EN 1997-1 Eurocode 7

Section 3 – Geotechnical Data

Section 6 – Spread Foundations

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EN 1997-1: Section 3

Geotechnical Data

Section 3 – Overview

- The fact that EN 1997-1 has a separate section on Geotechnical Data demonstrates that the **determination of geotechnical data** is an essential part of the **geotechnical design process**
- This is because soil is a **natural material**, unlike the manufactured materials in the other structural Eurocodes, where the data for these materials is **specified**
- **Section 3 Geotechnical Data** provides the general requirements for:
  - the **collection** of geotechnical data
  - the **evaluation** of geotechnical parameters
  - The **presentation** of geotechnical information
- It is linked to **Section 2** which presents the **factors to be considered** when **determining** geotechnical parameter values and the requirements for **selecting characteristic values**
- It is also linked to **EN 1997: Part 2** which gives the requirements for **deriving the values** of geotechnical parameters from field and laboratory tests

Geotechnical Investigations

- The importance of **carefully planned**, **appropriately executed** and **reported** investigations that provide sufficient data concerning the ground is stressed in 3.1 and 3.2

- Provisions for two types of investigations are given:
  - **Preliminary** investigations
  - **Design** investigations
  - **Control** investigations

- Requirements are given for the **reporting** of ground investigations in a **Ground Investigation Report**

Stages in Determining Parameter Values

- The procedures involved in **determining the design values** of geotechnical parameters from field or laboratory **test results** may be considered as consisting of **three stages or steps** (Frank et al. 2004)
- The **first step** is to go from measured values, taking account of the test conditions, and assess the **geotechnical parameter values** (i.e. the properties of soil or rock at a particular location in the ground) – 2.4.3 and **3.3**
- The **second step** is to take account of the design situation and assess the **characteristic value** as a cautious estimate of the geotechnical parameter values affecting the occurrence the limit state – 2.4.5.2
- The **third step** is to obtain the **design parameter value** by applying a partial factor to the characteristic value – 2.4.7.3.3

Characteristic Values from Measured Values

Step 1
Covered by:
EN 1997-1,
Clauses 2.4.3, **3.3**
and
EN 1997-2

Measured Values

Test related correction, independent of any further analysis

Test Results

Results of field tests at particular points in the ground or locations on a site or laboratory tests on particular specimens

Selection of relevant test results e.g. peak or constant volume strengths

Theory, empirical relationships or correlations to obtain *Derived values*

Assessment of influence of test and design conditions on parameter value

Geotechnical Parameter Values

Quantified for design calculations

Step 2
Covered by
EN 1997-1,
Clause 2.4 5.2

Cautious estimate of geotechnical parameter value taking account of:
- Test conditions, Nature of ground
- Particular limit state, Nature of structure

Characteristic Parameter Value

Evaluation of Geotechnical Parameters

- The **factors to be considered** when evaluating soil and rock parameters are given in the following sub-sections of **3.3**:
  - Characteristics of soil and rock types
  - Weight density
  - Density index
  - Degree of compaction
  - Soil shear strength
  - Soil stiffness
  - Quality and properties of rock masses
  - Permeability and consolidation parameters of soil and rock
  - Geotechnical parameters from field tests:
    - CPT
    - SPT
    - Vane test
    - Weight sounding test
    - Pressuremeter test
    - Dilatometer test
    - Compactability test

Ground Investigation Report

- Section 3 states that the results of a geotechnical investigation shall be presented in a **Ground Investigation Report**
- The Ground Investigation Report should form part of the **Geotechnical Design Report**
- A comprehensive list of items to be included in this report is provided
- The Ground Investigation Report should normally include**:**
  - A presentation of all the geotechnical information – i.e. a **factual report**
  - A geotechnical evaluation of the information, stating the assumptions made in the interpretation of the test results – i.e. an **interpretative report**

