Chapter 10

Design of footings

The design of footings is covered by Section 6 of Eurocode 7 Part 1, 'Spread foundations', whose contents are as follows:

§6.1 General (2 paragraphs)
§6.2 Limit states (1)
§6.3 Actions and design situations (3)
§6.4 Design and construction considerations (6)
§6.5 Ultimate limit state design (32)
§6.6 Serviceability limit state design (30)
§6.7 Foundations on rock; additional design considerations (3)
§6.8 Structural design of foundations (6)
§6.9 Preparation of the subsoil (2)

Section 6 of EN 1997-1 applies to pad, strip, and raft foundations and some provisions may be applied to deep foundations, such as caissons.

[EN 1997-1 §6.1(1)P and (2)]

10.1 Ground investigation for footings

Annex B.3 of Eurocode 7 Part 2 provides outline guidance on the depth of investigation points for spread foundations, as illustrated in **Figure 133**. (See Chapter 4 for guidance on the spacing of investigation points.)

The recommended minimum depth of investigation, z_a, for spread foundations supporting high-rise structures and civil engineering projects is the greater of:

$z_a \geq 3b_F$ and $z_a \geq 6m$

where b_F is the foundation's breadth. For raft foundations:

$z_a \geq 1.5b_B$

where b_B is the breadth of the raft.

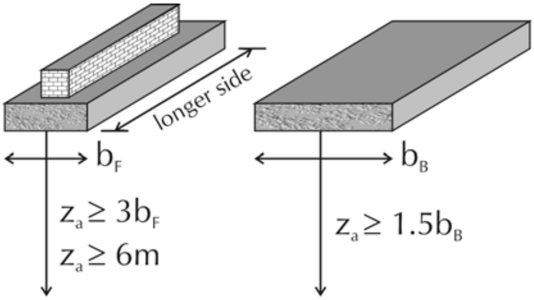

Figure 133. *Recommended depth of investigation for spread foundations*

The depth z_a may be reduced to 2m if the

foundation is built on competent strata† with 'distinct' (i.e. known) geology. With 'indistinct' geology, at least one borehole should go to at least 5m. If bedrock is encountered, it becomes the reference level for z_a.
[EN 1997-2 §B.3(4)]

Greater depths of investigation may be needed for very large or highly complex projects or where unfavourable geological conditions are encountered. *[EN 1997-2 §B.3(2)NOTE and B.3(3)]*

10.2 Design situations and limit states

Figure 134 shows some of the ultimate limit states that spread foundations must be designed to withstand. From left to right, these include: (top) loss of

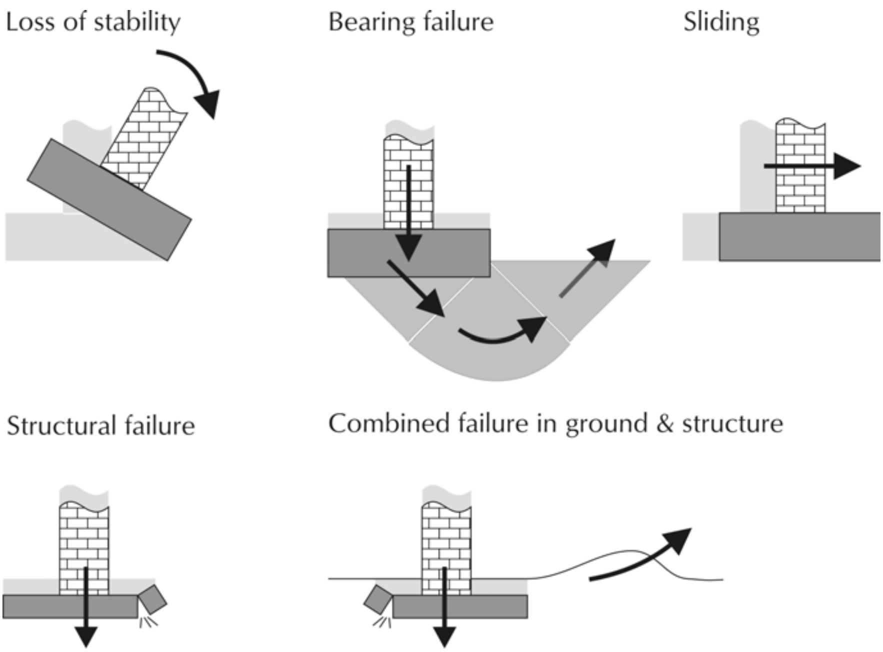

Figure 134. *Examples of ultimate limit states for footings*

stability owing to an applied moment, bearing failure, and sliding owing to an applied horizontal action; and (bottom) structural failure of the foundation base and combined failure in the structure and the ground.

