NEMETSCHEK
Scia

Stade des Alpes - Grenoble
Etudes et Techniques Internationales (ETI)

Theory

Pad Foundations according to EN 1997-1

Scia
Engineer

Table of contents

Version Information

Welcome to the Theoretical Background for Pad Foundations according to EN 1997-1.

This document provides background information regarding the Pad Foundation checks.

Version info

Document Title	Theoretical Background – Pad Foundations according to EN 1997-1
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Introduction

In this Theoretical Background, in depth information is given regarding the Pad Foundation checks according to EN 1997-1.

The checks are executed according to the following codes:

EN 1997-1:2004
Eurocode 7: Geotechnical design – Part 1: General rules
CEN, 2004.

EN 1997-1:2004/AC:2009 Correction Sheet
Eurocode 7: Geotechnical design – Part 1: General rules
CEN, 2009.

The annex to this Theoretical Background specifies the calculation of the stiffness factors of a Pad Foundation.

Pad Foundation Check

In this chapter the different steps of the Pad Foundation Checks are specified.

First of all, the required safety and resistance factors need to be determined depending on the chosen Design Approach.

Using these safety factors, the vertical design loading $\mathbf{V_d}$, horizontal design loading $\mathbf{H_d}$ and effective geometry of the pad are determined.

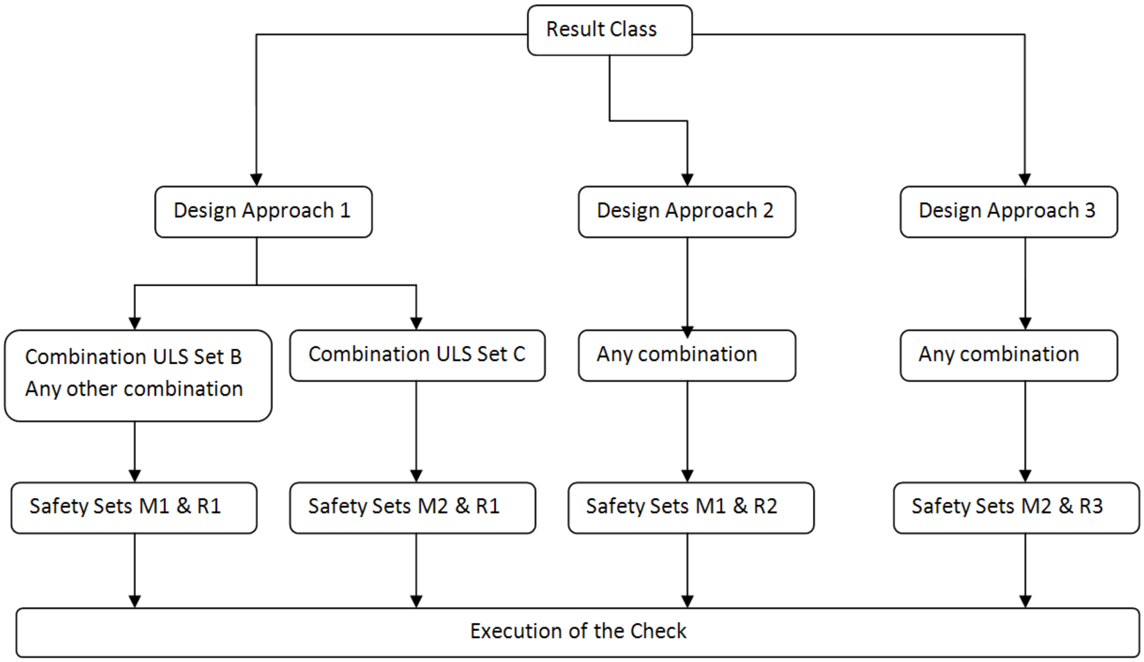
Based on this effective geometry the different checks are executed.

The above steps are detailed in the following paragraphs.

Determination of Design Values

The Pad Foundation check is executed for a Result Class.

