the footing base and below the water table.

3-2-3-1 Bowles's Equation

The effective depth equals the height of the wedge zone below the footing which is $H = 0.5B \times (\pi / 4 + \phi / 2)$. Effective unit weight considering the water table effect is calculated as [2]:

$$\gamma_e = (2H - d_w)\frac{d_w}{H^2}\gamma + \frac{\gamma'}{H^2}(H - d_w)^2$$

Where:

γ_e: effective unit weight considering the water table effect
H: height of wedge zone
d_w: depth to water table measured from the footing base
γ: unit weight
γ': submerged unit weight ($\gamma' = \gamma_{sat} - \gamma_{water}$)
"H" and "d_w" are illustrated in Figure 3-2.

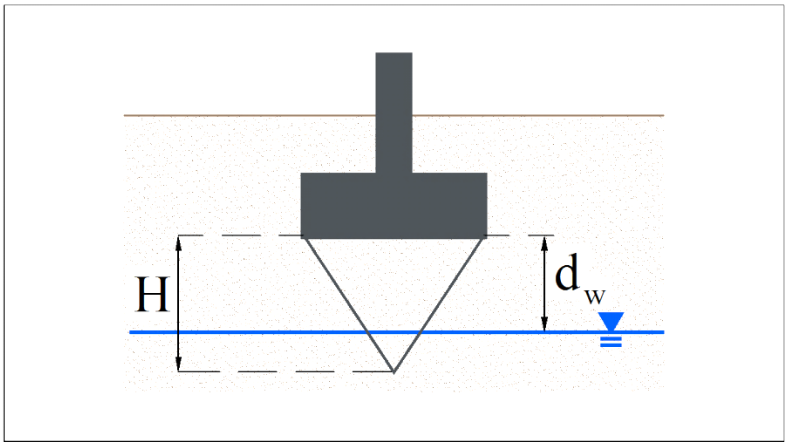

Figure 3-2 Parameters used for modifying soil unit weight considering water table effect

3-2-3-2 Das's Equation

The effective depth equals footing width. Effective unit weight considering the water table effect is calculated as [1]:

$$\gamma_e = \gamma' + \frac{d_w}{B}(\gamma - \gamma')$$

In the above equation, B is the footing width and the other parameters are the same as section 3-2-3-1.

3-2-4 BEARING CAPACITY EQUATIONS

General bearing capacity equations are as below:

$$q_{ult-sh} = cN_c s_c d_c i_c g_c b_c + \bar{q} N_q s_q d_q i_q g_q b_q + 0.5\gamma_e B N_\gamma s_\gamma d_\gamma i_\gamma g_\gamma b_\gamma$$

Where:

q_{ult-sh}: ultimate bearing capacity considering shear failure criterion
c: cohesion
$\overline{q}$: effective overburden pressure at the footing level
γ_e: effective unit weight considering the water table effect
B: footing width
$N_c, N_q \& N_\gamma$: bearing capacity factors
$s_c, s_q \& s_\gamma$: shape factors
$d_c, d_q \& d_\gamma$: depth factors
$i_c, i_q \& i_\gamma$: load inclination factors
$g_c, g_q \& g_\gamma$: ground inclination factors
$b_c, b_q \& b_\gamma$: base inclination factors

Not taking into account the effect of load, ground and base inclination, all of the mentioned factors are considered 1.

Various bearing capacity equations are presented similar to the current equation. Five methods are implemented in the software.

Table 3-1 Terzaghi's bearing capacity equation

$$q_{ult-sh} = cN_c s_c + \bar{q}N_q + 0.5\gamma_e B N_\gamma s_\gamma$$

Cohesion	Overburden pressure	Foundation width
$\phi = 0 \rightarrow N_c = 1.5\pi + 1$ $\phi > 0 \rightarrow N_c = (N_q - 1)\cot\phi$	$N_q = \dfrac{a^2}{2\cos^2\left(\pi/4 + \phi/2\right)}$ $a = e^{\left(0.75\pi - \phi/2\right)\tan\phi}$	$* N_\gamma = \dfrac{2(N_q + 1)\tan\phi}{1 + 0.4\sin(4\phi)}$

Shape	Strip	Circular	Square		Shape	Strip	Circular	Square
s_c	1.0	1.3	1.3	-----	s_γ	1.0	0.6	0.8

*The equation is a simplified formula for N_γ. It produces values within about 10 [%] of Terzaghi's values [3].

Table 3-2 Meyerhof's bearing capacity equation

$$q_{ult-sh} = cN_c s_c d_c + \bar{q}N_q s_q d_q + 0.5\gamma_e B N_\gamma s_\gamma d_\gamma$$