†i.e. weaker strata are unlikely to occur at depth, structural weaknesses such as faults are absent, and solution features and other voids are not expected

Eurocode 7 lists a number of things that must be considered when choosing the depth of a spread foundation, some of which are illustrated in **Figure 135**.
[EN 1997-1 §6.4(1)P]

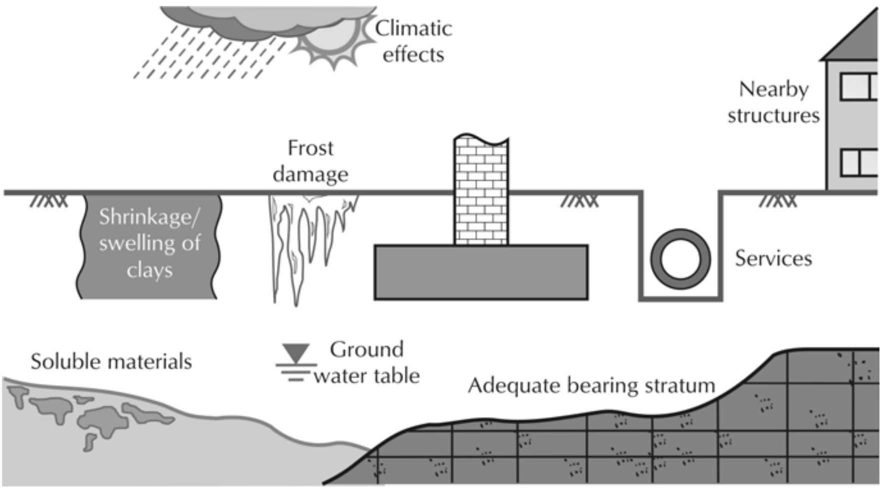

***Figure 135**. Design considerations for footings*

10.3 Basis of design

Eurocode 7 requires spread foundations to be designed using one of the following methods: *[EN 1997-1 §6.4(5)P]*

Method	Description	Constraints
Direct	Carry out separate analyses for each limit state, both ultimate (ULS) and serviceability (SLS)	(ULS) Model envisaged failure mechanism
		(SLS) Use a serviceability calculation
Indirect	Use comparable experience with results of field & laboratory measurements & observations	Choose SLS loads to satisfy requirements of all limit states
Prescriptive	Use conventional & conservative design rules and specify control of construction	Use presumed bearing resistance

The *indirect method* is used predominantly for Geotechnical Category 1 structures, where there is good local experience, ground conditions are well known and uncomplicated, and the risks associated with potential failure or excessive deformation of the structure are low. Indirect methods may also be applied to higher risk structures where it is difficult to predict the structural behaviour with sufficient accuracy from analytical solutions. In these cases, reliance is placed on the observational method and identification of a range potential behaviour. Depending on the observed behaviour, the final design of the foundation can be decided. This approach ensures that the serviceability condition is met but does not explicitly provide sufficient reserve against ultimate conditions. It is therefore important that the limiting design criteria for serviceability are suitably conservative.

The *prescriptive method* may be used for Geotechnical Category 1 structures, where ground conditions are well known. Unlike British standard BS 8004 – which gives allowable bearing pressures for rocks, non-cohesive soils, cohesive soils, peat and organic soils, made ground, fill, high porosity chalk, and Keuper Marl (now called the Mercia Mudstone)[1] – Eurocode 7 only provides values of presumed bearing resistance for rock (via a series of charts[†] in Annex G).

The *direct method* is discussed in some detail in the remainder of this chapter.