Depending on the **Design Approach** set in the National Annex Setup, the sets of safety factors are read from the setup as follows:



- For **Design Approach 1** the safety sets depend on the combination type.
  For combinations of type **EN-ULS (STR/GEO) Set B** sets **M1** & **R1** are used.

  For combinations of type **EN-ULS (STR/GEO) Set C** sets **M2** & **R1** are used.
  For any other combination sets **M1** & **R1** are used.
- For **Design Approach 2**, in all cases sets **M1** & **R2** are used.
- For **Design Approach 3**, in all cases sets **M2** & **R3** are used.

For detailed information regarding the different combination types, reference is made to EN 1990 [Ref.4]

In case the functionality 'Subsoil' is activated in the Project Data
a new class 'GEO' is generated automatically for use in the Pad Foundation check.

This class contains all combinations of the following types:
EN-ULS (STR/GEO) Set B
EN-ULS (STR/GEO) Set C

A Result Class may also contain load cases or non-linear combinations. These are seen as 'Any combination' for the check.

For Design Approach 1 the class for which the check is executed needs to contain at least one combination of each of the following types:
EN-ULS (STR/GEO) Set B
EN-ULS (STR/GEO) Set C

In case the class for which the user wishes to execute the check does not comply with this requirement, the check is not executed and a warning is shown instead.

For Design Approaches 2 & 3 there is no requirement for the content of the class.

Using the above information, the design values for the soil properties are determined:

Design Value	Formula
φ'_d	$= \text{atan}\left[\frac{\tan(\varphi')}{\gamma_{\varphi'}}\right]$ With: φ' read from Subsoil Library $\gamma_{\varphi'}$ read from National Annex Setup
c'_d	$= \frac{c'}{\gamma_{c'}}$ With: c' read from Subsoil Library $\gamma_{c'}$ read from National Annex Setup
c_{ud}	$= \frac{c_u}{\gamma_{cu}}$ With: c_u read from Subsoil Library γ_{cu} read from National Annex Setup
γ'_d	$= \frac{\gamma'}{\gamma_\gamma}$ With: γ' specific weight read from Library γ_γ read from National Annex Setup
$\gamma_{Backfill,d}$	$= \frac{\gamma_{Backfill}}{\gamma_\gamma}$ With: $\gamma_{Backfill}$ weight read from Pad foundation input Data γ_γ read from National Annex Setup