Cohesion	Overburden pressure	Foundation width
$\phi = 0 \rightarrow N_c = \pi + 2$ $\phi > 0 \rightarrow N_c = (N_q - 1)\cot\phi$	$N_q = e^{\pi\tan\phi}\tan^2\left(\pi/4 + \phi/2\right)$	$N_\gamma = (N_q - 1)\tan(1.4\phi)$
$s_c = 1 + 0.2K_p\dfrac{B}{L}$	$\phi = 0 \rightarrow s_q = 1$ $\phi > 0 \rightarrow s_q = 1 + 0.1K_p\dfrac{B}{L}$	$\phi = 0 \rightarrow s_\gamma = 1$ $\phi > 0 \rightarrow s_\gamma = 1 + 0.1K_p\dfrac{B}{L}$
$d_c = 1 + 0.2\sqrt{K_p}\dfrac{D}{B}$	$\phi = 0 \rightarrow d_q = 1$ $\phi > 0 \rightarrow d_q = 1 + 0.1\sqrt{K_p}\dfrac{D}{B}$	$\phi = 0 \rightarrow d_\gamma = 1$ $\phi > 0 \rightarrow d_\gamma = 1 + 0.1\sqrt{K_p}\dfrac{D}{B}$

$$* K_p = \tan^2\left(\pi/4 + \phi/2\right)$$

Table 3-3 Hansen's bearing capacity equation

$q_{ult-sh} = \begin{cases} (\pi+2)c \times (1+s'_c+d'_c)+\bar{q} & \phi = 0 \\ cN_c s_c d_c + \bar{q} N_q s_q d_q + 0.5\gamma_e B N_\gamma s_\gamma d_\gamma & \phi > 0 \end{cases}$		
Cohesion	Overburden pressure	Foundation width
$N_c = (N_q - 1)\cot\phi$	$N_q = e^{\pi\tan\phi}\tan^2\left(\pi/4 + \phi/2\right)$	$N_\gamma = 1.5(N_q - 1)\tan\phi$
$s_c = 1 + \frac{N_q}{N_c}.\frac{B}{L}$ $s'_c = 0.2\frac{B}{L}$	$s_q = 1 + \frac{B}{L}.\sin\phi$	$s_\gamma = \max\left(1 - 0.4\frac{B}{L}, 0.6\right)$
$d_c = 1 + 0.4k$ $d'_c = 0.4k$	$d_q = 1 + 2\tan\phi\,(1 - \sin\phi)^2 k$	$d_\gamma = 1$
	$* k = \begin{cases} D/B & D/B \le 1 \\ \tan^{-1}(D/B) & D/B > 1 \end{cases}$ Note that "k" has to be in radians.	

Table 3-4 Vesic's bearing capacity equation

$q_{ult-sh} = cN_c s_c d_c + \bar{q} N_q s_q d_q + 0.5\gamma_e B N_\gamma s_\gamma d_\gamma$		
Cohesion	Overburden pressure	Foundation width
$\phi = 0 \rightarrow N_c = \pi + 2$ $\phi > 0 \rightarrow N_c = (N_q - 1)\cot\phi$	$N_q = e^{\pi\tan\phi}\tan^2\left(\pi/4 + \phi/2\right)$	$N_\gamma = 2(N_q + 1)\tan\phi$
$s_c = 1 + \frac{N_q}{N_c}.\frac{B}{L}$	$s_q = 1 + \frac{B}{L}.\tan\phi$	$s_\gamma = \max\left(1 - 0.4\frac{B}{L}, 0.6\right)$
$d_c = 1 + 0.4k$	$d_q = 1 + 2\tan\phi\,(1 - \sin\phi)^2 k$	$d_\gamma = 1$
	$* k = \begin{cases} D/B & D/B \le 1 \\ \tan^{-1}(D/B) & D/B > 1 \end{cases}$ Note that "k" has to be in radians.	

Table 3-5 Eurocode's bearing capacity equation

$q_{ult-sh} = cN_c s_c + \bar{q}N_q s_q + 0.5\gamma_e BN_\gamma s_\gamma$		
Cohesion	Overburden pressure	Foundation width
$\phi = 0 \rightarrow N_c = \pi + 2$ $\phi > 0 \rightarrow N_c = (N_q - 1)\cot\phi$	$N_q = e^{\pi\tan\phi}\tan^2\left({}^{\pi}/_{4} + {}^{\phi}/_{2}\right)$	$N_\gamma = 2(N_q - 1)\tan\phi$
$s_c = \begin{cases} 1 + 0.2\,{}^{B}/_{L} & \phi = 0 \\ \dfrac{s_q N_q - 1}{N_q - 1} & \phi > 0 \end{cases}$	$s_q = 1 + \frac{B}{L}.\sin\phi$	$s_\gamma = 1 - 0.3\frac{B}{L}$

3-2-5 LARGE FOOTING EFFECT

There is some evidence, from using small footings up to about 1 [m] for *B*, that the BN_γ term does not increase the bearing capacity without bound, and for very large values of *B*, both Vesic (1969) and De Beer (1965) suggest that the limiting value of q_{ult-sh} approaches that of a deep foundation. It is suggested to use the following reduction factor [2]:

$$r_\gamma = 1 - 0.25\,log\left(\frac{B}{K}\right) \quad ; \quad B \geq 2\ [m]$$

Where:

r_γ: reduction factor regarding footing width

B: footing width

K: Equals 2 for SI and Metric units. It may also be converted to other units as appropriate.

3-3 Settlement criterion

Apart from shear failure criterion, the footing settlement (including elastic and consolidation) has to be controlled not to exceed the allowable value.