This book does not attempt to provide complete guidance on the design of spread foundations, for which the reader should refer to any well-established text on the subject.[2]

10.4 Footings subject to vertical actions

For a spread foundation subject to vertical actions, Eurocode 7 requires the design vertical action V_d acting on the foundation to be less than or equal to the design bearing resistance R_d of the ground beneath it:

$$V_d \leq R_d \qquad \textit{[EN 1997-1 exp (6.1)]}$$

V_d should include the self-weight of the foundation and any backfill on it.

This equation is merely a re-statement of the inequality:

$$E_d \leq R_d$$

discussed at length in Chapter 6. Rather than work in terms of forces, engineers more commonly consider pressures and stresses, so we will rewrite this equation as:

[†]which also appear in BS 8004

$$q_{Ed} \leq q_{Rd}$$

where q_{Ed} is the design bearing pressure on the ground (an action effect), and q_{Rd} is the corresponding design resistance.

Figure 136 shows a footing carrying characteristic vertical actions V_{Gk} (permanent) and V_{Qk} (variable) imposed on it by the super-structure. The characteristic self-weights of the footing and of the backfill upon it are both permanent actions (W_{Gk}). The following sub-sections explain how q_{Ed} and q_{Rd} are obtained from V_{Gk}, V_{Qk}, W_{Gk}, and ground properties.

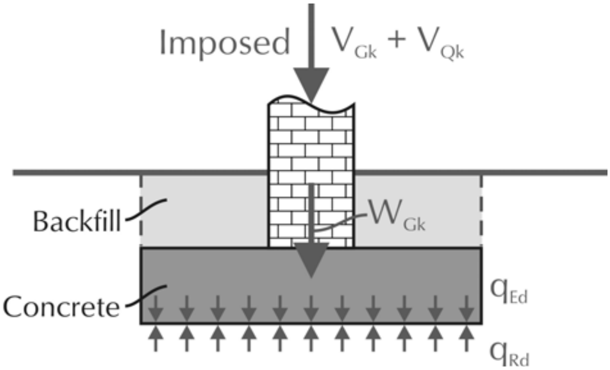

***Figure 136**. Vertical actions on a spread foundation*

10.4.1 Effects of actions

The characteristic bearing pressure q_{Ek} shown in **Figure 136** is given by:

$$q_{Ek} = \frac{\sum V_{rep}}{A'} = \frac{(V_{Gk} + \sum_i \psi_i V_{Qk,i}) + W_{Gk}}{A'}$$

where V_{rep} is a representative vertical action; V_{Gk}, V_{Qk}, and W_{Gk} are as defined above; A′ is the footing's effective area (defined in Section 10.4.2); and ψ_i is the combination factor applicable to the *i*th variable action (see Chapter 2).

If we assume that only one variable action is applied to the footing, this equation simplifies to:

$$q_{Ek} = \frac{(V_{Gk} + V_{Qk,1}) + W_{Gk}}{A'}$$

since $\psi = 1.0$ for the leading variable action ($i = 1$).

The design bearing pressure q_{Ed} beneath the footing is then:

$$q_{Ed} = \frac{\sum V_d}{A'} = \frac{\gamma_G (V_{Gk} + W_{Gk}) + \gamma_Q V_{Qk,1}}{A'}$$

where γ_G and γ_Q are partial factors on permanent and variable actions, respectively.

10.4.2 Eccentric loading and effective foundation area

The ability of a spread foundation to carry forces reduces dramatically when those forces are applied eccentrically from the centre of the foundation.

To prevent contact with the ground being lost at the footing's edges, it is customary to keep the total action within the foundation's 'middle-third'. In other words, the eccentricity of the action from the centre of the footing is kept within the following limits:

$$e_B \le \frac{B}{6} \text{ and } e_L \le \frac{L}{6}$$

where B and L are the footing's breadth and length, respectively; and e_B and e_L are eccentricities in the direction of B and L (see **Figure 137**).