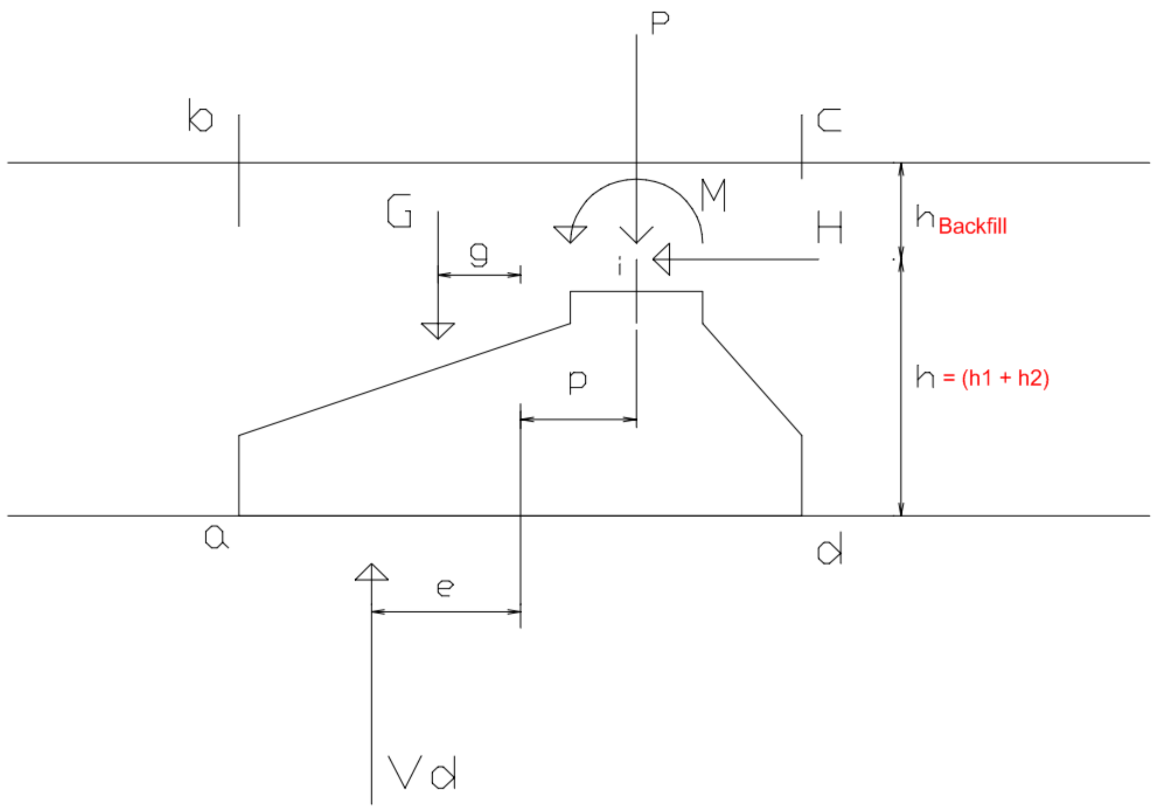
A final safety factor which needs to be determined concerns the safety factor for the weight of the pad foundation and the backfill material. This safety factor is taken as the safety factor for the first permanent load case for the combination under consideration i.e. γ_G.

In case a combination does not have a permanent load case, γ_G is taken as 1,00.

Determination of Effective Geometry

The next step in the check concerns the determination of the effective geometry of the pad foundation.

The following picture illustrates the different actions working on the foundation.



In this picture the following notations are used:

Action	Info
G	Weight of the foundation and of any backfill material inside the area of abcd.
g	Load application point for load **G** referenced to the center point of the foundation base
P	Vertical **Rz** reaction of the support
p	Load application point for load **P** referenced to the center point of the foundation base. This is read as the load eccentricities ex and ey from the Pad Foundation library.
H	Horizontal **Rx** or **Ry** reaction of the support
h	=(h1 + h2) Load application point of the horizontal load H referenced to the foundation base. With h1 and h2 read from the Pad Foundation Library.

M	Moment **Mx** or **My** reaction of the support
V_d	= G + P Ultimate load vertical to the foundation base including the weight of the foundation and any backfill material.
e	Load application point for load $\mathbf{V_d}$ referenced to the center point of the foundation base

Using the Support Reaction Elimination factors defined in the Geotechnics Setup the reaction forces Rx, Ry, Rz, Mx, My can be modified.

These factors can be used in case the user for example models only a pad foundation and omits other foundation elements like a ring beam. The user can then specify that for example only 50% of a reaction should be used to design the pad foundation since the other 50% goes into the ring beam.

The eccentricity **e** is calculated as follows:

$$e = \frac{M + G * g + H * h - P * p}{V_d}$$

For a general 3D case this formula is written as:

$$e_x = \frac{M_y + G * g_x + H_x * h - P * p_x}{V_d}$$

$$e_y = \frac{M_x + G * g_y + H_y * h - P * p_y}{V_d}$$

Weight G

The weight G consists of three parts:

1) The weight of the foundation block, $\mathbf{G_{Block}}$

   This depends on the shape of the block (prismatic or pyramidal), dimensions and also the density γ_{Block} of the block material.

   The density of the block depends on the **Water table level**.