3-3-1 Effective stratum depth

Effective stratum depth is calculated considering the following criteria:

3-3-1-1 Pressure isobars

In this method the depth at which the increase in stress due to foundation loading is reduced to a specific percentage of its value (by user's will), is taken as the effective stratum depth. The following three methods are used in order to perform the mentioned calculations:

a- Approximate 2V:1H method

This method has the great advantage of simplicity. If the stress zone is defined by a 2:1 slope, the pressure increase (Δq) at a depth (Z) beneath the load area is:

$$\Delta q = \frac{q_0 \times B \times L}{(B+Z) \times (L+Z)}$$

Where q_0 is the initial pressure at the footing level.

b- Boussinesq's method

One of the most common methods for obtaining Δq is the Boussinesq equation based on the theory of elasticity. Boussinesq's equation considers a point load on the surface of a semi-infinite, homogeneous, isotropic, weightless and elastic half-space.

The method that is applicable to square or rectangular bases (and round ones converted to equivalent squares) is to use the Boussinesq equation integrated over a rectangle of dimensions $B \times L$. The equation given by Newmark applicable beneath the corner of an area $B \times L$ is:

$$\Delta q = q_0 \times {}^{1}/_{4\pi} \left[\frac{2MN\sqrt{V}}{V+V_1} . \frac{V+1}{V} + tan^{-1}\left(\frac{2MN\sqrt{V}}{V-V_1}\right)\right]$$

$$M = \frac{B}{Z} \;\; ; \;\; N = \frac{L}{Z} \quad (\Delta q = q_0 \;\; for \;\; Z = 0)$$

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

$$V_1 = (MN)^2$$

When $V_1 > V$, the tan^{-1} term is negative and it is necessary to add π.

c- Westergaard's method

When the soil mass consists of layered strata of fine and coarse materials, as beneath a road pavement, or alternating layers of clay and sand, some authorities are of the opinion the Westergaard equations give a better estimate of the stress (Δq). The integration of stresses for a rectangle *of* $B \times L$ gives the following equation for the corner of a rectangular area as:

$$\Delta q = \frac{q_0}{2\pi} tan^{-1}\left(\frac{MN}{\sqrt{a}(M^2 + N^2 + a)^{1/2}}\right)$$

Where:

M & N: are previously defined in Boussinesq's equation

a: $\frac{1-2\nu}{2-2\nu}$

The tan^{-1} term is in radians.

3-3-1-2 Multiple of footing width

Effective stratum depth is calculated as a user-defined multiple of the footing depth.

Note:

1- User may define a rigid layer if encountered. This can be done by choosing "Rigid" as the USCS code. Consequently, the effective stratum depth is calculated by one the mentioned criteria and is compared with the rigid layer. The minimum is considered as the final effective depth.

2- Layers have to be specified to a significant depth below footing. Therefore, increase in footing width and as a result increase in effective stratum depth, especially in settlement calculations, does not lead to any limitations in the software output. **The last defined layer is considered infinite.**

3-3-2 ELASTIC SETTLEMENT

Elastic or immediate settlement takes place either as the load is applied or within a time period of about 7 days. Immediate settlement analyses are used for all fine-grained soils including silts and clays with a degree of saturation less than 90 [%] (*S<90%*) and for all coarse-grained soils with a large coefficient of permeability [2]. Various methods have been presented by researchers in order to calculate elastic settlement. Two of them are applied in the software and defined in the following sections.

3-3-2-1 DAS'S EQUATION

a- Flexible footing [4]

$$S_e = \frac{qB}{E_s}(1-\nu^2)\frac{\alpha}{2}$$ Settlement in the corner of a flexible footing - Das

$$S_e = \frac{qB}{E_s}(1-\nu^2)\alpha$$ Settlement in the center of a flexible footing - Das

Where:

α: $1/_{\pi}\left[ln\left(\frac{\sqrt{1+m^2}+m}{\sqrt{1+m^2}-m}\right)+m\,.\,ln\left(\frac{\sqrt{1+m^2}+1}{\sqrt{1+m^2}-1}\right)\right]$

B: footing width

L: footing length

m : $L/_B$

q: magnitude of the exerted pressure

E_s: soil modulus of elasticity when normally consolidated

ν: Poisson's ratio

b- Rigid footing [4]

$$S_e = \frac{qB}{E_s}(1-\nu^2)\alpha_r$$ Settlement in a rigid footing - Das

All of the above parameters are previously defined in "flexible footing" mode. Figure 3-3 shows the variation of α_r with $L/_B$.

