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- [ ] nein / no
- [ ] begrenzt bis / limited until:

SENVION
wind energy solutions

Senvion **Wind Turbine**

# General Specification for the Design of Onshore Foundations

SENVION

In diesem Dokument wurde der Name des Unternehmens aufgrund einer Umfirmierung zu „Senvion SE" (ehemals „REpower Systems SE") geändert. Der sachliche und rechtliche Inhalt bleibt unverändert.

Within this document the name of the company has been changed to „Senvion SE" (formerly „REpower Systems SE"). The factual and legal content remains unchanged.

| | |
|---|---|
| Geändert am / Changed at: | 06.03.2014 |

## Änderungsverzeichnis / *Change Index*:

| Revision | Ausgabe-datum / Date of issue | Aus-tausch-seiten / Replaced pages | Änderungen / Modifications |
|---|---|---|---|
| A | 2006-03-20 | - | Erstausgabe / First Issue |
| B | 2006-03-23 | all | |
| C | 2007-08-28 | all | |
| D | 2008-01-21 | all | |
| E | 2008-07-14 | all | |
| F | 2008-10-14 | all | |
| G | 2009-12-18 | all | |
| H | 2010-06-07 | p.24, p.26-27 | General requirements for 3.XM @ 96.50 to 100 m hh; External Tower Stair Section added |
| I | 2011-01-11 | -- | Section 4.4 added; Section 5.1 to 5.3 modified; Section 5.7; modified; Section 7.1 modified |
| J | 2011-05-27 | -- | Section 5 modified; Minimum values for the Senvion MM100 added; Section 4.4.1: detailed definition “compacted” |
| K | 2013-07-24 | all | • “Soil Investigations and Geotechnical Date” deleted<br>• “Minimum Requirements for Foundation Design” deleted<br>• “Rock Anchor Foundations” compiled |

## Zugehörige aktuelle Dokumente dieser Unterlage / *Other Applicable Documents*

| Bezeichnung / Designation | Dokumenten-Nr. / Document No. | Revisions-Nr. | Ausgabedatum / Date of issue |
|---|---|---|---|
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## Anlagen / Annex:

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# Table of Content

# 1 Introduction

The design of foundations for Senvion wind turbines has to be carried out based on the Senvion load specification. National requirements and standards have to be taken into account. The design of the embedded steel can is carried out by Senvion **EUROCODES shall be applied preferably if recognised in that particular country.**

# 2 Design Review

Senvion is entitled to do a design-review. However Senvion does not accept responsibility as a result of the design review. If the foundation design does not meet Senvion requirements the design may have to be revised. These are the standard documents to be submitted for the design-review:

- Report on Ground Investigation
- General arrangement drawing of the foundation
- Reinforcement Drawings
- Bar Schedule
- Work Instructions
- Design-Report

Technical documentation should be in German and/or in English. Other languages can be accepted as an exception. The following information shall be found on the drawings:

- Turbine (e. g. MM82 or 3.2M114), hub height, name of the project / site
- Allowable groundwater level for the foundation
- Material properties for concrete and reinforcement steel (yield strength, ultimate strength etc.)
- Demands on the subsoil (allowable bearing pressure etc.)

To advance the projects, consulting-engineers should be able to communicate in English and/or in German.

# 3 Foundation Types

## 3.1 Gravity Foundations

### 3.1.1 General Requirements

For economical reasons, gravity foundations should preferably be designed with a circular base. Octagonal or polygonal (n ≥ 8) bases are also acceptable. To simplify the analysis of polygonal bases, a circular base with an equal area may be modelled as well. To improve the overall stability of the foundation it is generally recommended to arrange a layer of ballast on top of the foundation slab.

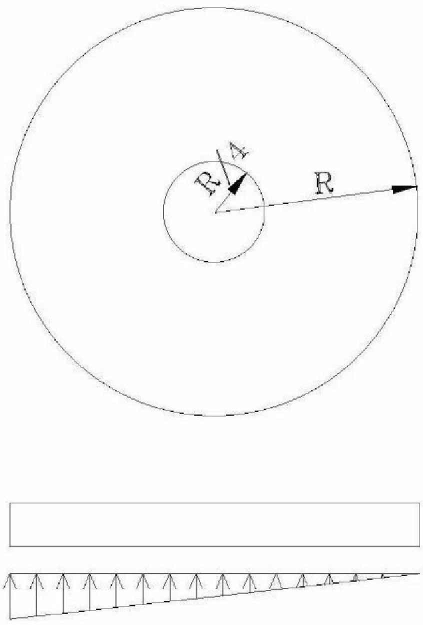
The design shall include the following key elements:

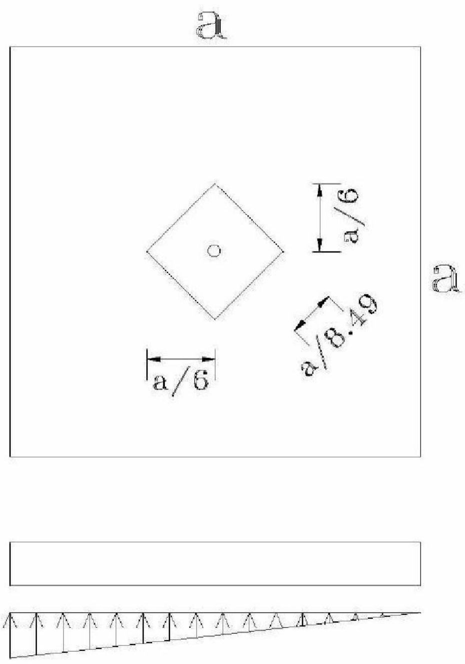
- Overall stability assessments taking into account the ground water level
- Reinforced concrete design
- Fatigue analysis for the reinforcement and the concrete

### 3.1.2 Gapping under the Foundation

**No inactive area** (zero-pressure zone) under the base of a gravity foundation is admissible for the tower moment specified by Senvion No safety factors have to be applied. It has to be proven that the excentricity of the total vertical load (turbine, foundation slab, pedestal, ballast etc.) due to the tower moment is

| | |
|---|---|
| e < R / 4 | for circular bases |
| e < a / 6 | for square bases with tower moment parallel to edges |
| e < a / 8.485 | for square bases with tower moment in 45° direction to edges |

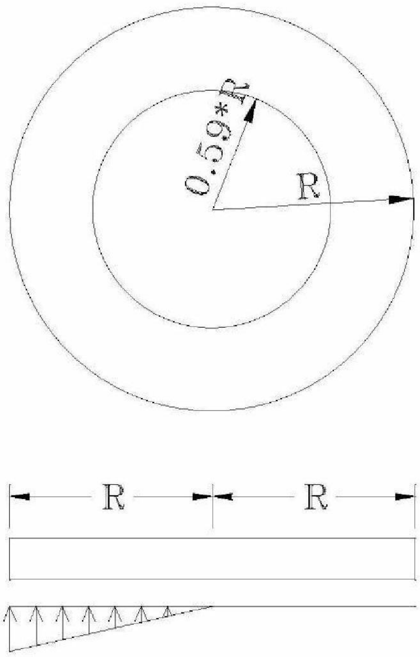


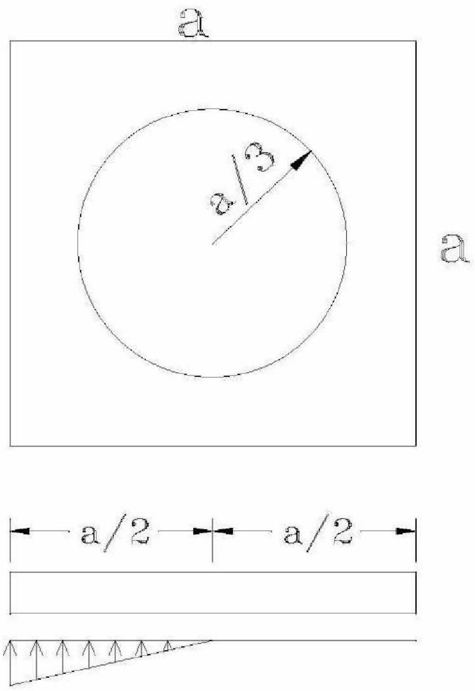



For unscaled ultimate loads ($\gamma_F$ = 1.0) not **more than 50%** of the base may be without compression. No safety factors have to be applied. It has to be proven that the resultant of all forces (tower moment, turbine, foundation slab, pedestal, ballast) is within a circle

e < 0.59 * R    for circular bases

e < a / 3    for square bases



### 3.1.3 Soil Bearing Pressure for Circular Bases

The bearing pressure beneath a circular base has to be calculated as follows

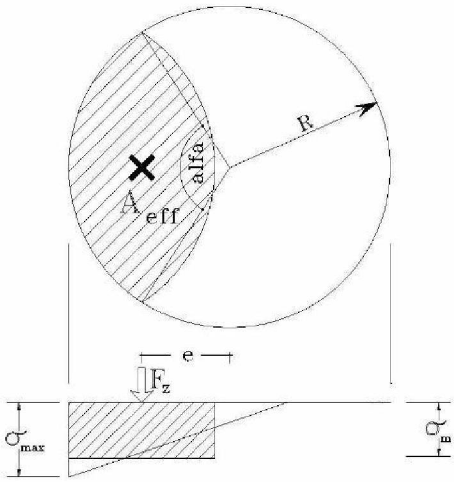
- Ultimate bearing pressure at the edge of the foundation for characteristic loads