Water level	Block Density
No influence	γ_{Block}
at foundation base	γ_{Block}
at ground level	$(\gamma_{Block} - \gamma_W)$

   The Water Density γ_W is taken as **9,81 kN/m³**

2) The weight of the backfill around h2, $\mathbf{G_{Backfill,Around}}$

   This depends on the shape of the block (prismatic or pyramidal), dimensions and also the density of the backfill material.

   The backfill density $\gamma_{Backfill,d}$ is specified in Determination of Design Values

   The density of the backfill depends on the **Water table level**.

Water level	Backfill Density
No influence	$\gamma_{Backfill,d}$
at foundation base	$\gamma_{Backfill,d}$
at ground level	$(\gamma_{Backfill,d} - \gamma_W)$

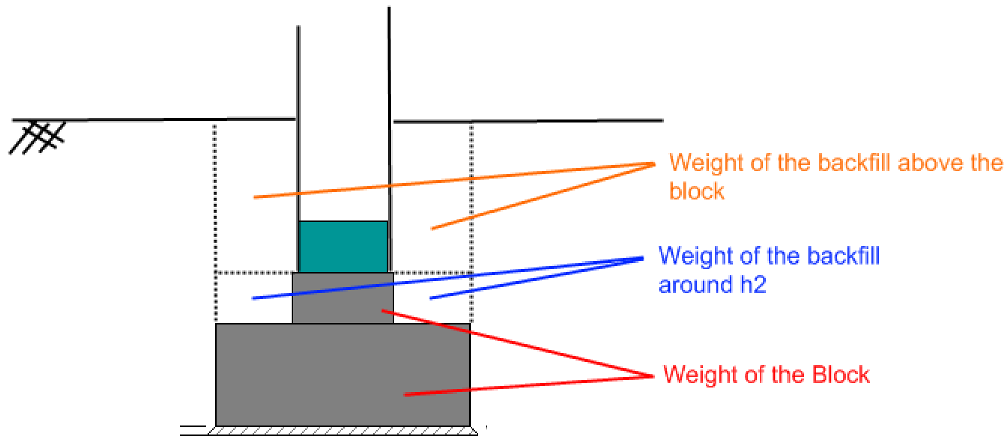
   The Water Density γ_W is taken as **9,81 kN/m³**

3) The weight of the backfill above the foundation block, $\mathbf{G_{Backfill,Above}}$

   This depends on the height and density of the backfill as specified in the input of the Pad Foundation.

> ***Note that the height of the backfill material can also be negative. A negative value is used to indicate that the soil is lower than the top of the foundation block.***

The three parts are illustrated on the following picture:



The design value of the total weight G can then be calculated as follows:

$G_d = \gamma_G * [G_{Block} + G_{Backfill,Around} + G_{Backfill,Above}]$

With γ_G the safety factor of the permanent loading for the combination under consideration, as defined in Determination of Design Values.

Distances gx & gy

Using the weight and the volume, the center of gravity of the block and backfill are determined. The distances gx and gy are then calculated from this centroid to the center point of the foundation base.

Effective Geometry

As a final step, using the eccentricities ex and ey the effective geometry of the foundation base is calculated as follows:

L1 = A – 2 * |ex|

L2 = B – 2 * |ey|

With A & B read from the Pad Foundation library.

B' = min (L1 ; L2)

L' = max (L1 ; L2)

A' = B' * L'

> ***In case B' < 0 m or L' < 0 m the geometry is incorrect.***
>
> ***In this case, the check is not executed and a warning is given on the output***

Bearing Check

The Bearing check is executed according to **EN 1997-1 art. 6.5.2** and **Annex D** [Ref.1]

$$V_d \leq R_d$$

The Bearing resistance $\mathbf{R_d}$ depends on the fact if the soil condition is drained or undrained.

In case the user 'knows' the soil capacity, for example from a geotechnical report, $\mathbf{R_d}$ can be read directly from the input data instead of calculated.

Undrained Bearing Resistance

The formulas in this paragraph are used in case the **Type** field in the Subsoil Library is set to **Undrained**.