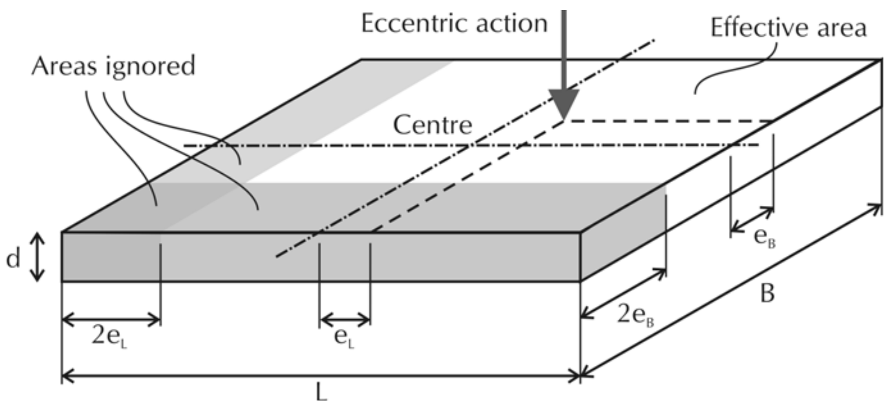

***Figure 137**. Effective area of spread foundation*

Eurocode 7 Part 1 requires 'special precautions' to be taken where:

> *...the eccentricity of loading exceeds 1/3 of the width of a rectangular footing or [60%] of the radius of a circular footing.* *[EN 1997-1 §6.5.4(1)P]*

Note that this is *not* the middle-third rule, but rather a 'middle-two-thirds' rule. We recommend that foundations continue to be designed using the middle-third rule until the implications of Eurocode 7's more relaxed Principle have been thoroughly tested in practice.

Bearing capacity calculations take account of eccentric loading by assuming that the load acts at the centre of a smaller foundation, as shown in **Figure 137**. The shaded parts of the foundation are therefore ignored. The actual foundation area is therefore reduced to an 'effective area' A', which can be calculated from:[3]

Report (GDR) so that responsibilities are clearly articulated and the Client is informed about what to do if monitoring indicates that the structure is not performing adequately. The aims are to ensure the structure is adequately constructed and will perform within the project's acceptance criteria.

10.9 Summary of key points

The design of footings to Eurocode 7 involves checking that the ground has sufficient bearing resistance to withstand vertical actions, sufficient sliding resistance to withstand horizontal and inclined actions, and sufficient stiffness to prevent unacceptable settlement. The first two of these guard against ultimate limit states and the last against a serviceability limit state.

Verification of ultimate limit states is demonstrated by satisfying the inequalities:

$V_d \le R_d$ and $H_d \le R_d + R_{pd}$

(where the symbols are defined in Section 10.3). These equations are merely specific forms of:

$E_d \le R_d$

which is discussed at length in Chapter 6.

Verification of serviceability limit states (SLSs) is demonstrated by satisfying the inequality:

$s_{Ed} = s_0 + s_1 + s_2 \le s_{Cd}$

(where the symbols are defined in Section 10.6). This equation is merely a specific form of:

$E_d \le C_d$

which is discussed at length in Chapter 8. Alternatively, SLSs may be verified by satisfying:

$$E_k \le \frac{R_k}{\gamma_{R,SLS}}$$

where the partial factor $\gamma_{R,SLS} \ge 3$.

10.10 Worked examples

The worked examples in this chapter consider the design of a pad footing on dry sand (Example 10.1); the same footing but eccentrically loaded (Example 10.2); a strip footing on clay (Example 10.3); and, for the same footing, verification of the serviceability limit state (Example 10.4).

Specific parts of the calculations are marked ❶, ❷, ❸, etc., where the numbers refer to the notes that accompany each example.

10.10.1 Pad footing on dry sand

Example 10.1 considers the design of a simple rectangular spread footing on dry sand, as shown in **Figure 141**. It adopts the calculation method given in Annex D of EN 1997-1.

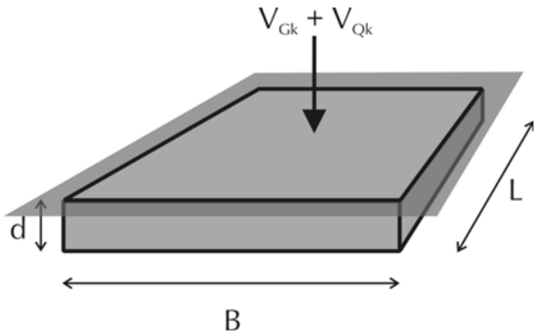

***Figure 141**. Pad footing on dry sand*

In this example it is assumed that ground surface is at the top of the footing, i.e. the base of the footing is 0.5m below ground level.