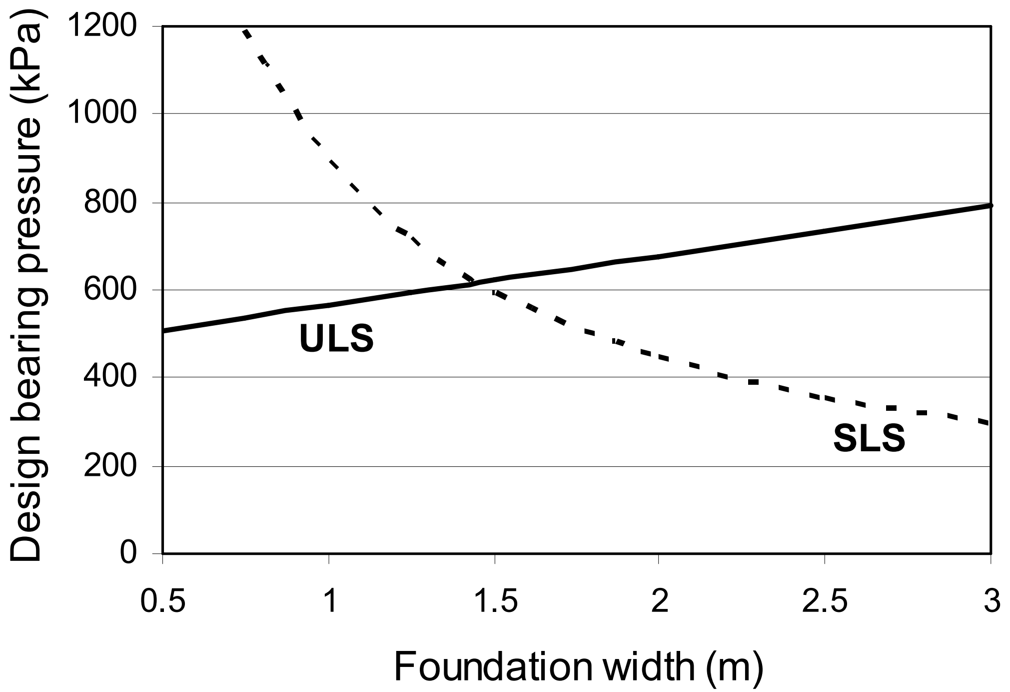
EN 1997-1: Section 6

Spread Foundations

Limit States

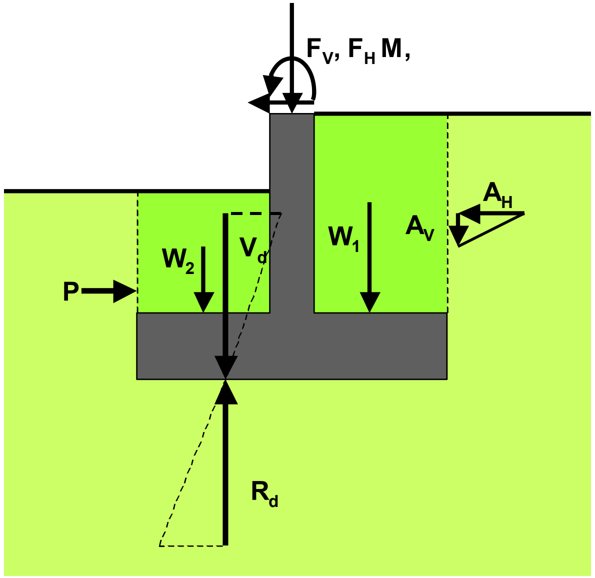
- Provisions apply to **pads, strip and raft** foundations
- Relevant to foundations for **gravity retaining walls** and **bridges** as well as buildings
- **List of limit states** to be considered and compiled is given:
  - Loss of overall stability
  - Bearing resistance failure
  - Failure by sliding
  - Combined failure in ground and structure
  - Structural failure due to ground movement
  - Excessive settlements
  - Excessive heave due to swelling frost heave and other causes
  - Unacceptable vibrations
- Some of above are ultimate limit states and some are serviceability limit states – **both** need to be **considered**
- Note term “bearing **resistance**” is used instead of “bearing **capacity**”
- Failure by **overturning** is **not** a **relevant** limit state – failure by bearing resistance will occur first

Controlling Limit State



As the **load** that a foundation has to support **increases**, and hence as the foundation **width increases**, the **controlling limit state changes** from bearing failure (ULS) to excessive settlement (SLS). Hence **need to check both ULS** and **SLS**

Calculation Model



from Frank et al.

- **Equilibrium** Equation to be satisfied $F_d \leq R_d$
- Equation is in terms of **forces**, **not** ensuring stresses do not exceed the **allowable stress**, as in traditional design
- Hence the **model** for bearing resistance failure is a rectangular **plastic stress block** at the limiting stress beneath the foundation, similar to the plastic stress block in the ultimate limit state design of a concrete beam
- The design bearing resistance force, R_d acts through the **centre** of this **stress block** over effective foundation area, **A'**
- Need to consider both **drained** and **undrained** conditions