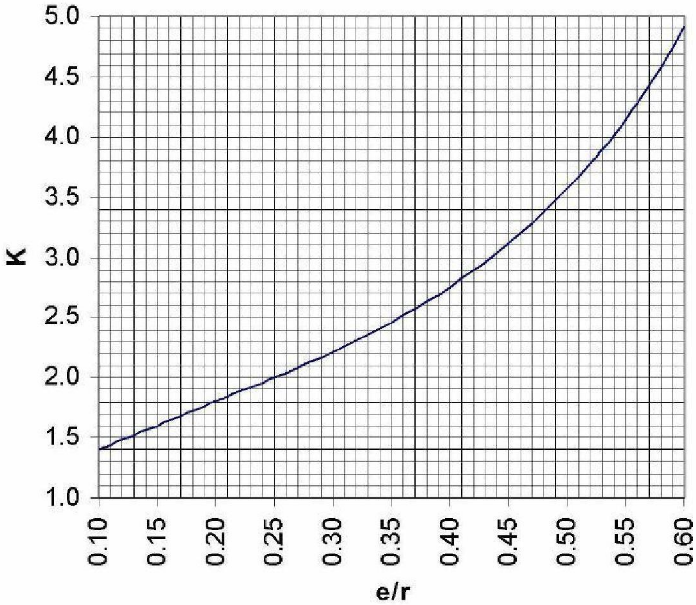
  $|F_z|$ = resultant of all vertical forces ( turbine, tower, foundation, ballast etc.)

  $e = M / |F_z|$ excentricity

  K = coefficient according to the graph below

  $\sigma_{max} = K * |F_z| / (\pi * R^2)$ soil pressure at the edge




- Ultimate averaged bearing pressure for characteristic loads as shown in the sketch

  $\alpha = 2 * \arccos(e / R)$ (included angle of sector circle)

  $A_{eff} = R^2 * (\alpha - \sin \alpha)$ (area with constant pressure)

  $\sigma_m = |F_z| / A_{eff}$

### 3.1.4 Soil Bearing Pressure for Square Bases

The bearing pressure beneath a square base has to be calculated as follows:

- Ultimate bearing pressure at the edge of the foundation for the characteristic loads

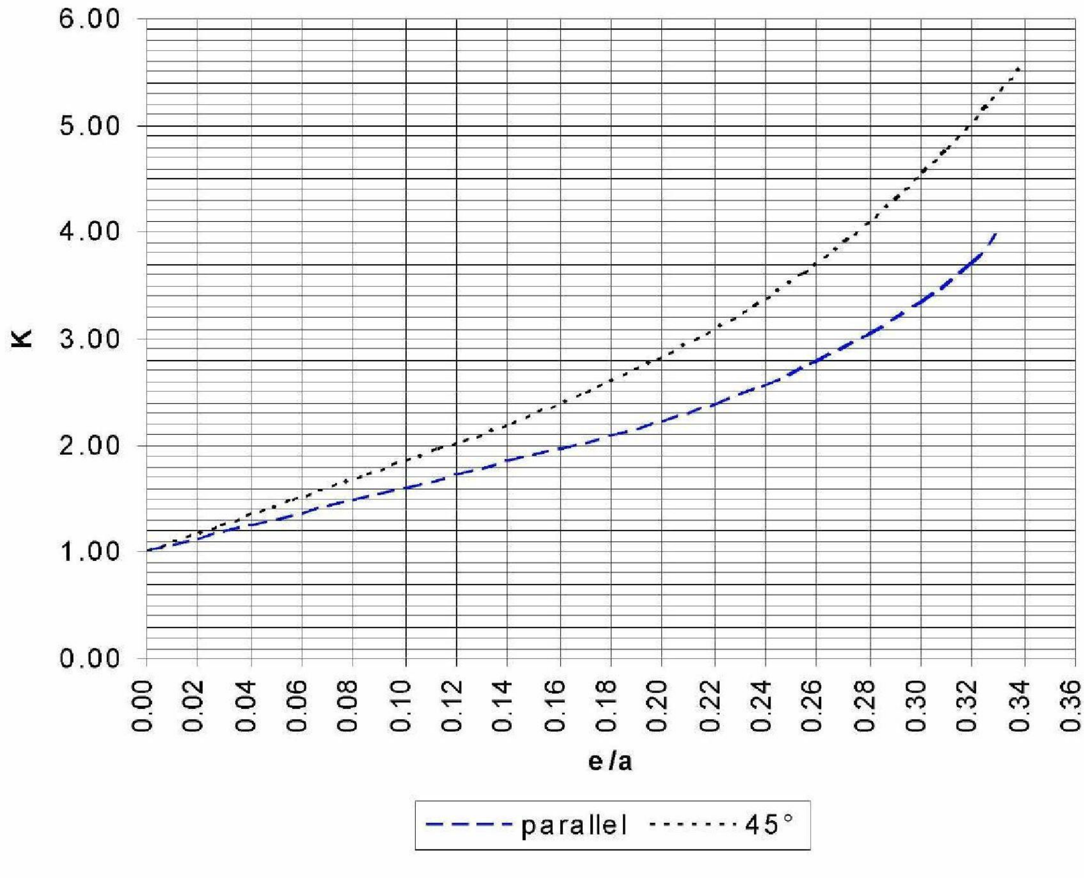
  $|F_z|$ = resultant of all vertical forces ( turbine, tower, foundation, ballast etc.)

  $e = M / |F_z|$ excentricity

  K = coefficient according to the graph below

  $\sigma_{max} = K * |F_z| / a^2$ soil pressure at the edge of the foundation

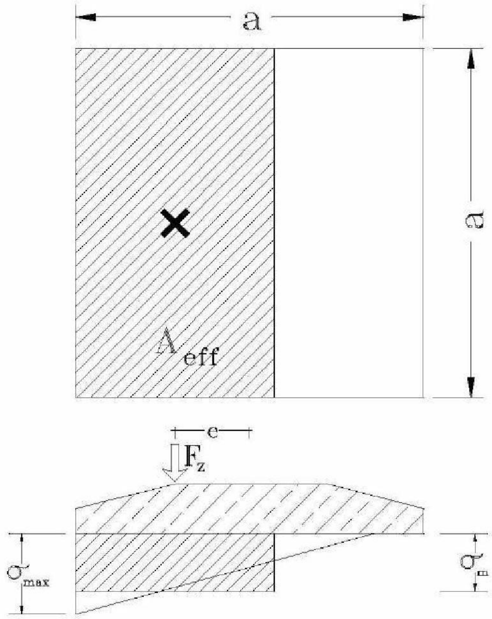
foundations with a square base



– Ultimate averaged bearing pressure for characteristic loads as shown in the sketch (90° direction):

$A_{eff} = a^2 - 2 * a * e$ area with constant pressure

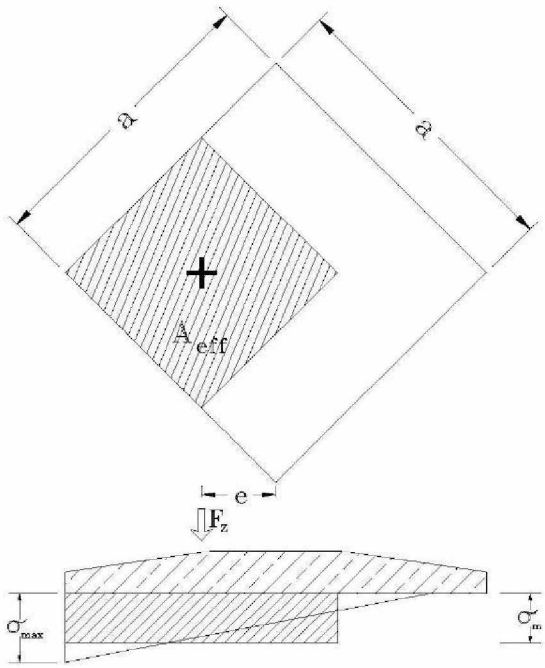
$\sigma_m = |F_z| / A_{eff}$




– Ultimate averaged bearing pressure for the characteristic loads as shown in the sketch (45° direction):

$A_{eff} = (a - e * 2^{0.50})^2$ area with constant pressure

$\sigma_m = |F_z| / A_{eff}$



### 3.1.5 Foundation Stiffness

Senvion specifies minimum dynamic foundation stiffness ($k_{\varphi,dyn}$ and $k_{xy,dyn}$) in order to ensure that the overall system natural frequency stays above the main excitation loads. This requirement enables Senvion to demonstrate that fatigue life will be acceptable as that foundation stiffness has been assumed in the turbine fatigue simulations. Furthermore Senvion specifies a statical foundation stiffness ($k_{\varphi,stat}$) to ensure stability and to limit moments from second order theory.

$$k_{\varphi,dyn} = \frac{M_{\varphi,dyn}}{\theta} \qquad k_{x,y,dyn} = \frac{F_{x,y,dyn}}{\Delta x,y} \qquad k_{\varphi,stat} = \frac{M_{\varphi,stat}}{\theta}$$