The loading is applied centrally to the footing and therefore eccentricity can be ignored. Ground water is also not considered. The example concentrates on the application of the partial factors under the simplest of conditions. In reality, the assessment of a footing would need to consider a number of other situations before a design may be finalized.

Notes on Example 10.1

❶ In order to concentrate on the EC7 rather than the geotechnical related issues a relatively simple problem has been selected which excludes the effects of groundwater.

❷ The formulas for bearing capacity factors and shape factors are those given in Annex D. Other formulas could be used where they are thought to give a better theoretical/practical model for the design situation being considered.

❸ The suggested method in Annex D does not include depth factors which are present in other formulations of the extended bearing capacity formula (e.g. Brinch Hansen or Vesic). There has been concern in using these depth factors as their influence can be significant and the reliance on the additional capacity provided by its inclusion is not conservative.

❹ For Design Approach 1, DA1-2 is critical with a utilization factor of 97% implying that the requirements of the code are only just met.

❺ For Design Approach 2 the uncertainty in the calculation is covered through partial factors on the actions and an overall factor on the calculated resistance.

❻ The calculated utilization factor is 75% which would indicate that according to DA2 the footing is potentially over-designed.

❼ Design Approach 3 applies partial factors to both actions and material properties at the same time.

❽ The resultant utilization factor is 123% thus the DA3 calculation suggests the design is unsafe and re-design would be required.

The three Design Approaches give different assessments of the suitability of the proposed foundation for the design loading. Of the three approaches, DA1 suggests the footing is only just satisfactory whilst DA3 suggests redesign would be required and DA2 may indicate that the footing is overdesigned!

Which approach is the most appropriate cannot be determined although DA3 would appear unnecessarily conservative by providing significant partial factors on both actions and material properties.

Example 10.1
Pad footing on dry sand
Verification of strength (limit state GEO)

Design situation

Consider a rectangular pad footing of length $L = 2.5\text{m}$, breadth $B = 1.5\text{m}$, and depth $d = 0.5\text{m}$, which is required to carry an imposed permanent action $V_{Gk} = 800\text{kN}$ and an imposed variable action $V_{Qk} = 450\text{kN}$, both of which are applied at the centre of the foundation. The footing is founded on dry sand❶ with characteristic angle of shearing resistance $\varphi_k = 35°$, effective cohesion $c'_k = 0\text{kPa}$, and weight density $\gamma_k = 18\frac{\text{kN}}{\text{m}^3}$. The weight density of the reinforced concrete is $\gamma_{ck} = 25\frac{\text{kN}}{\text{m}^3}$ (as per EN 1991-1-1 Table A.1).

Design Approach 1

Actions and effects

Characteristic self-weight of footing is $W_{Gk} = \gamma_{ck} \times L \times B \times d = 46.9\,\text{kN}$

Partial factors from sets A1 and A2: $\gamma_G = \begin{pmatrix} 1.35 \\ 1 \end{pmatrix}$ and $\gamma_Q = \begin{pmatrix} 1.5 \\ 1.3 \end{pmatrix}$

Design vertical action: $V_d = \gamma_G \times \left(W_{Gk} + V_{Gk}\right) + \gamma_Q \times V_{Qk} = \begin{pmatrix} 1818.3 \\ 1431.9 \end{pmatrix}\text{kN}$

Area of base: $A_b = L \times B = 3.75\,\text{m}^2$

Design bearing pressure: $q_{Ed} = \frac{V_d}{A_b} = \begin{pmatrix} 484.9 \\ 381.8 \end{pmatrix}\text{kPa}$

Material properties and resistance

Partial factors from sets M1 and M2: $\gamma_\varphi = \begin{pmatrix} 1 \\ 1.25 \end{pmatrix}$ and $\gamma_c = \begin{pmatrix} 1 \\ 1.25 \end{pmatrix}$

Design angle of shearing resistance is $\varphi_d = \tan^{-1}\left(\frac{\tan(\varphi_k)}{\gamma_\varphi}\right) = \begin{pmatrix} 35 \\ 29.3 \end{pmatrix}°$