Design Method

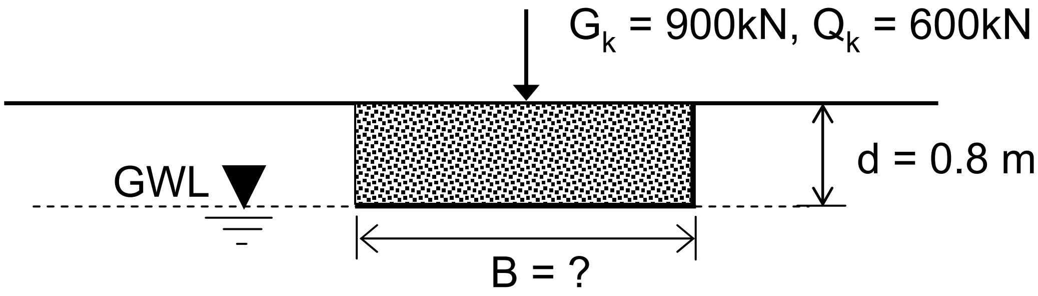
Direct Method

- Carry out a **separate analysis for each limit state**. Calculation method shall model as closely as possible the failure mechanism envisaged, e.g.
  - Bearing resistance model for ULS
  - Settlement calculation for SLS

Indirect Method

- Using comparable experience and field or laboratory measurements or observations, chosen in relation to SLS loads, so as satisfy the requirements of all limit states
- Example: considering **SLS** for conventional structures founded on clays, the ratio between the bearing resistance of the ground, at its initial characteristic shear strength, to the applied serviceability loading, $R_{u,k} / F_k$, should be calculated (6.6.2(16)):
  - If $R_{u,k} / F_k < 3$, calculation of settlements should **always be undertaken**
  - If $R_{u,k} / F_k < 2$, calculation of settlements should take account of **non-linear stiffness effects** of the ground

Spread Foundation Example



Design Situation:

Square pad foundation for a building, 0.8m embedment depth; groundwater level at base of foundation. Central vertical load. Allowable settlement is 25mm.

Characteristic values of actions:

Permanent vertical load = 900 kN + weight of foundation
Variable vertical load = 600 kN
Concrete weight density = 24 kN/m^3.

Ground Properties:

Overconsolidated glacial till, $c_{u;k}$ = 200 kPa, c'_k = 0kPa, $\varphi'_k = 35^o$, γ_k = 22kN/m^3
SPT N = 40, $m_{v;k}$ = 0.015 m^2/MN.

Require foundation width, B

To satisfy both **ULS** (drained and undrained conditions) and **SLS**

Using **recommended partial factors values**

Direct Method

ULS calculations for 3 Design Approaches

- DA1 - Combination 1
  Combination 2
- DA2
- DA3

For:
- Undrained Conditions
- Drained Conditions

SLS calculation

Undrained Conditions

General Equation for undrained design bearing resistance $R_{u;d}$ **/ A'** for all Design Approaches

Annex D - Eqn. D.1:

$$R_{u;d} / A' = ((\pi + 2)\, c_{u;d}\, b_c\, s_c\, i_c + q_d) / \gamma_R$$

$$= ((\pi + 2)(c_{u,k}/\gamma_{cu})\, b_c\, s_c\, i_c + \gamma_\gamma\, q_k) / \gamma_R$$

$$= ((\pi + 2)(c_{u;k}/\gamma_{cu})\, b_c\, s_c\, i_c + \gamma_\gamma\, \gamma\, d) / \gamma_R$$

where : $c_{u;k}$, $c_{u;d}$ = characteristic and design values of c_u

b_c = 1.0 for a horizontal foundation base

s_c = 1.2 for a square foundation and

i_c = 1.0 for a vertical load

` γ = 22.0 = weight density of the soil

γ_{cu} = partial factor on c_u

γ_γ = partial factor on soil weight density, always = 1.0

γ_R = partial resistance factor

Substituting known values in Eqn. D.1:

$$R_{u;d} / A' = (5.14 \times (200 / \gamma_{cu}) \times 1.0 \times 1.2 \times 1.0 + 1.0 \times 22 \times 0.8) / \gamma_R$$

$$= (6.17 \times 200 / \gamma_{cu} + 17.6) / \gamma_R$$

General Equation: $R_{u;d}/A' = (1234.0 / \gamma_{cu} + 17.6) / \gamma_R$

Design Approach 1 – Combination 1

Check $V_d \leq R_d$ for a **1.32 m x 1.32 m pad,** where $V_d = F_d$

- Design value of the vertical action

$$V_d = \gamma_G(G_k + G_{pad;k}) + \gamma_Q Q_k = \gamma_G (G_k + A\,\gamma_c d) + \gamma_Q Q_k$$

where $G_{pad;k}$ = characteristic weight of the concrete pad, γ_c = weight density of concrete, d = depth of the pad and γ_Q = partial factor on variable actions. Substituting values for parameters gives:

$$\mathbf{V_d} = 1.35\,(900 + 1.32^2 \times 24.0 \times 0.8) + 1.5 \times 600 = \underline{\mathbf{2160.2\ kN}}$$

- Design value of the bearing resistance

$$\mathbf{R_d} = 1.32^2(1234.0 / \gamma_{cu} + 17.6) / \gamma_R = 1.742(1234.0 / 1.0 + 17.6) / 1.0 = \underline{\mathbf{2180.8\ kN}}$$

The ULS design requirement $\mathbf{V_d \leq R_d}$ **is fulfilled** as 2160.2 kN < 2180.8 kN.