The design value of the undrained bearing resistance is calculated as follows:

$$R_d = \frac{[(\pi + 2) * c_{ud} \ * b_c * s_c * i_c + q] * A'}{\gamma_{R,v}}$$

Value	Formula
c_{ud}	As specified in Determination of Design Values
b_c	Inclination of the foundation base (always horizontal base) = 1,00
s_c	Shape of the foundation (rectangular shape) $= 1 + 0{,}2 * \frac{B'}{L'}$
i_c	Inclination of the load, caused by horizontal load H_d $= \frac{1}{2}\left[1 + \sqrt{1 - \frac{H_d}{A' * c_{ud}}}\right]$ and $H_d \leq A' * c_{ud}$ in case $H_d > A' * c_{ud}$ the value of $\mathbf{i_c}$ is set to **0,5**
H_d	Resulting horizontal load $= \sqrt{H_x^2 + H_y^2}$
H_x	Horizontal support reaction Rx as defined in Determination of Effective Geometry
H_y	Horizontal support reaction Ry as defined in Determination of Effective Geometry
B'	Effective width as defined in Determination of Effective Geometry
L'	Effective length as defined in Determination of Effective Geometry
A'	Effective area as defined in Determination of Effective Geometry

q	Overburden at the foundation base [Ref.5] $=(h1 + h2 + h_{backfill})* \gamma_{Backfill,d}$ With: h1 & h2 read from the Pad Foundation Library $h_{backfill}$ read from the Pad Foundation input $\gamma_{Backfill,d}$ as defined in Determination of Design Values
$\gamma_{R,v}$	Resistance factor read from the National Annex Setup

Drained Bearing Resistance

The formulas in this paragraph are used in case the **Type** field in the Subsoil Library is set to **Drained**.

The design value of the drained bearing resistance is calculated as follows:

$$R_d = \frac{\left[c'_d * N_c * b_c * s_c * i_c + q'_d * N_q * b_q * s_q * i_q + 0{,}5 * \gamma'_d * B' * N_\gamma * b_\gamma * s_\gamma * i_\gamma\right] * A'}{\gamma_{R,v}}$$

Value	Formula
c_d'	As specified in Determination of Design Values
N_c	Bearing resistance factor $= \left(N_q - 1\right) * \cot\left(\varphi'_d\right)$
N_q	Bearing resistance factor $= e^{\pi * \tan\left(\varphi'_d\right)} * \tan^2\left(45 + \frac{\varphi'_d}{2}\right)$
N_γ	Bearing resistance factor $= 2 * \left(N_q - 1\right) * \tan\left(\varphi'_d\right)$
b_c	Inclination of the foundation base (always horizontal base) = 1,00
b_q	Inclination of the foundation base (always horizontal base) = 1,00
b_γ	Inclination of the foundation base (always horizontal base) = 1,00
s_c	Shape of the foundation (rectangular shape) $= \frac{s_q * N_q - 1}{N_q - 1}$
s_q	Shape of the foundation (rectangular shape) $= 1 + \left(\frac{B'}{L'}\right) * \sin\left(\varphi'_d\right)$