- $k_{\varphi,dyn}$ : dynamic rotational stiffness of the foundation
- $k_{xy,dyn}$ : dynamic horizontal stiffness of the foundation
- $k_{\varphi,stat}$ : statical rotational stiffness of the foundation
- $\theta$: rotation at reference height
- $\Delta x,y$: horizontal displacement at reference height
- $M_{\varphi,dyn}$ : resultant dynamic moment at reference height
- $M_{\varphi,stat}$ : resultant statical moment at reference height
- $F_{xy,dyn}$ : resultant horizontal force at reference height

For circular gravity bases dynamic foundation stiffness is calculated using a rigid footing on elastic half-space formulation:

$$K_{\varphi,dyn} = E_{s,dyn}\frac{4}{3}\cdot\frac{r^3 * (1-\nu-2\nu^2)}{(1+\nu)\cdot(1-\nu)^2}$$

r: radius of the base
$E_{S,dyn}$: dynamic module of compressibility
$\nu$: Poisson's ratio

For squared gravity bases dynamic foundation stiffness is calculated using a rigid footing on elastic half-space formulation:

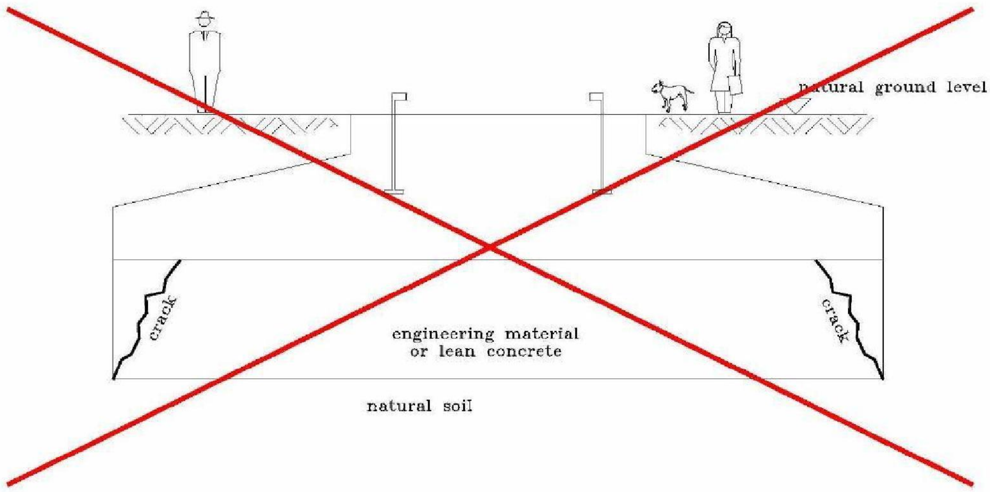
$$K_{\varphi,dyn} = E_{s,dyn} * \frac{2 * a^3 * (1-\nu-2\nu^2)}{(1+\nu)\cdot(1-\nu)^2}$$

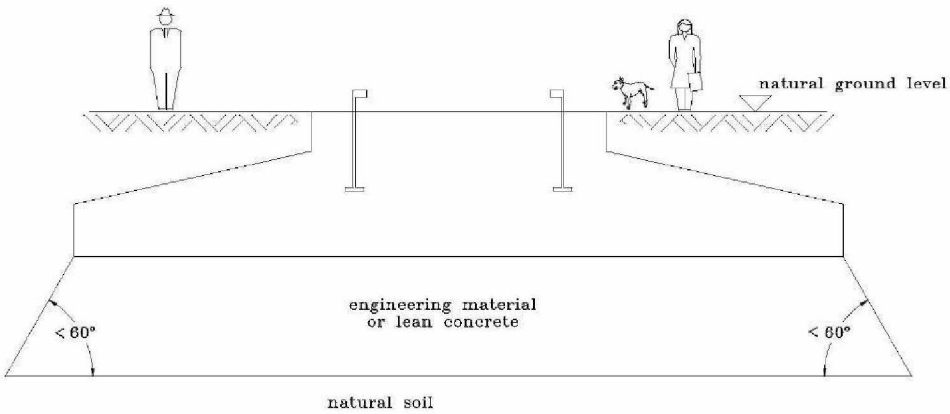
a: half side length
$E_{S,dyn}$: dynamic module of compressibility
$\nu$: Poisson's ratio

In the estimation of foundation stiffness at the design stage, sufficient allowance should be made for ground variability across the site. Regardless of this requirement, the rotational stiffness of the foundation shall be proven by the designer using adequate equations.

### 3.1.6 Lean Concrete underneath the Foundation Slab

If the ground conditions do not allow to set up a gravity foundation directly on the natural soil, poor soil may be exchanged by lean concrete or engineering backfill. The backfill has to be arranged in a conical way:




**For US projects only:** Due to patent reasons no reinforced sub bases or lean concrete layers are allowed to be used on site in the USA. The embedded steel can has to be placed on a non-reinforced sub base layer. It is required to use a minimum of 100 mm lean concrete to support the levelling legs of the embedded steel can.

## 3.2 Pile Foundations

If the ground conditions do not permit gravity foundations, piled foundations are required. The piles have to bear the axial forces due to the tower moment and dead loads as well as the horizontal forces due to torsion and lateral forces. It is recommended to use raked piles. Senvion exclusively accepts reinforced concrete piles. Steel piles and wooden piles are not admissible. Reinforcement cages for the piles may not be welded. Even spot welding is not admissible because the performance of the pile regarding to fatigue would decrease dramatically.

## 3.3 Pier Foundations

A pier foundation is neither a gravity foundation nor a piled foundation. A pier foundation can be referred to as a caisson, a mono-pile with a large diameter. The proprietary name is “Patrick & Henderson” foundation.

For pier foundations the centre of rotation is located at a lower height indication compared with gravity foundations or piled foundations. If the point of rotation is placed too low, the pier foundation acts like an extension of the tower, which affects the natural eigenfrequencies of the tower-foundation system. The engineer of record has to assure, that the tower-foundation system does not become softer than the minimum dynamic rotational stiffness specified by Senvion

Among other things the design of a pier foundation has to include the following elements:

- Verification of the rotational and lateral stiffness at a reference height indication as specified by Senvion If the centre of rotation is at a lower height indication than specified by Senvion the complete system (nacelle, tower and foundation) has to be taken into consideration.
- Overall stability
- Structural design of the foundation body
- Fatigue analysis for the reinforcement and/or anchor bars as well as for the concrete

For pier foundations (caisson, Patrick & Henderson, and similar) excavating using explosives is prohibited. Where necessary, a hydraulic excavator or other applicable devices shall be used instead. Especially for P&H-Foundations the excavation method may not degrade the texture of the in-situ soil/rock. The engineer of record has to propose a suitable method for excavation works.

## 3.4 Rock Anchor Foundations

Rock anchor foundations are one way to reduce concrete and rebar in regions where strong bedrock is reachable at shallow depth. The foundation resists loads through a combination of bearing pressure beneath the cap at the bearing layer and tension in rock anchors that are grouted into boreholes and post-tensioned. Rock anchor foundations can be designed using either an embedded steel can or a bolt cage instead. Rock anchors shall never be directly connected to the bottom flange of the tubular steel tower.

Design requirements:

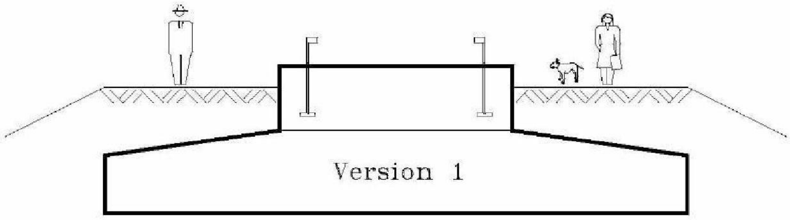
- The geotechnical design of the foundation has to follow the recommendations of a site-specific geotechnical report. The bearing capacity and the lateral resistance calculations have to be in accordance with the parameters given with the recommendations of the site-specific geotechnical report.
- Gaping beneath the foundation: Following chapter 3.1.2 no foundation gapping shall occur under operational loads as specified by Senvion Tension losses (creep losses, anchor relaxation etc. have to be taken into account).
- Only rock anchors with approval certificate shall be used in the design. The foundation shall be designed in a way that no re-tensioning is required during the life cycle of the turbine.
- The rock anchors shall have an unbonded length (free stress zone) of at least 8 m followed by a bonded length that transfers the axial loads into the rock through skin friction.
- Rotational Stiffness: It has to be verified that the combined foundation-soil-system meets the requirements in respect of both the dynamic rotational stiffness as well as the statical rotational stiffness as specified by Senvion
- The structural capacity of the anchors as well as the anchor pullout (geotechnical) capacity have to be verified.

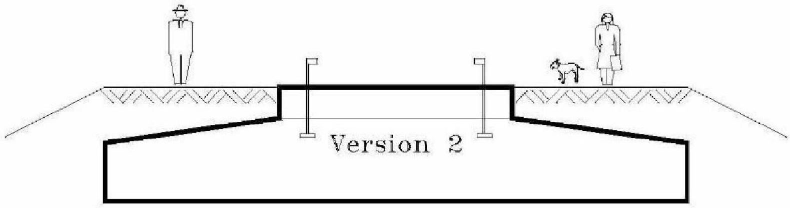
# 4 Construction and Design Details

Depending on the design of the tubular steel tower, the interface between tower and foundation is accomplished either with an embedded steel can or with a bolt cage.