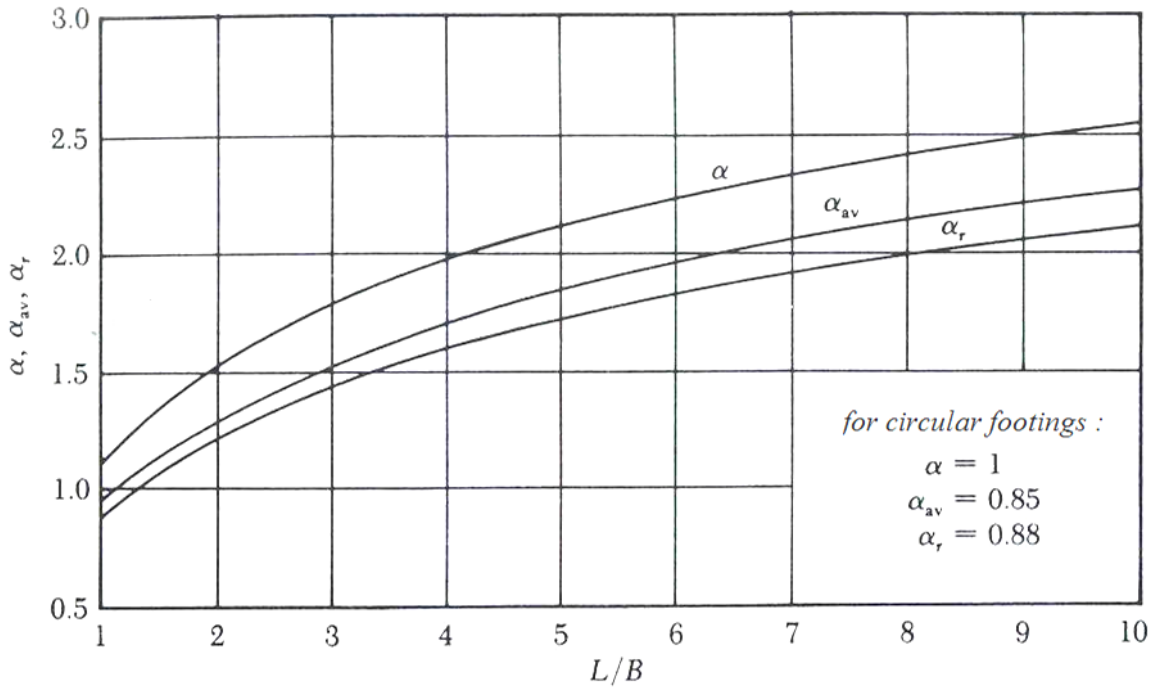

Figure 3-3 Variation of α and α_r with $^L/_B$ [4]

As can be concluded from the above equations, settlement in the center of a flexible footing is considered two times the corner. In rigid footings, however; the settlement is assumed to be equal all across the footing.

3-3-2-2 STEINBRENNER'S EQUATION

a- Flexible footing

$$S_e = \frac{qB'}{E_s}(1-\nu^2)I_{sf}I_F m$$ Settlement in a flexible footing - Steinbrenner

Where:

q, E_s & ν: are previously defined

B': width of contributing rectangle

I_{sf}: Steinbrenner's influence factor in a flexible footing which is calculated as $I_{sf} = I_1 + \frac{1-2\nu}{1-\nu} I_2$ (I_1 and I_2 are defined later)

I_F: Fox's influence factor which is shown in Figure 3-4

m: number of corners contributing to settlement

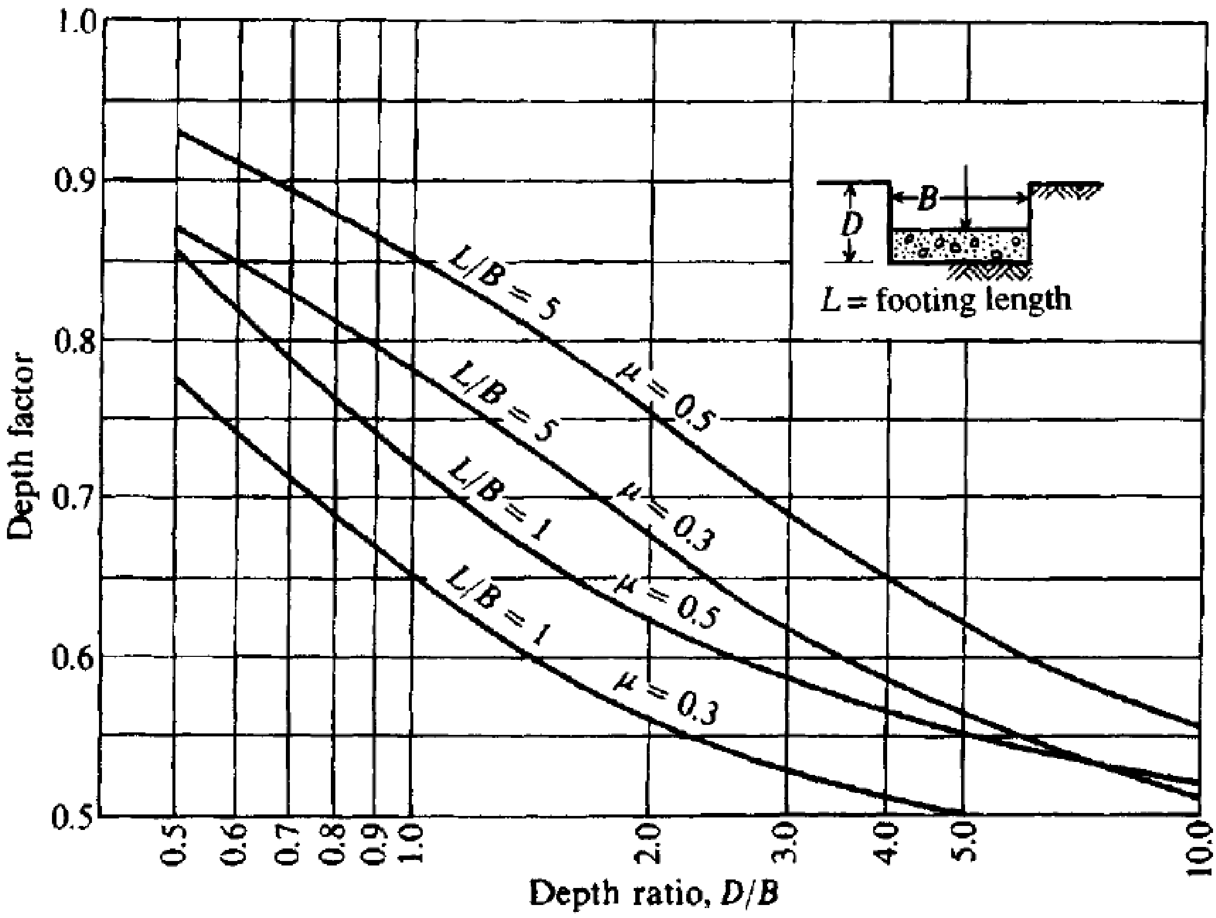

Figure 3-4 Fox's influence factor for footing at depth D [2]