s_γ	Shape of the foundation (rectangular shape) $= 1 - 0{,}3 * \frac{B'}{L'}$
i_c	Inclination of the load, caused by horizontal load H_d $= i_q - \frac{(1 - i_q)}{N_c * \tan(\varphi'_d)}$
i_q	Inclination of the load, caused by horizontal load H_d $= \left[1 - \frac{H_d}{V_d + A' * c'_d * cot(\varphi'_d)}\right]^m$
i_γ	Inclination of the load, caused by horizontal load H_d $= \left[1 - \frac{H_d}{V_d + A' * c'_d * cot(\varphi'_d)}\right]^{m+1}$
m	$= m_L * \cos^2(\theta) + m_B * \sin^2(\theta)$
m_L	$= \frac{\left[2 + \left(\frac{L'}{B'}\right)\right]}{\left[1 + \left(\frac{L'}{B'}\right)\right]}$
m_B	$= \frac{\left[2 + \left(\frac{B'}{L'}\right)\right]}{\left[1 + \left(\frac{B'}{L'}\right)\right]}$
θ	Angle of the horizontal load H_d with the direction L’
φ'_d	As specified in Determination of Design Values
B’	Effective width as defined in Determination of Effective Geometry
L’	Effective length as defined in Determination of Effective Geometry
A’	Effective area as defined in Determination of Effective Geometry
H_d	Resulting horizontal load $= \sqrt{H_x^2 + H_y^2}$
H_x	Horizontal support reaction Rx as defined in Determination of Effective Geometry
H_y	Horizontal support reaction Ry as defined in Determination of Effective Geometry
V_d	As specified in Determination of Effective Geometry
q'_d	Effective overburden at the foundation base [Ref.5] $=(h1 + h2 + h_{backfill})* \gamma'_t$ With: h1 & h2 read from the Pad Foundation Library $h_{backfill}$ read from the Pad Foundation input

<table>
<tr><td></td><td>γ'_t is depending on the water level as follows:

<table><tr><th>Water level</th><th>γ'_t</th></tr><tr><td>No influence</td><td>$\gamma_{Backfill,d}$</td></tr><tr><td>at foundation base</td><td>$\gamma_{Backfill,d}$</td></tr><tr><td>at ground level</td><td>$(\gamma_{Backfill,d} - \gamma_W)$</td></tr></table>$\gamma_{Backfill,d}$ as defined in Determination of Design Values
γ_W is taken as **9,81 kN/m³**</td></tr>
<tr><td>γ'_d</td><td>Effective weight density of the soil below the foundation level depending on the water level as follows:

<table><tr><th>Water level</th><th>γ'_d</th></tr><tr><td>No influence</td><td>γ'_d</td></tr><tr><td>at foundation base</td><td>$(\gamma'_d - \gamma_W)$</td></tr><tr><td>at ground level</td><td>$(\gamma'_d - \gamma_W)$</td></tr></table>γ'_d as defined in Determination of Design Values
γ_W is taken as **9,81 kN/m³**</td></tr>
<tr><td>$\gamma_{R,v}$</td><td>Resistance factor read from the National Annex Setup</td></tr>
</table>

Known Soil Capacity Bearing Resistance

In case the Soil capacity is known, this value can be used directly instead of using the EN 1997-1 bearing resistance calculation outlined above.

This procedure is applied in case the checkbox **Known soil capacity, use Sigma oc** is activated in the Geotechnical Design Setup.

The design value of the bearing resistance is calculated as follows:

$$R_d = A' * \sigma_{od}$$

Value	Formula
A’	Effective area as defined in Determination of Effective Geometry
σ_{od}	Design value of the admissible soil capacity, taken as $\boldsymbol{\sigma_{oc}}$
σ_{oc}	Read from the Subsoil Library

Sliding Check

The Sliding check is executed according to **EN 1997-1 art. 6.5.3** [Ref.1]

$$H_d \leq R_d + R_{p,d}$$

The Sliding resistance $\mathbf{R_d}$ depends on the fact if the soil condition is drained or undrained.

The value $\mathbf{R_{p,d}}$ specifies the positive effect of the earth pressure at the side of the foundation. Since this effect cannot be relied upon, this value is taken as zero [Ref.2].