## 4.1 Foundations with Embedded Steel Can

According to the design of the embedded steel can which is provided by Senvion the foundation should be engineered as follows. Due to patent reasons the version 1 is not allowed in the USA using a cold joint between the slab and the pedestal.




## 4.2 Anchor Bolt Foundations

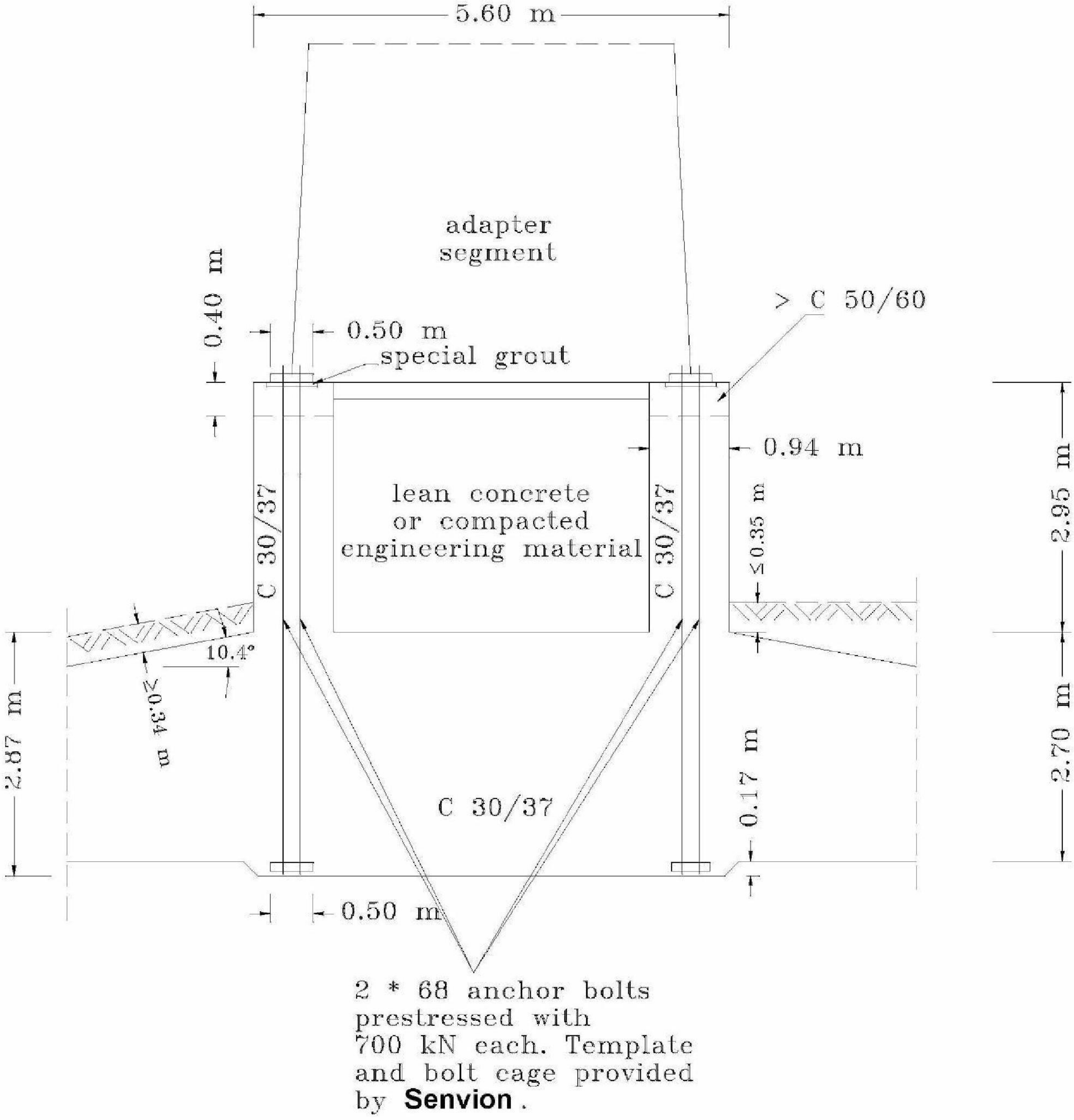
A tubular steel towers of a Senvion wind turbine may be designed to be connected to the foundation with an anchor cage. The proposed anchor cage consists of an embedment ring as well as an inner and outer circular array of holding down bolts fixed to the embedment ring with threads. The bolts will be post-tensioned after erection of the tower.

Generally neither the bolt cage nor the template for the erection of the bolt cage belongs to Senvion's scope of supply. In such cases the design of the bolt cage is carried out by the designer of the foundation. The number of bolts, the mean diameter of the inner & outer bolt ring as well as the proposed bolt diameter can be found on the drawing of the tubular steel tower.
However for some turbines the bolt cage as well as the template for the erection of the bolt cage is provided by

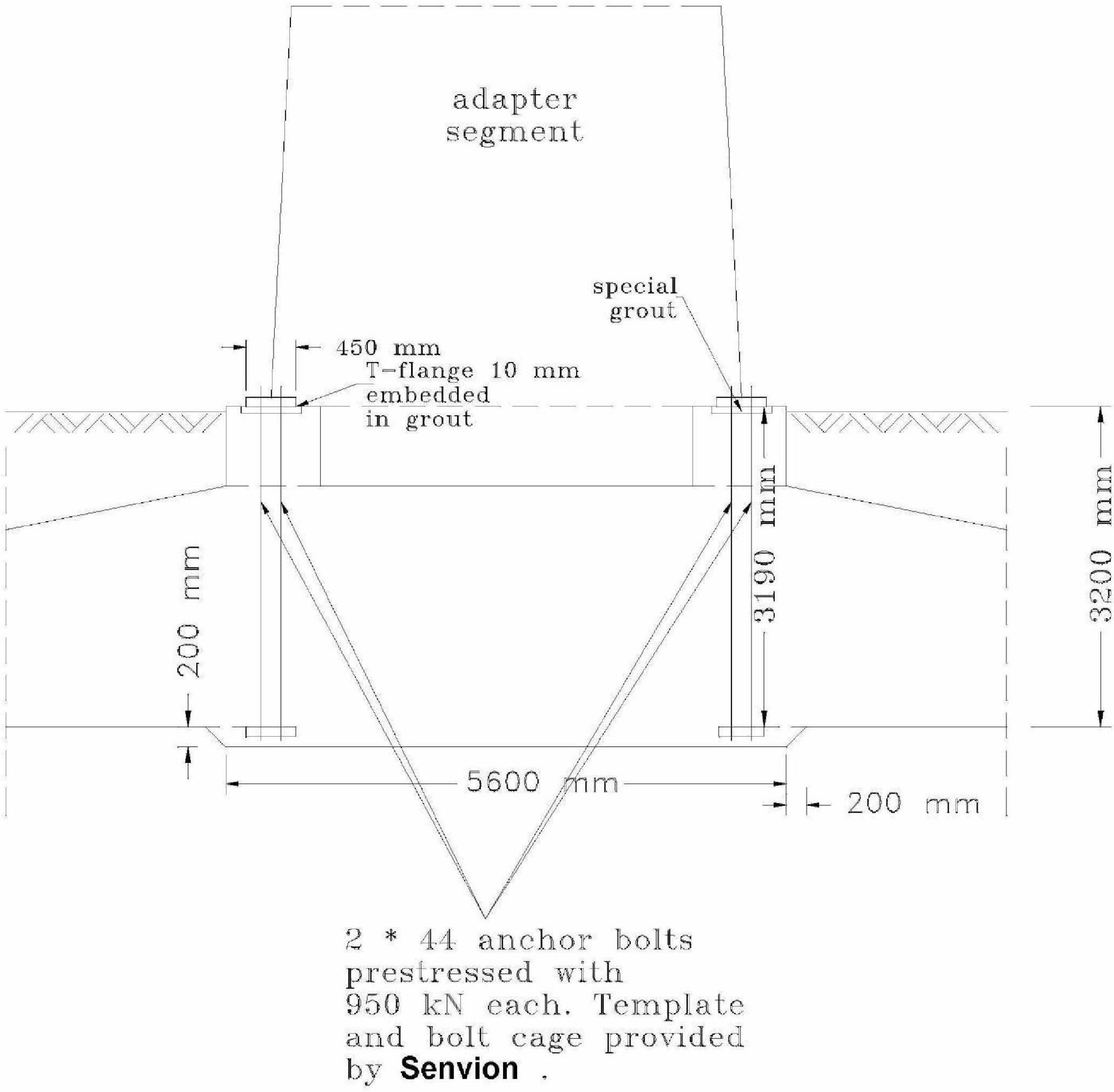
- 3.4M104 @ 96.5 m – 100 m hub height
- 3.4M104 @ 90.0 m – 93 m hub height
- 3.2M114 @ 90.0 m – 93 m hub height

Therefore the design of each foundation shall be based on Senvion's standard foundation design which will be provided on demand. Only country-specific inevitable modifications are permitted. The general arrangement of the base shall comply with the sketches below:

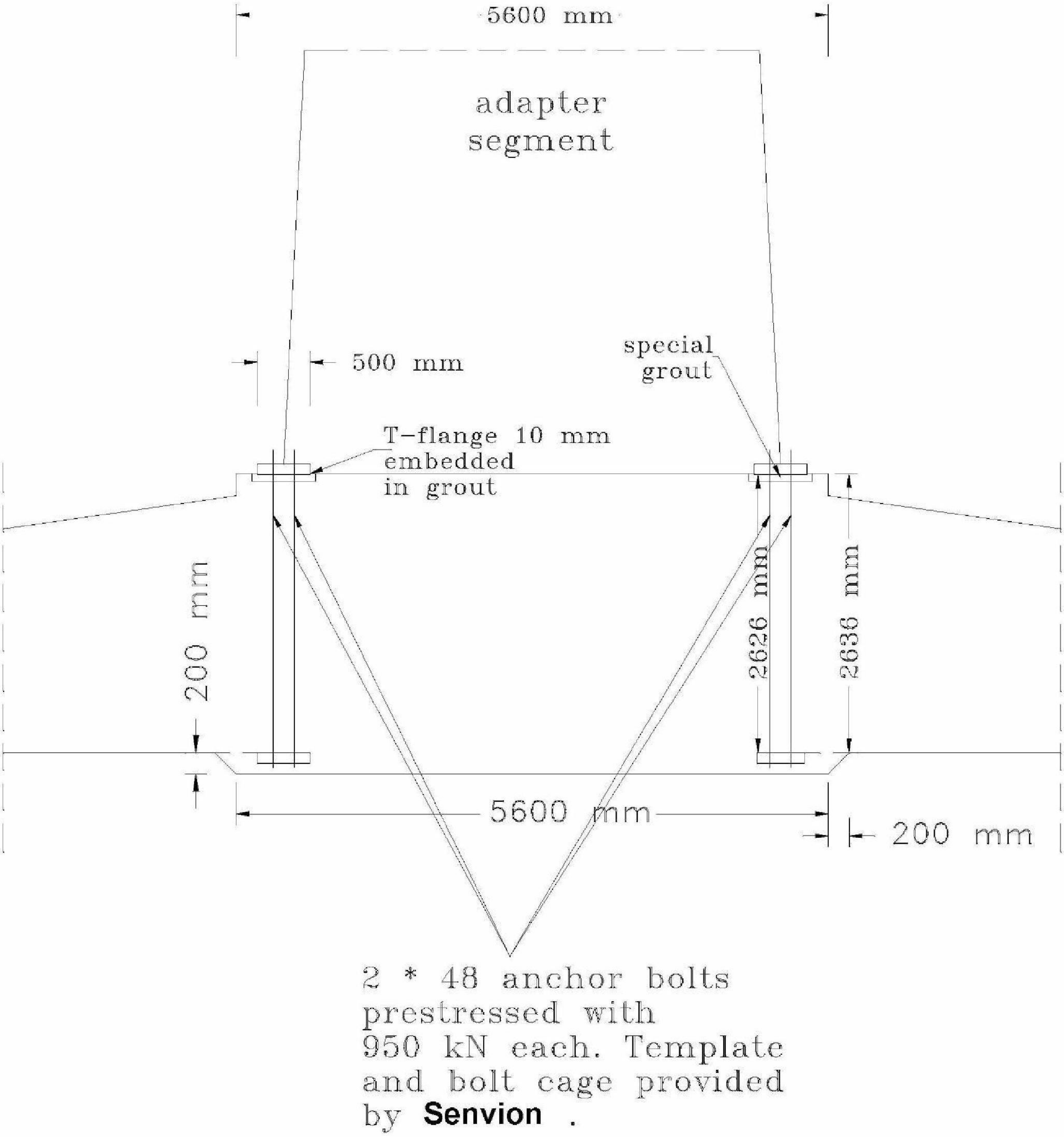
Senvion **3.4M104 @ 96.50m – 100 m hh:**



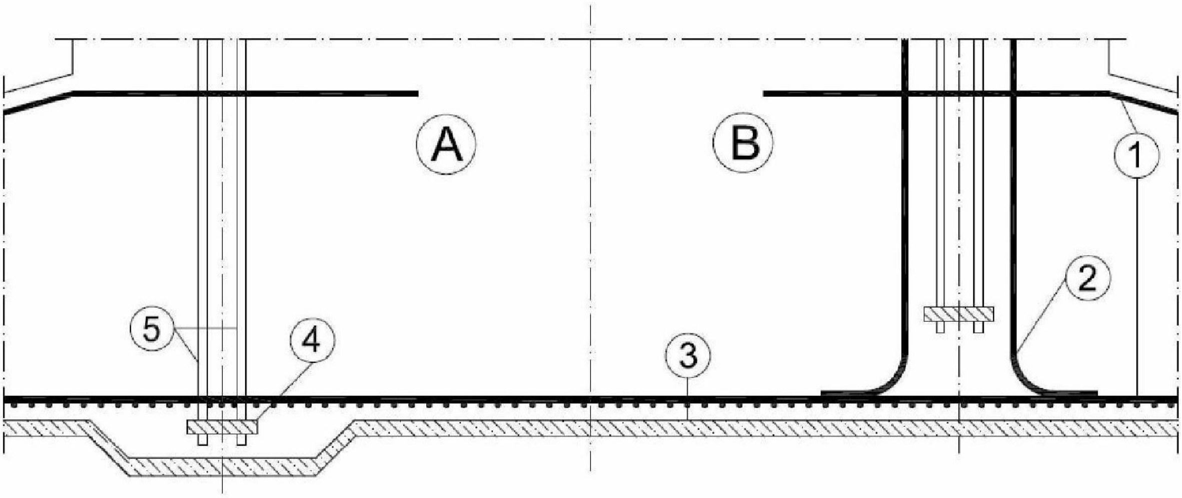
Senvion **3.2M114 @ 90.00 – 93.00 m hh:**



Senvion **3.4M104 @ 93.00 m hh:**



Senvion accepts the following two principle positions of the embedment ring. The following figure does not represent a complete structural drawing. It only shows basic parts of a proposed foundation design.



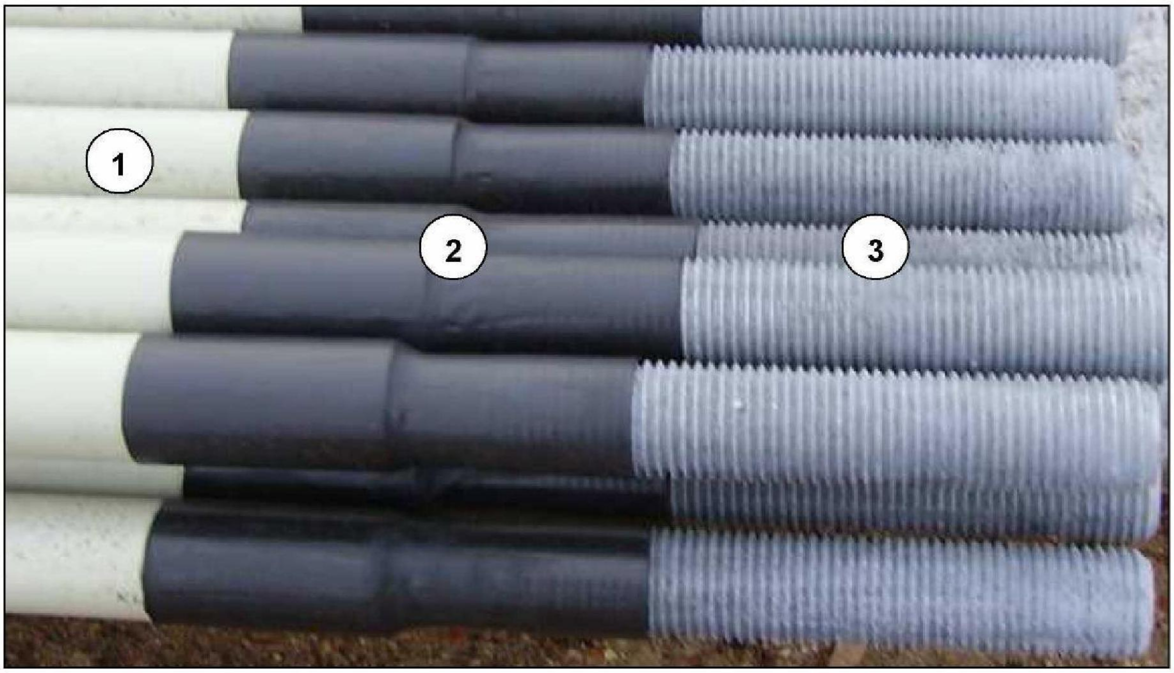

| | |
|---|---|
| 1 | Obere & Untere Bewehrung<br>*Top & Bottom Reinforcement* |
| 2 | Rückhängebewehrung<br>*Anchor Reinforcement* |
| 3 | Sauberkeitsschicht<br>*Blinding Layer* |
| 4 | Ankerring<br>*Embedment Ring* |
| 5 | Ankerstangen<br>*Anchor Bolts* |

**Option A:** The embedment ring is placed below the bottom reinforcement. In that case no anchor reinforcement around the holding down bolts is needed.