Design cohesion is $c'_d = \frac{c'_k}{\gamma_c} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}\text{kPa}$

Bearing capacity factors

For overburden: $N_q = \overrightarrow{\left[e^{(\pi \times \tan(\varphi_d))} \times \left(\tan\left(45° + \frac{\varphi_d}{2}\right)\right)^2\right]} = \begin{pmatrix} 33.3 \\ 16.9 \end{pmatrix}$

For cohesion: $N_c = \overrightarrow{\left[(N_q - 1) \times \cot(\varphi_d)\right]} = \begin{pmatrix} 46.1 \\ 28.4 \end{pmatrix}$

For self-weight: $N_\gamma = \overrightarrow{\left[2(N_q - 1) \times \tan(\varphi_d)\right]} = \begin{pmatrix} 45.2 \\ 17.8 \end{pmatrix}$ ❷

Shape factors

For overburden: $s_q = \overrightarrow{\left[1 + \left(\frac{B}{L}\right) \times \sin(\varphi_d)\right]} = \begin{pmatrix} 1.34 \\ 1.29 \end{pmatrix}$

For cohesion: $s_c = \frac{\overrightarrow{(s_q \times N_q - 1)}}{N_q - 1} = \begin{pmatrix} 1.35 \\ 1.31 \end{pmatrix}$

For self-weight: $s_\gamma = 1 - 0.3 \times \left(\frac{B}{L}\right) = 0.82$ ❸

Bearing resistance

Overburden at foundation base is $\sigma'_{vk,b} = \gamma_k \times d = 9\,kPa$

Partial factors from set R1: $\gamma_{Rv} = \begin{pmatrix} 1.0 \\ 1.0 \end{pmatrix}$

From overburden $q_{ult_1} = \overrightarrow{(N_q \times s_q \times \sigma'_{vk,b})} = \begin{pmatrix} 402.8 \\ 196.9 \end{pmatrix} kPa$

From cohesion $q_{ult_2} = \overrightarrow{(N_c \times s_c \times c'_d)} = \begin{pmatrix} 0 \\ 0 \end{pmatrix} kPa$

From self-weight $q_{ult_3} = \overrightarrow{\left(N_\gamma \times s_\gamma \times \gamma_k \times \frac{B}{2}\right)} = \begin{pmatrix} 500.7 \\ 197.5 \end{pmatrix} kPa$

Total resistance $q_{ult} = \sum_{i=1}^{3} \overrightarrow{q_{ult_i}} = \begin{pmatrix} 903.5 \\ 394.4 \end{pmatrix} kPa$

Design resistance is $q_{Rd} = \frac{q_{ult}}{\gamma_{Rv}} = \begin{pmatrix} 903.5 \\ 394.4 \end{pmatrix} kPa$

Verification of bearing resistance

Utilization factor $\boxed{\Lambda_{GEO,1} = \frac{q_{Ed}}{q_{Rd}} = \begin{pmatrix} 54 \\ 97 \end{pmatrix} \%}$ ❹

Design is unacceptable if utilization factor is > 100%

Design Approach 2

Actions and effects

Partial factors from set A1: $\gamma_G = 1.35$ and $\gamma_Q = 1.5$

Design action is $V_d = \gamma_G \times \left(W_{Gk} + V_{Gk}\right) + \gamma_Q \times V_{Qk} = 1818.3\,\text{kN}$

Design bearing pressure is $q_{Ed} = \frac{V_d}{A_b} = 484.9\,\text{kPa}$

Material properties and resistance

Partial factors from set M1: $\gamma_\varphi = 1.0$ and $\gamma_c = 1.0$

Design angle of shearing resistance is $\varphi_d = \tan^{-1}\left(\frac{\tan\left(\varphi_k\right)}{\gamma_\varphi}\right) = 35\,°$

Design cohesion is $c'_d = \frac{c'_k}{\gamma_c} = 0\,\text{kPa}$

Bearing capacity factors

For overburden: $N_q = e^{\left(\pi \times \tan\left(\varphi_d\right)\right)}\left(\tan\left(45° + \frac{\varphi_d}{2}\right)\right)^2 = 33.3$