b- <u>Rigid footing</u>

$$S_e = \frac{qB'}{E_s}(1-\nu^2)I_{sr}I_F m \qquad \text{Settlement in a rigid footing - Steinbrenner}$$

All of the parameters are the same as "flexible footing" mode, except that $I_{sr} = 0.93 I_{sf}$. In the last given equation, I_{sf} has to be calculated in center of the footing ($m = 4;\ B' = B\,/\,2;\ \ L' = L\,/\,2$). I_1 and I_2 are calculated as:

$$I_1 = {}^{1}\!/_{\pi}\left[M\ \ ln\frac{\left(1+\sqrt{M^2+1}\right)\sqrt{M^2+N^2}}{M\left(1+\sqrt{M^2+N^2+1}\right)} + ln\frac{\left(M+\sqrt{M^2+1}\right)\sqrt{1+N^2}}{M+\sqrt{M^2+N^2+1}}\right]$$

$$I_2 = {}^{N}\!/_{2\pi}\, tan^{-1}\left(\frac{M}{N\sqrt{M^2+N^2+1}}\right)$$

$$M = \frac{L'}{B'} \quad ; \quad N = \frac{Z}{B'}$$

$$B' = \frac{B}{2}\ \ for\ center;\ \ = B\ \ for\ corner$$

$$L' = \frac{L}{2}\ \ for\ center;\ \ = L\ \ for\ corner$$

As can be seen in the above equations:

B′: width of contributing rectangle

L′: length of contributing rectangle

Z: effective depth in settlement calculations

Note that tan^{-1} term is in radians.

In order to avoid confusion in the calculation reports, *M* and *N* are replaced with M_{St} and N_{St}.

3-3-3 Consolidation settlement

Consolidation settlement (S_c) is a time-dependent process that occurs due to the expulsion of excess pore water pressure in saturated clayey soils below the groundwater table and is created by the increase in stress caused by the foundation load. It is calculated as follows:

a- Normally consolidated clay

$$S_c = \frac{C_c H_c}{1+e_0} log \frac{P'_0 + \Delta q}{P'_0}$$

b- Overconsolidated clay ($P'_0 + \Delta q < P'_c$)

$$S_c = \frac{C_s H_c}{1+e_0} log \frac{P'_0 + \Delta q}{P'_0}$$

c- Overconsolidated clay ($P'_0 < P'_c < P'_0 + \Delta q$)

$$S_c = \frac{C_s H_c}{1+e_0} log \frac{P'_c}{P'_0} + \frac{C_c H_c}{1+e_0} log \frac{P'_0 + \Delta q}{P'_c}$$

Where:

C_c: compression index
C_s: swelling index
H_c: thickness of the clay layer
e_0: initial void ratio
P'_0: initial effective overburden pressure
Δq: average increase in effective pressure on the clay layer caused by the foundation
P'_c: effective preconsolidation pressure

Note:

1- Depending on the situation and the engineering judgment, P'_0 and P'_c can be calculated by 9 methods that are described in section 3-3-3-1.

2- In the situations where the consolidating layer is close to the footing base, according to the significant changes in stress increase (*Δq*), the layer has to be divided to sublayers so as to minimize the calculation errors. In SO-Foundation, this can be done by defining the number of sublayers in each layer.
By gradually increasing the number of sublayers, the over-estimated bearing capacity approaches the actual bearing capacity and the importance of the sublayers is realized.

3- The user can consider a specific percentage of the consolidation settlement using the α_{cons} option.

3-3-3-1 DETERMINATION OF P'_0 AND P'_c

3-3-3-1-1 DETERMINATION OF P'_0

Depending on the excavation effect and the footing type (Spread, Continuous & Mat), there are 3 modes for the calculation of initial effective overburden pressure (P'_0).

Table 3-6 Various modes for the determination of P'_0

Mode	Excavation effect	Footing type
a	False	All types
b	True	Spread
c	True	Continuous & Mat

a- Mode a

As can be seen in Table 3-6, the excavation effect is ignored in this mode. Thus, P'_0 is calculated from the ground surface. Although some references have used such assumptions, this approach is not recommended.

b- Mode b

This approach considers the excavation effect and is based on the assumption that the footing dimensions are small compared to the excavation dimensions. As a result, P'_0 is calculated from the footing base.

c- Mode c

This approach also considers the excavation effect and is based on the assumption that the footing (Continuous & Mat) dimensions are identical to the excavation dimensions. Therefore, stress decrease due to excavation, can be calculated using each of the stress distribution methods (previously defined in section 3-3-1-1).