**Option B:** The embedment ring is placed above the bottom reinforcement. In that case anchor reinforcement around the holding down bolts is required. The anchor reinforcement has to be in accordance with the design approach in section 5.2 on page 24.

The following general requirements have to be taken into account:

- A suitable long term corrosion protection of the bolts has to be assured. The bolts have to be protected against corrosion for the proposed design life of 20 years.
- Concrete is sensible to creeping and shrinkage effects. The foundation engineer generally specifies the post-tension force of the bolts. The post-tension force shall be checked periodically after initial pretension of the bolts. The designer of the foundation has to specify the period in which the pretension of the bolts shall be readjusted.
- It has to be assured that neither water, grout nor concrete comes into contact with the holding down bolts. Typically a high temperature (HT) tube is used to prevent contact between concrete, grout and water. A heat shrinkage tube seals the HT tube at both ends. See figure below:




1. HT tube avoiding contact between concrete and bolt
2. Heat shrinkage tube for sealing
3. Threaded bolt end

## 4.3 Hybrid Towers

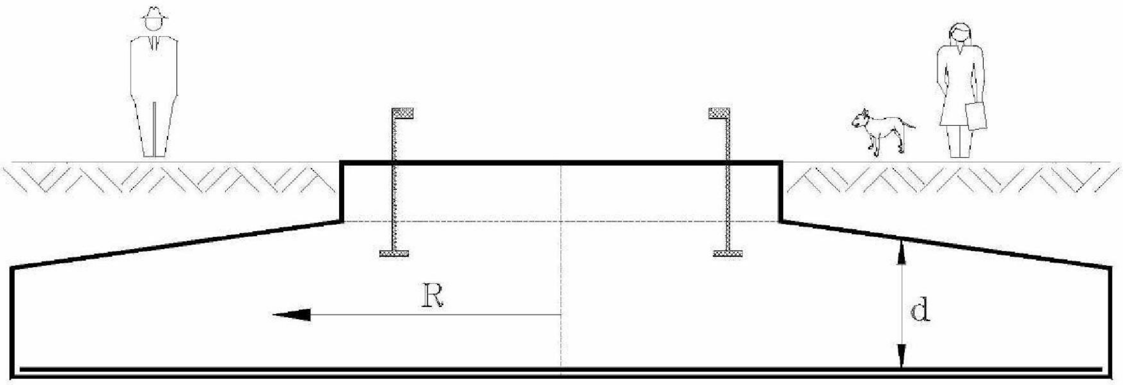
The concrete tower is connected to the foundation by means of the tendons which are placed inside the concrete tower. Senvion has carried out a standard design for a gravity base as well as a piled base. As the interface between the concrete tower and the foundation is very complex minor modifications to the standard foundation may only be carried out according to prior agreement with Senvion

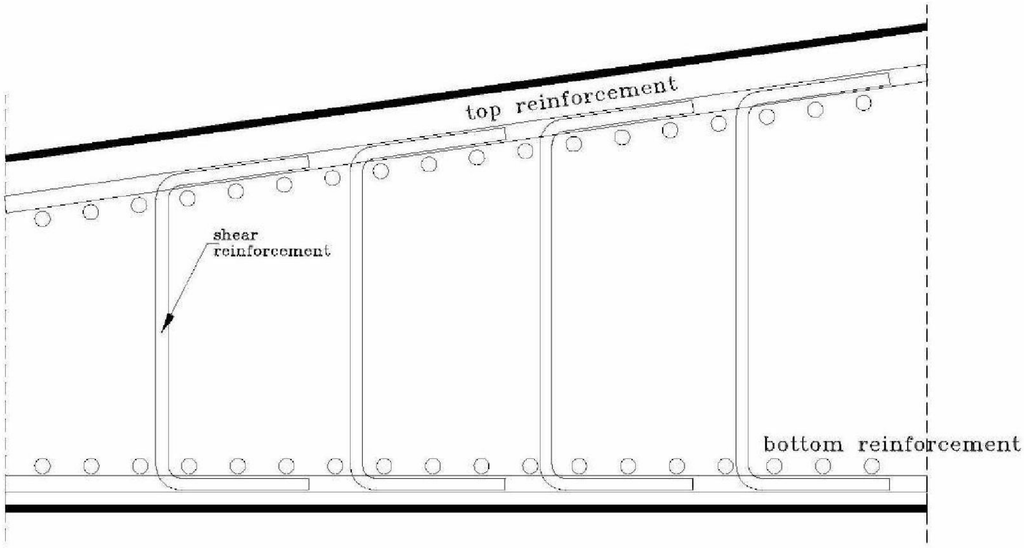
# 5 Senvion Requirements

To assure a proper foundation design Senvion specifies the following minimum requirements. Nevertheless for the foundation design local codes and standards have to be considered.

## 5.1 Shear Reinforcement

Senvion specifies a minimum shear reinforcement depending on the shear forces in the foundation slab. Furthermore local codes and standards have to be considered. Regardless of Senvion`s requirement, the adequacy of the shear reinforcement has to be proven by the designer. Shear reinforcement generally shall embrace the bottom layer of reinforcement as well as the top layer of reinforcement.



| | (Concrete: C30/37) | | | | | | | | | VEd [KN/m] | | | (γ incl.) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| d ↓ | 200 | 400 | 600 | 800 | 1000 | 1200 | 1400 | 1600 | 1800 | 2000 | 2200 | 2400 | 2600 | 2800 | 3000 |
| [cm] | [cm²/m²] | [cm²/m²] | [cm²/m²] | [cm²/m²] | [cm²/m²] | [cm²/m²] | [cm²/m²] | [cm²/m²] | [cm²/m²] | [cm²/m²] | [cm²/m²] | [cm²/m²] | [cm²/m²] | [cm²/m²] | [cm²/m²] |
| 100 | 0.00 | 3.41 | 5.11 | 6.81 | 8.52 | 11.26 | 15.52 | 19.78 | 24.04 | 28.30 | 32.56 | 36.82 | 41.08 | 45.34 | 49.60 |
| 110 | 0.00 | 3.10 | 4.65 | 6.20 | 7.74 | 9.29 | 12.81 | 16.68 | 20.56 | 24.43 | 28.30 | 32.17 | 36.05 | 39.92 | 43.79 |
| 120 | 0.00 | 2.84 | 4.26 | 5.68 | 7.10 | 8.52 | 10.55 | 14.10 | 17.65 | 21.20 | 24.75 | 28.30 | 31.85 | 35.40 | 38.95 |
| 130 | 0.00 | 2.62 | 3.93 | 5.24 | 6.55 | 7.86 | 9.17 | 11.92 | 15.20 | 18.47 | 21.75 | 25.02 | 28.30 | 31.58 | 34.85 |
| 140 | 0.00 | 2.43 | 3.65 | 4.87 | 6.08 | 7.30 | 8.52 | 10.05 | 13.09 | 16.13 | 19.17 | 22.22 | 25.26 | 28.30 | 31.34 |
| 150 | 0.00 | 2.27 | 3.41 | 4.54 | 5.68 | 6.81 | 7.95 | 9.09 | 11.26 | 14.10 | 16.94 | 19.78 | 22.62 | 25.46 | 28.30 |
| 160 | 0.00 | 2.13 | 3.19 | 4.26 | 5.32 | 6.39 | 7.45 | 8.52 | 9.67 | 12.33 | 14.99 | 17.65 | 20.31 | 22.98 | 25.64 |
| 170 | 0.00 | 2.00 | 3.01 | 4.01 | 5.01 | 6.01 | 7.02 | 8.02 | 9.02 | 10.76 | 13.27 | 15.77 | 18.28 | 20.78 | 23.29 |
| 180 | 0.00 | 1.89 | 2.84 | 3.79 | 4.73 | 5.68 | 6.63 | 7.57 | 8.52 | 9.47 | 11.74 | 14.10 | 16.47 | 18.84 | **21.20** |
| 190 | 0.00 | 1.79 | 2.69 | 3.59 | 4.48 | 5.38 | 6.28 | 7.17 | 8.07 | 8.97 | 10.37 | 12.61 | 14.85 | 17.09 | 19.33 |
| 200 | 0.00 | 1.70 | 2.56 | 3.41 | 4.26 | 5.11 | 5.96 | 6.81 | 7.67 | 8.52 | 9.37 | 11.26 | 13.39 | 15.52 | 17.65 |
| 210 | 0.00 | 1.62 | 2.43 | 3.25 | 4.06 | 4.87 | 5.68 | 6.49 | 7.30 | 8.11 | 8.92 | 10.05 | 12.08 | 14.10 | 16.13 |
| 220 | 0.00 | 0.00 | 2.32 | 3.10 | 3.87 | 4.65 | 5.42 | 6.20 | 6.97 | 7.74 | 8.52 | 9.29 | 10.88 | 12.81 | 14.75 |
| 230 | 0.00 | 0.00 | 2.22 | 2.96 | 3.70 | 4.44 | 5.19 | 5.93 | 6.67 | 7.41 | 8.15 | 8.89 | 9.78 | 11.63 | 13.49 |
| 240 | 0.00 | 0.00 | 2.13 | 2.84 | 3.55 | 4.26 | 4.97 | 5.68 | 6.39 | 7.10 | 7.81 | 8.52 | 9.23 | 10.55 | 12.33 |
| 250 | 0.00 | 0.00 | 2.04 | 2.73 | 3.41 | 4.09 | 4.77 | 5.45 | 6.13 | 6.81 | 7.50 | 8.18 | 8.86 | 9.56 | 11.26 |