For cohesion: $N_c = \left(N_q - 1\right) \times \cot\left(\varphi_d\right) = 46.1$

For self-weight: $N_\gamma = 2\left(N_q - 1\right) \times \tan\left(\varphi_d\right) = 45.2$

Shape factors

For overburden: $s_q = 1 + \left(\frac{B}{L}\right) \times \sin\left(\varphi_d\right) = 1.34$

For cohesion: $s_c = \frac{s_q \times N_q - 1}{N_q - 1} = 1.35$

For self-weight: $s_\gamma = 1 - 0.3 \times \left(\frac{B}{L}\right) = 0.82$

Bearing resistance

Partial factor from set R2: $\gamma_{Rv} = 1.4$ ❺

From overburden $q_{ult_1} = N_q \times s_q \times \sigma'_{vk,b} = 402.8\,kPa$

From cohesion $q_{ult_2} = N_c \times s_c \times c'_d = 0\,kPa$

From self-weight $q_{ult_3} = N_\gamma \times s_\gamma \times \gamma_k \times \frac{B}{2} = 500.7\,kPa$

Total resistance $q_{ult} = \sum q_{ult} = 903.5\,kPa$

Design resistance is $q_{Rd} = \frac{q_{ult}}{\gamma_{Rv}} = 645.3\,kPa$

Verification of bearing resistance

Utilization factor $\boxed{\Lambda_{GEO,2} = \frac{q_{Ed}}{q_{Rd}} = 75\,\%}$ ❻

Design is unacceptable if utilization factor is > 100%

Design Approach 3

Actions and effects

Partial factors on structural actions from set A1: $\gamma_G = 1.35$ and $\gamma_Q = 1.5$

Design vertical action $V_d = \gamma_G \times \left(W_{Gk} + V_{Gk}\right) + \gamma_Q \times V_{Qk} = 1818.3\,kN$

Design bearing pressure $q_{Ed} = \frac{V_d}{A_b} = 484.9\,kPa$

Material properties and resistance

Partial factors from set M1: $\gamma_\varphi = 1.25$ and $\gamma_c = 1.25$ ❼

Design angle of shearing resistance is $\varphi_d = \tan^{-1}\left(\frac{\tan(\varphi_k)}{\gamma_\varphi}\right) = 29.3\,°$

Design cohesion is $c'_d = \frac{c'_k}{\gamma_c} = 0\,kPa$

Bearing capacity factors

For overburden: $N_q = e^{(\pi \times \tan(\varphi_d))} \times \left(\tan\left(45° + \frac{\varphi_d}{2}\right)\right)^2 = 16.9$

For cohesion: $N_c = (N_q - 1) \times \cot(\varphi_d) = 28.4$

For self-weight: $N_\gamma = 2(N_q - 1) \times \tan(\varphi_d) = 17.8$

Shape factors

For overburden: $s_q = 1 + \left(\frac{B}{L}\right) \times \sin(\varphi_d) = 1.29$

For cohesion: $s_c = \frac{s_q \times N_q - 1}{N_q - 1} = 1.31$

For self-weight: $s_\gamma = 1 - 0.3 \times \left(\frac{B}{L}\right) = 0.82$

Bearing resistance

Partial factor from set R2: $\gamma_{Rv} = 1$

From overburden $q_{ult_1} = N_q \times s_q \times \sigma'_{vk,b} = 196.9\,\text{kPa}$

From cohesion $q_{ult_2} = N_c \times s_c \times c'_d = 0\,\text{kPa}$

From self-weight $q_{ult_3} = N_\gamma \times s_\gamma \times \gamma_k \times \frac{B}{2} = 197.5\,\text{kPa}$

Total resistance $q_{ult} = \sum q_{ult} = 394.4\,\text{kPa}$

Design resistance $q_{Rd} = \frac{q_{ult}}{\gamma_{Rv}} = 394.4\,\text{kPa}$

Verification of bearing resistance

Utilization factor $\boxed{\Lambda_{GEO,3} = \frac{q_{Ed}}{q_{Rd}} = 123\,\%}$ ❽

Design is unacceptable if utilization factor is > 100%