3-3-3-1-2 Determination of P'_c

The following three approaches are available for the determination of effective preconsolidation pressure (P'_c):

a- Auto

This method can be used in a wide range of practical problems and corresponds to the situation where the soil is normally consolidated. It is assumed that P'_c is due to the existing soil layers and does exceed it.

b- P'_c

P'_c regarding each of the layers is directly defined by the user.

c- OCR

In this approach, the initial effective overburden pressure is **measured from the ground surface** and is multiplied by the user-defined OCR; the result equals P'_c.

3-3-3-1-3 SUMMARY OF P'_0 AND P'_c DETERMINATION METHODS

All of the methods described in sections 3-3-3-1-1and 3-3-3-1-2 are summarized and illustrated in Figure 3-5.

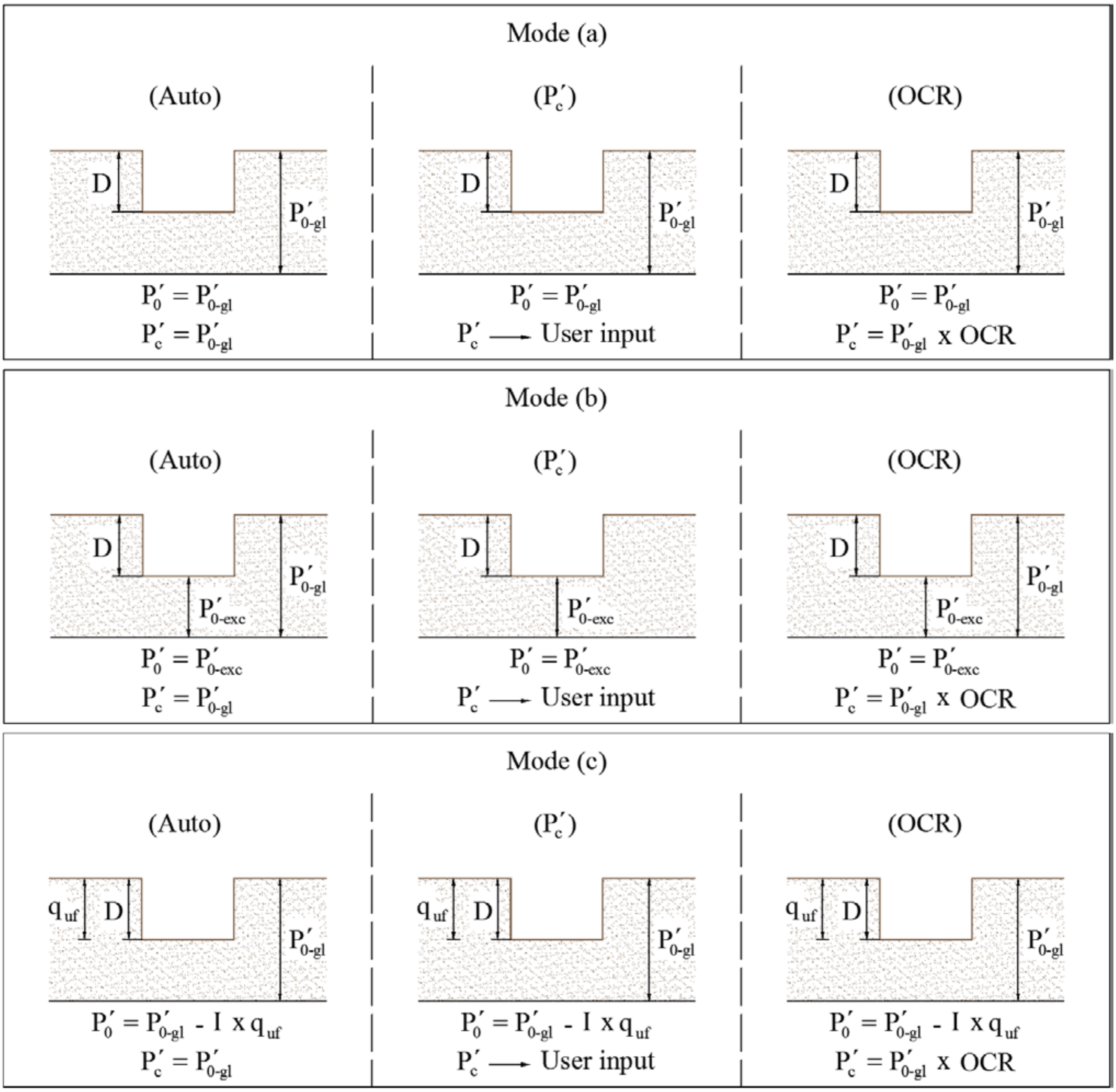

Figure 3-5 Assumptions and the calculation of P'_0 and P'_c according to each of the methods

3-3-4 Excavation effect

Excavations have an increasing effect on the bearing capacity considering settlement criterion. The mentioned effect is applied by the use of P'_c and C_s in the consolidation settlement. In case of elastic settlement, the following two methods are available in the software:

Note: Whenever the excavation effect is ignored in consolidation settlement (Mode a which is previously defined in section 3-3-3-1-1), options regarding excavation effect in elastic settlement (as will be discussed below) should not be used. These two are in contradiction.

a- E_r/E_s

The most important factor influencing the compressibility of granular soils is the stress history, or more precisely, the strain history of the deposit. If the sand deposit has been previously loaded or strained, a large decrease in compressibility (increase in equivalent modulus), and therefore a large decrease in settlement, results.