| | (Concrete: C30/37) | | | | | | | | | VEd [KN/m] | | | (γ incl.) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| d ↓ | 3200 | 3400 | 3600 | 3800 | 4000 | 4200 | 4400 | 4600 | 4800 | 5000 | 5200 | 5400 | 5600 | 5800 | 6000 |
| [cm] | [cm²/m²] | [cm²/m²] | [cm²/m²] | [cm²/m²] | [cm²/m²] | [cm²/m²] | [cm²/m²] | [cm²/m²] | [cm²/m²] | [cm²/m²] | [cm²/m²] | [cm²/m²] | [cm²/m²] | [cm²/m²] | [cm²/m²] |
| 100 | 53.86 | 58.12 | 62.38 | 66.63 | 70.89 | 75.15 | 79.41 | 83.67 | 87.93 | 92.19 | 96.45 | 100.71 | 104.97 | 109.23 | 113.49 |
| 110 | 47.66 | 51.53 | 55.41 | 59.28 | 63.15 | 67.02 | 70.89 | 74.77 | 78.64 | 82.51 | 86.38 | 90.25 | 94.13 | 98.00 | 101.87 |
| 120 | 42.50 | 46.05 | 49.60 | 53.15 | 56.70 | 60.25 | 63.79 | 67.34 | 70.89 | 74.44 | 77.99 | 81.54 | 85.09 | 88.64 | 92.19 |
| 130 | 38.13 | 41.41 | 44.68 | 47.96 | 51.24 | 54.51 | 57.79 | 61.06 | 64.34 | 67.62 | 70.89 | 74.17 | 77.45 | 80.72 | 84.00 |
| 140 | 34.39 | 37.43 | 40.47 | 43.51 | 46.55 | 49.60 | 52.64 | 55.68 | 58.72 | 61.77 | 64.81 | 67.85 | 70.89 | 73.94 | 76.98 |
| 150 | 31.14 | 33.98 | 36.82 | 39.66 | 42.50 | 45.34 | 48.18 | 51.02 | 53.86 | 56.70 | 59.54 | 62.38 | 65.21 | 68.05 | 70.89 |
| 160 | 28.30 | 30.96 | 33.63 | 36.29 | 38.95 | 41.61 | 44.27 | 46.94 | 49.60 | 52.26 | 54.92 | 57.58 | 60.25 | 62.91 | 65.57 |
| 170 | 25.80 | 28.30 | 30.81 | 33.31 | 35.82 | 38.32 | 40.83 | 43.33 | 45.84 | 48.34 | 50.85 | 53.36 | 55.86 | 58.37 | 60.87 |
| 180 | 23.57 | 25.93 | 28.30 | 30.67 | 33.03 | 35.40 | 37.77 | 40.13 | 42.50 | 44.86 | 47.23 | 49.60 | 51.96 | 54.33 | 56.70 |
| 190 | 21.58 | 23.82 | 26.06 | 28.30 | 30.54 | 32.78 | 35.03 | 37.27 | 39.51 | 41.75 | 43.99 | 46.23 | 48.48 | 50.72 | 52.96 |
| 200 | 19.78 | 21.91 | 24.04 | 26.17 | 28.30 | 30.43 | 32.56 | 34.69 | 36.82 | 38.95 | 41.08 | 43.21 | 45.34 | 47.47 | 49.60 |
| 210 | 18.16 | 20.19 | 22.22 | 24.24 | 26.27 | 28.30 | 30.33 | 32.36 | 34.39 | 36.41 | 38.44 | 40.47 | 42.50 | 44.53 | 46.55 |
| 220 | 16.68 | 18.62 | 20.56 | 22.49 | 24.43 | 26.36 | 28.30 | 30.24 | 32.17 | 34.11 | 36.05 | 37.98 | 39.92 | 41.85 | 43.79 |
| 230 | 15.34 | 17.19 | 19.04 | 20.89 | 22.75 | 24.60 | 26.45 | 28.30 | 30.15 | 32.00 | 33.86 | 35.71 | 37.56 | 39.41 | 41.26 |
| 240 | 14.10 | 15.88 | 17.65 | 19.43 | 21.20 | 22.98 | 24.75 | 26.53 | 28.30 | 30.08 | 31.85 | 33.63 | 35.40 | 37.17 | 38.95 |
| 250 | 12.97 | 14.67 | 16.38 | 18.08 | 19.78 | 21.49 | 23.19 | 24.89 | 26.60 | 28.30 | 30.00 | 31.71 | 33.41 | 35.12 | 36.82 |

Example: $V_{Ed}$ = 3000 KN/m d = 180 cm ➔ $a_{s,req}$ = 21.20 cm²/m²

| | (Concrete: C35/45) | | | | | | | | | $V_{Ed}$ [KN/m] | | ($\gamma$ incl.) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| d ↓ | 200 | 400 | 600 | 800 | 1000 | 1200 | 1400 | 1600 | 1800 | 2000 | 2200 | 2400 | 2600 | 2800 | 3000 |
| [cm] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] |
| 100 | 0.00 | 3.41 | 5.11 | 6.81 | 8.52 | 10.51 | 14.77 | 19.03 | 23.29 | 27.55 | 31.81 | 36.07 | 40.33 | 44.58 | 48.84 |
| 110 | 0.00 | 3.10 | 4.65 | 6.20 | 7.74 | 9.29 | 12.06 | 15.93 | 19.80 | 23.68 | 27.55 | 31.42 | 35.29 | 39.16 | 43.04 |
| 120 | 0.00 | 2.84 | 4.26 | 5.68 | 7.10 | 8.52 | 9.94 | 13.35 | 16.90 | 20.45 | 24.00 | 27.55 | 31.10 | 34.65 | 38.20 |
| 130 | 0.00 | 2.62 | 3.93 | 5.24 | 6.55 | 7.86 | 9.17 | 11.17 | 14.44 | 17.72 | 20.99 | 24.27 | 27.55 | 30.82 | 34.10 |
| 140 | 0.00 | 0.00 | 3.65 | 4.87 | 6.08 | 7.30 | 8.52 | 9.74 | 12.34 | 15.38 | 18.42 | 21.46 | 24.51 | 27.55 | 30.59 |
| 150 | 0.00 | 0.00 | 3.41 | 4.54 | 5.68 | 6.81 | 7.95 | 9.09 | 10.51 | 13.35 | 16.19 | 19.03 | 21.87 | 24.71 | 27.55 |
| 160 | 0.00 | 0.00 | 3.19 | 4.26 | 5.32 | 6.39 | 7.45 | 8.52 | 9.58 | 11.58 | 14.24 | 16.90 | 19.56 | 22.22 | 24.89 |
| 170 | 0.00 | 0.00 | 3.01 | 4.01 | 5.01 | 6.01 | 7.02 | 8.02 | 9.02 | 10.02 | 12.51 | 15.02 | 17.53 | 20.03 | 22.54 |
| 180 | 0.00 | 0.00 | 2.84 | 3.79 | 4.73 | 5.68 | 6.63 | 7.57 | 8.52 | 9.47 | 10.98 | 13.35 | 15.72 | 18.08 | **20.45** |
| 190 | 0.00 | 0.00 | 2.69 | 3.59 | 4.48 | 5.38 | 6.28 | 7.17 | 8.07 | 8.97 | 9.86 | 11.86 | 14.10 | 16.34 | 18.58 |
| 200 | 0.00 | 0.00 | 2.56 | 3.41 | 4.26 | 5.11 | 5.96 | 6.81 | 7.67 | 8.52 | 9.37 | 10.51 | 12.64 | 14.77 | 16.90 |
| 210 | 0.00 | 0.00 | 2.43 | 3.25 | 4.06 | 4.87 | 5.68 | 6.49 | 7.30 | 8.11 | 8.92 | 9.74 | 11.32 | 13.35 | 15.38 |
| 220 | 0.00 | 0.00 | 2.32 | 3.10 | 3.87 | 4.65 | 5.42 | 6.20 | 6.97 | 7.74 | 8.52 | 9.29 | 10.12 | 12.06 | 14.00 |
| 230 | 0.00 | 0.00 | 2.22 | 2.96 | 3.70 | 4.44 | 5.19 | 5.93 | 6.67 | 7.41 | 8.15 | 8.89 | 9.63 | 10.88 | 12.73 |
| 240 | 0.00 | 0.00 | 2.13 | 2.84 | 3.55 | 4.26 | 4.97 | 5.68 | 6.39 | 7.10 | 7.81 | 8.52 | 9.23 | 9.94 | 11.58 |
| 250 | 0.00 | 0.00 | 2.04 | 2.73 | 3.41 | 4.09 | 4.77 | 5.45 | 6.13 | 6.81 | 7.50 | 8.18 | 8.86 | 9.54 | 10.51 |