The sliding resistance is dependent on the condition of the subsoil.

a) In case the **Type** field in the Subsoil Library is set to **Undrained**.

$$R_d = \frac{A' * c_{ud}}{\gamma_{R,h}}$$

Value	Formula
c_{ud}	As specified in Determination of Design Values
A'	Effective area as defined in Determination of Effective Geometry
$\gamma_{R,h}$	Resistance factor read from the National Annex Setup

In case the checkbox **Water/air in clay subgrade** in the Subsoil Library is activated, the value of $\mathbf{R_d}$ is limited as follows:

$$R_d \leq 0{,}4 * V_d$$

Value	Formula
V_d	As specified in Determination of Effective Geometry

b) In case the **Type** field in the Subsoil Library is set to **Drained**.

$$R_d = \frac{V_d * \tan(\delta_d)}{\gamma_{R,h}}$$

Value	Formula
V_d	As specified in Determination of Effective Geometry
δ_d	Design friction angle at the foundation base

	Dependent on the **Cast condition** specified in the Pad Foundation Library: Cast Condition / δ_d: Prefabricated: $\frac{2}{3} * \varphi'_d$ In situ: φ'_d
φ'_d	As specified in Determination of Design Values
$\gamma_{R,h}$	Resistance factor read from the National Annex Setup

Cast Condition	δ_d
Prefabricated	$\frac{2}{3} * \varphi'_d$
In situ	φ'_d

Eccentricity check

EN 1997-1 art. 6.5.4 specifies that special precautions are required for loads with large eccentricities.

According to [Ref.3] this is done by checking if the design load is within a critical ellipse or critical diamond.

More specifically the eccentricity of the load should not exceed **1/3** or **1/6** of the width.

The maximal value of the eccentricity is defined in the Geotechnical Design Setup.

Based on the maximal value an eccentricity check is executed as follows according to [Ref.3].

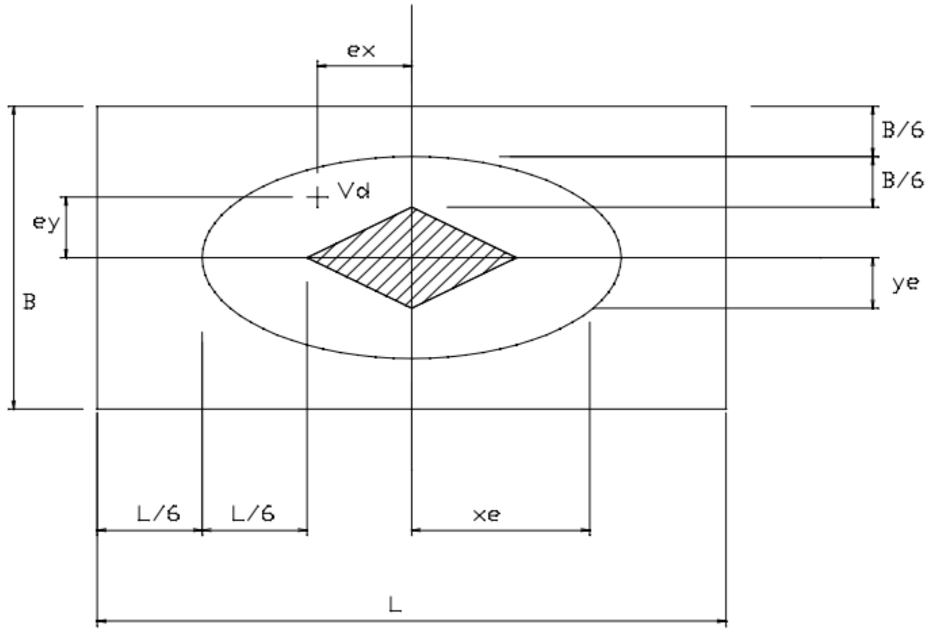
a) In case the maximal eccentricity is set to **1/3**

$$\left(\frac{e_x}{A}\right)^2 + \left(\frac{e_y}{B}\right)^2 \leq \frac{1}{9}$$

b) In case the maximal eccentricity is set to **1/6**

$$\frac{e_x}{A} + \frac{e_y}{B} \leq \frac{1}{6}$$

Value	Formula
e_x	As specified in Determination of Effective Geometry
e_y	As specified in Determination of Effective Geometry
A	Read from Pad Foundation Library
B	Read from Pad Foundation Library



c) In case the maximal eccentricity is set to **No limit**

In this case there is no limit i.e. any eccentricity is allowed. The unity check is then set to **0,00**.