The normally consolidated compressibility is at least 5 times greater, with typical values between 8 and 16 times, and it may even approach 30 times greater than the overconsolidated or prestrained compressibility. This occurs because if a sand is loaded in compression, for example in a triaxial test, and somewhere before failure the sample is unloaded and then reloaded, the unload/reload modulus (E_r) is much steeper than the initial tangent modulus (E_t). This effect is greater in a loose sand. The unload/reload modulus in very loose sand can easily be 5 to 30 times greater than the initial tangent modulus [5].

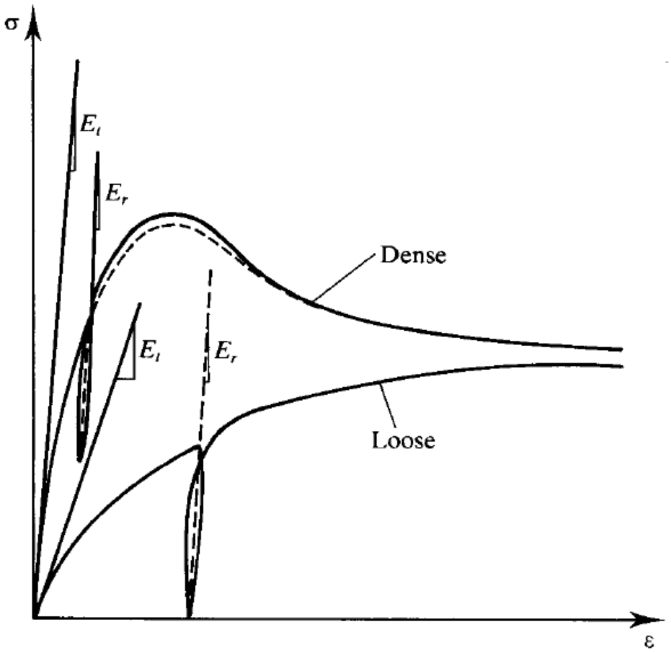

Figure 3-6 Stress-strain curves for a typical sand in loose and dense states [5]

As can be seen in Figure 3-6, modulus of elasticity of the overconsolidated granular soil before approaching the preconsolidation pressure (P'_c), is higher than the normally consolidated state.

SO-Foundation allows for arbitrary values of (E_r/E_s) depending on the soil layers. According to the above, before approaching preconsolidation overburden pressure and in higher stresses, E_r and E_s have to be used, respectively.

$$if\ q \begin{cases} \leq P'_c & \rightarrow E = E_r \\ > P'_c & \rightarrow E = E_s \end{cases}$$

b- U.W. (%)

Some engineers add a specified percentage of the footing overburden pressure to the bearing capacity considering settlement criterion. The percentage varies depending on the engineering judgment (based on soil layers, site conditions and the project importance) and is added with the assumption that the footing does not settle before approaching the preconsolidation overburden pressure, which is not correct. Therefore, this option has to be used with caution.

3-4 Allowable bearing capacity

After determination of bearing capacity considering both shear failure and settlement criteria, the minimum is reported as the allowable bearing capacity.

$$q_{all} = min(q_{all-sh}, q_{set})$$

Where:

q_{all}: allowable bearing capacity
q_{all-sh}: allowable bearing capacity considering shear failure criteria
q_{set}: allowable bearing capacity considering settlement criteria

3-5 Settlement due to the allowable bearing capacity

After the allowable bearing capacity is determined, the corresponding settlement is calculated and reported as S_{q-all}.

3-6 Modulus of subgrade reaction

The modulus of subgrade reaction is a conceptual relationship between soil pressure and deflection that is widely used in the structural analysis of footings and is calculated by dividing the minimum of q_{ult-sh} and q_{set} by its corresponding settlement.

- In flexible footings, k_s is presented in center, corner and as an average across the footing.

$$k_{s-center} = \frac{min(q_{ult-sh}, q_{set})}{S_{ks-center}}$$

$$k_{s-corner} = \frac{min(q_{ult-sh}, q_{set})}{S_{ks-corner}}$$

$$k_{s-average} = \frac{4 \times k_{s-center} + k_{s-corner}}{5}$$

- k_s is constant across rigid footings.

$$k_{s-rigid} = \frac{min(q_{ult-sh}, q_{set})}{S_{ks-rigid}}$$

4 Contact us

Feel free to contact us regarding any criticism, recommendation or additional information.

1- Visit www.soiloffice.com/ContactUs
2- Send an e-mail to info@soiloffice.com
3- Call (+98) 912 313 4107 – Emad Zargaran.
   (Also available on WhatsApp)
4- Call "Emad.Zargaran" via Skype.

5 References

[1] B. M. Das, Principles of Foundation Engineering, 7th ed., Stamford: Cengage Learning, 2010.

[2] J. E. Bowles, Foundation Analysis and Design, 5th ed., New York: McGrow-Hill, 1997.

[3] D. P. Coduto, Foundation Design: Principles and practices, 2nd ed., New Jersey: Prentice Hall, 2001.

[4] ب. ام. داس، اصول مهندسی ژئوتکنیک، ویرایش دوم، جلد ۲، تهران: موسسه انتشارات پارس آئین، ۱۳۸۳.