| | (Concrete: C35/45) | | | | | | | | | $V_{Ed}$ [KN/m] | | ($\gamma$ incl.) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| d ↓ | 3200 | 3400 | 3600 | 3800 | 4000 | 4200 | 4400 | 4600 | 4800 | 5000 | 5200 | 5400 | 5600 | 5800 | 6000 |
| [cm] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] | [cm$^2$/m$^2$] |
| 100 | 53.10 | 57.36 | 61.62 | 65.88 | 70.14 | 74.40 | 78.66 | 82.92 | 87.18 | 91.44 | 95.70 | 99.95 | 104.21 | 108.47 | 112.73 |
| 110 | 46.91 | 50.78 | 54.65 | 58.52 | 62.40 | 66.27 | 70.14 | 74.01 | 77.88 | 81.76 | 85.63 | 89.50 | 93.37 | 97.24 | 101.12 |
| 120 | 41.75 | 45.29 | 48.84 | 52.39 | 55.94 | 59.49 | 63.04 | 66.59 | 70.14 | 73.69 | 77.24 | 80.79 | 84.34 | 87.89 | 91.44 |
| 130 | 37.38 | 40.65 | 43.93 | 47.21 | 50.48 | 53.76 | 57.03 | 60.31 | 63.59 | 66.86 | 70.14 | 73.42 | 76.69 | 79.97 | 83.25 |
| 140 | 33.63 | 36.67 | 39.72 | 42.76 | 45.80 | 48.84 | 51.89 | 54.93 | 57.97 | 61.01 | 64.06 | 67.10 | 70.14 | 73.18 | 76.22 |
| 150 | 30.39 | 33.23 | 36.07 | 38.91 | 41.75 | 44.58 | 47.42 | 50.26 | 53.10 | 55.94 | 58.78 | 61.62 | 64.46 | 67.30 | 70.14 |
| 160 | 27.55 | 30.21 | 32.87 | 35.53 | 38.20 | 40.86 | 43.52 | 46.18 | 48.84 | 51.51 | 54.17 | 56.83 | 59.49 | 62.15 | 64.82 |
| 170 | 25.04 | 27.55 | 30.05 | 32.56 | 35.06 | 37.57 | 40.07 | 42.58 | 45.09 | 47.59 | 50.10 | 52.60 | 55.11 | 57.61 | 60.12 |
| 180 | 22.81 | 25.18 | 27.55 | 29.91 | 32.28 | 34.65 | 37.01 | 39.38 | 41.75 | 44.11 | 46.48 | 48.84 | 51.21 | 53.58 | 55.94 |
| 190 | 20.82 | 23.06 | 25.31 | 27.55 | 29.79 | 32.03 | 34.27 | 36.51 | 38.76 | 41.00 | 43.24 | 45.48 | 47.72 | 49.96 | 52.21 |
| 200 | 19.03 | 21.16 | 23.29 | 25.42 | 27.55 | 29.68 | 31.81 | 33.94 | 36.07 | 38.20 | 40.33 | 42.45 | 44.58 | 46.71 | 48.84 |
| 210 | 17.41 | 19.43 | 21.46 | 23.49 | 25.52 | 27.55 | 29.58 | 31.60 | 33.63 | 35.66 | 37.69 | 39.72 | 41.75 | 43.77 | 45.80 |
| 220 | 15.93 | 17.87 | 19.80 | 21.74 | 23.68 | 25.61 | 27.55 | 29.48 | 31.42 | 33.36 | 35.29 | 37.23 | 39.16 | 41.10 | 43.04 |
| 230 | 14.58 | 16.44 | 18.29 | 20.14 | 21.99 | 23.84 | 25.70 | 27.55 | 29.40 | 31.25 | 33.10 | 34.95 | 36.81 | 38.66 | 40.51 |
| 240 | 13.35 | 15.12 | 16.90 | 18.67 | 20.45 | 22.22 | 24.00 | 25.77 | 27.55 | 29.32 | 31.10 | 32.87 | 34.65 | 36.42 | 38.20 |
| 250 | 12.21 | 13.92 | 15.62 | 17.33 | 19.03 | 20.73 | 22.44 | 24.14 | 25.84 | 27.55 | 29.25 | 30.95 | 32.66 | 34.36 | 36.07 |

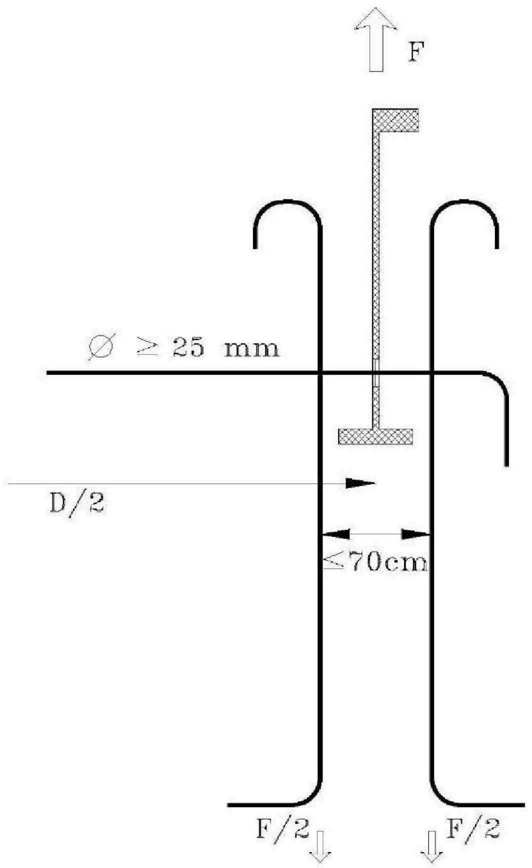
Example: $V_{Ed}$ = 3000 KN/m d = 180 cm → $a_{s,req}$ = 20.45 cm$^2$/m$^2$

## 5.2 Anchor Reinforcement

The embedded steel can is tied back to the foundation slab by anchor reinforcement. Bars within a section of 70 cm may only be taken into account. Regardless of Senvion's requirement, the adequacy of the anchor reinforcement subjected to fatigue as well as to ultimate loads has to by proven by the designer.

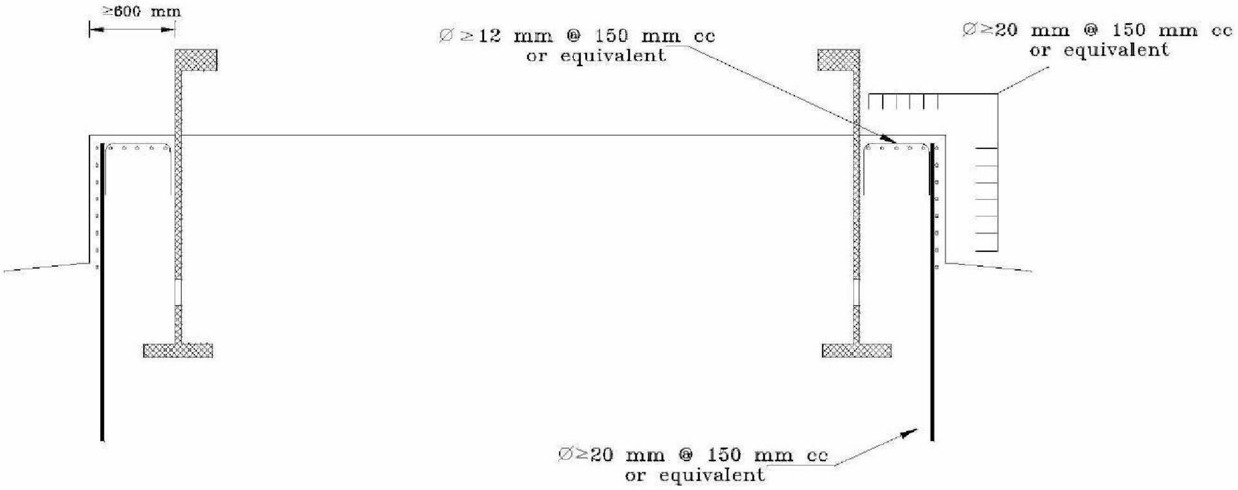
Senvion requirement:

- $M_{res}$ = resultant tower moment incl. safety factor
- $|F_z|$ = vertical load of the tower reduced by safety factor $\gamma = 0.90$
- D = Diameter of the tower
- $F = 4 * M_{res} / D - |F_z|$ force to be covered by anchor reinforcement around the circumference



## 5.3 Design of the Pedestal

To avoid cracking of the pedestal Senvion specifies a minimum reinforcement according to the sketch below:




## 5.4 Top and Bottom Layer Reinforcement

The top and the bottom layer of reinforcement should preferably be arranged using long reinforcement bars which cover the entire width of the foundation slab. If the required length of the bars is not available, the overlap joint should be designed according to the sketch below. Overlap joints have to be placed staggered. It should be avoided to arrange overlaps in the area of high bending moments in the foundation slab. Regardless of Senvion's requirement, the adequacy of the arrangement of reinforcement subjected to fatigue as well as ultimate loads has to by proven by the designer.

Where overlap joints can't be avoided the overlap length shall not be less than **45 times the diameter** of the reinforcement bars.

Because of the high fatigue loads neither “bar to bar connections” like couplers or locks nor welded connections (including spot welds) must be used. The reinforcement cage shall be arranged using tie wires preferably.

The top and the bottom layer of reinforcement has to be designed by means of the finite-element-method taking into account the stiffness of the soil. The curve of moments has to be enveloped by the resistance. Averaging the curve of moments is not admissible.