Uplift Check

In case the vertical design loading $\mathbf{V_d}$ is negative, it implies that the pad foundation is in tension and may thus be 'uplifted' from the ground.

The uplift check is written out as follows:

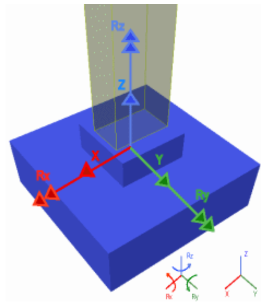
$$|P| \leq G_d$$

Value	Formula
P	The vertical **Rz** reaction as specified in Determination of Effective Geometry
G_d	The weight of the foundation and any backfill as specified in Determination of Effective Geometry

> ***This check is executed instead of the Bearing, Sliding and Eccentricity checks.***

Annex: Pad Foundation Stiffness

This annex specifies the calculation of the stiffness coefficients of a pad foundation.



Stiffness	Formula
Stiffness X	$A \cdot B \cdot C1x$
Stiffness Y	$A \cdot B \cdot C1y$
Stiffness Z	$A \cdot B \cdot C1z + 2 \cdot (A + B) \cdot \sqrt{C1z \cdot C2x} + 2 \cdot C2x$
Stiffness Rx	$B^3 \cdot \frac{A \cdot C1z + 2 \cdot \sqrt{C1z \cdot C2x}}{6} + \frac{A \cdot B^2 \cdot \sqrt{C1z \cdot C2x}}{2} + \frac{B^2 \cdot C2x}{2} + A \cdot B \cdot C2x$
Stiffness Ry	$A^3 \cdot \frac{B \cdot C1z + 2 \cdot \sqrt{C1z \cdot C2x}}{6} + \frac{B \cdot A^2 \cdot \sqrt{C1z \cdot C2x}}{2} + \frac{A^2 \cdot C2x}{2} + B \cdot A \cdot C2x$
Stiffness Rz	$C1y \cdot Ix + C1x \cdot Iy + \frac{h1 \cdot A^3 \cdot C1z}{6} + \frac{h1 \cdot B^3 \cdot C1z}{6} \ldots$ $+ \frac{2 \cdot \sqrt{C1z \cdot C2x} \cdot A^2 \cdot h1}{4} + \frac{2 \cdot \sqrt{C1z \cdot C2x} \cdot B^2 \cdot h1}{4} + \frac{C2x \cdot A^2}{2} + \frac{C2x \cdot B^2}{2}$

With:

Parameter	
A	Dimension read from Pad Foundation library
B	Dimension read from Pad Foundation library
C1x	Soil stiffness read from Subsoil Library
C1y	Soil stiffness read from Subsoil Library
C1z	Soil stiffness read from Subsoil Library
C2x	Soil stiffness read from Subsoil Library
Ix	$\frac{A \cdot B^3}{12}$
Iy	$\frac{B \cdot A^3}{12}$

References

[1]	EN 1997-1 *Eurocode 7: Geotechnical design – Part 1: General rules* CEN, 2004.
[2]	Frank R., Baudoin C., Driscoll R., Kavvadas M., Krebs Ovesen N., Orr T., Schuppener B., *Designer's Guide to EN 1997-1 Eurocode 7: Geotechnical design – Part 1: General rules*, Thomas Telford, 2004.
[3]	Schneider K.-J., Bautabellen für Ingenieure, 13. Auflage, Werner Verlag, 1998.
[4]	EN 1990, *Eurocode – Basis of Structural Design*, CEN, 2002.
[5]	Lambe T., Whitman R., *Soil Mechanics*, MIT, John Wiley & Sons, Inc, 1969.
[6]	EN 1997-1:2004/AC:2009 Correction Sheet *Eurocode 7: Geotechnical design – Part 1: General rules* CEN, 2009.