[5] R. D. Holtz, "Stress Distribution and Settlement of Shallow Foundations," in *Foundation Engineering Handbook*, 2nd ed., H. Fang, Ed., New York, Chapman & Hall, 1991, pp. 166-222.

6 List of symbols

Symbol	Description
a	*one of the parameters used in Westergaard's method which is a function of Poisson's ratio*
b_c, b_q & b_γ	*base inclination factors*
B	*footing width*
B'	*width of contributing rectangle (in each of the methods; Boussinesq, Westergaard and Steinbrenner)*
c	*cohesion*
C_c	*compression index*
C_s	*swelling index*
d_c, d_q & d_γ	*depth factors*
d'_c	*depth factor in Hansen's bearing capacity equation when ϕ=0*
d_w	*depth to water table measured from the footing base*
D	*depth to footing base measured from the ground surface*
D_w	*depth to water table measured from the ground surface*
e_0	*initial void ratio*
E_r	*soil modulus of elasticity while reloading*
E_s	*soil modulus of elasticity when normally consolidated*
$F.S.$	*factor of safety*
g	*gravitational acceleration*
g_c, g_q & g_γ	*ground inclination factors*
H	*height of wedge zone*
i_c, i_q & i_γ	*load inclination factors*
I	*ratio of stress increase (at a specific point below the footing base) due to loading at the footing level, to the initial value in percent*
I_1 & I_2	*parameters used to calculate Steinbrenner's influence factor*
I_{center}	*the "I" parameter in a specific depth below the center of a flexible footing*
I_{corner}	*the "I" parameter in a specific depth below the corner of a flexible footing*
I_F	*Fox's influence factor*
I_{rigid}	*the "I" parameter in a specific depth below a rigid footing*
I_{sf}	*Steinbrenner's influence factor in a flexible footing*
I_{sr}	*Steinbrenner's influence factor in a rigid footing*
$k_{s-average}$	*average of modulus of subgrade reaction in a flexible footing*
$k_{s-center}$	*modulus of subgrade reaction at the center of a flexible footing*
$k_{s-corner}$	*modulus of subgrade reaction at the corner of a flexible footing*
$k_{s-rigid}$	*modulus of subgrade reaction in a rigid footing*
L	*footing length*
L'	*length of contributing rectangle (in each of the methods; Boussinesq, Westergaard and Steinbrenner)*
M_B & N_B	*parameters used in Boussinesq's method*
M_{St} & N_{St}	*parameters used in Steinbrenner's method*
M_W & N_W	*parameters used in Westergaard's method*
N_c, N_q & N_γ	*bearing capacity factors*
OCR	*overconsolidation ratio*
P'_0	*initial effective overburden pressure*
P'_c	*effective preconsolidation pressure*
$\bar{q}$	*effective overburden pressure at the footing level*
q_{all}	*allowable bearing capacity*
q_{all-sh}	*allowable bearing capacity considering shear failure criteria*

Symbol	Description
q_{set}	*allowable bearing capacity considering settlement criteria*
$q_{uf(\%)}$	*percentage of the footing overburden pressure that according to the engineer's judgment, is added to the bearing capacity with settlement criteria*
q_{uf}	*footing overburden pressure*
q_{ult-sh}	*ultimate bearing capacity considering shear failure criteria*
r_{γ}	*large footing reduction factor*
RF_c	*strength reduction factor - cohesion*
RF_{ϕ}	*strength reduction factor – internal friction angle*
s_c, s_q & s_{γ}	*shape factors*
s'_c	*shape factor in Hansen's bearing capacity equation when ϕ=0*
S	*total footing settlement*
S_c	*consolidation settlement of the footing*
S_e	*elastic settlement of the footing*
$S_{ks-center}$	*settlement value used to calculate modulus of subgrade reaction in the center of a flexible footing*
$S_{ks-corner}$	*settlement value used to calculate modulus of subgrade reaction in the corner of a flexible footing*
$S_{ks-rigid}$	*settlement value used to calculate modulus of subgrade reaction in a rigid footing*
S_{q-all}	*footing settlement induced by allowable bearing capacity*
T	*footing thickness*
$U.W.(\%)$	*percentage of the footing overburden pressure that according to the engineer's judgment, is added to the bearing capacity with settlement criteria*
$USCS$	*Unified Soil Classification System*
Z	*effective depth in settlement calculations*
$Z_{I(\%)}$	*effective depth in settlement calculations - pressure isobars criteria*
Z_{Rigid}	*depth to the rigid layer measured from the footing base*
Z_{xB}	*effective depth in settlement calculations – multiple of footing width*
α	*influence factor in Das's method in flexible footings*
α_{cons}	*fraction of the consolidation settlement which will be taken into account by user's will*
α_r	*influence factor in Das's method in rigid footings*
Δq_{center}	*stress increase in a specific depth below the center of a flexible footing*
Δq_{corner}	*stress increase in a specific depth below the corner of a flexible footing*
Δq_{rigid}	*stress increase in a specific depth below a rigid footing*
ϕ	*internal friction angle*
γ	*unit weight*
γ'	*submerged unit weight*
γ_e	*effective unit weight considering the water table effect*
γ_{uf}	*average of soil layers' unit weight above the footing level*
γ_{water}	*water unit weight*
ν	*Poisson's ratio*