Design Approach 1 – Combination 2

Check $V_d \leq R_d$ for a **1.39 m x 1.39 m pad**

- Design value of the vertical action

$$V_d = \gamma_G(G_k + G_{pad;k}) + \gamma_Q Q_k = 1.0\,(900 + 1.39^2 \times 24.0 \times 0.8) + 1.3 \times 600 = \underline{\mathbf{1717.1\ kN}}$$

- Design value of the bearing resistance

$$R_d = 1.39^2\,(1234.0 / 1.4 + 17.6)\,/\,1.0 = \underline{\mathbf{1737.0\ kN}}$$

The ULS design requirement $\mathbf{V_d \leq R_d}$ **is fulfilled** as 1717.1 kN < 1737.0 kN

Since B = 1.39m for DA1.C2 > B = 1.32m for DA1.C1

DA1 Design Width for Undrained Conditions: DA1 = 1.39m (given by DA1.C2)

Designs for DA2 and DA3 – Undrained Conditions

Design Approach 2

Check $V_d \le R_d$ for a **1.57 m x 1.57 m pad**

- Design value of the vertical action

$V_d = \gamma_G (G_k + A\, \gamma_c d) + \gamma_Q Q_k$

$\mathbf{V_d} = 1.35\,(900 + 1.57^2 \times 24.0 \times 0.8) + 1.5 \times 600 = \underline{\mathbf{2178.9\ kN}}$

- Design value of the bearing resistance

$\mathbf{R_d} = 1.57^2(1234.0 / \gamma_{cu} + 17.6) / \gamma_R = 2.465(1234.0 / 1.0 + 17.6) / 1.4 = \underline{\mathbf{2203.6\ kN}}$

The ULS design requirement **$V_d \le R_d$ is fulfilled** as 2178.9 kN < 2203.6 kN.

DA2 Design Width for Undrained Conditions: DA2 = 1.57m

Design Approach 3

Check $V_d \le R_d$ for a **1.56 m x 1.56 m pad**

- Design value of the vertical action

$V_d = \gamma_G(G_k + G_{pad;k}) + \gamma_Q Q_k = 1.35\,(900 + 1.56^2 \times 24.0 \times 0.8) + 1.5 \times 600 = \underline{\mathbf{2178.1\ kN}}$

- Design value of the bearing resistance

$R_d = 1.56^2\,(1234.0 / 1.4 + 17.6\,) / 1.0 = \underline{\mathbf{2187.8\ kN}}$

The ULS design requirement **$V_d \le R_d$ is fulfilled** as 2178.1 kN < 2187.8 kN

DA3 Design Width for Undrained Conditions: DA3 = 1.56m

Overall Factor of Safety (OFS)

$OFS = R_{u;k} / V_k$

- For permanent load only and undrained conditions:
- $V_k = G_k$ $V_d = \gamma_G G_k$
- $R_{u;k} / A' = (\pi + 2)\, c_{u;k}\, b_c\, s_c\, i_c$ $R_{u;d} / A' = ((\pi + 2)\, (c_{u;k} / \gamma_{cu})\, b_c\, s_c\, i_c) / \gamma_R$
- If $V_d = R_{u;d}$, $OFS = R_{u;k} / V_k = (R_{u;d} \times \gamma_{cu} \times \gamma_R) / (V_d / \gamma_G) = \gamma_G \times \gamma_{cu} \times \gamma_R$
- Hence OFS for 3 Design Approaches

	γ_G (A)	G_{cu} (M)	γ_R (R)	OFS
DA1.C1	1.35	1.0	1.0	1.35
DA1.C2	1.0	1.4	1.0	**1.4**
DA2	1.35	1.0	1.4	**1.89**
DA3	1.35	1.4	1.0	**1.89**

- **OFS values less** than value of 2 – 3 traditionally used for design, particularly for DA1
- Hence **SLS more likely** to control foundation design on cohesive soils
- Greater use of **SLS in future** as models and analytical methods for predicting foundation settlements improve

Drained Conditions

General Equation for drained design bearing resistance **$R_{d;d}$ / A'** for all Design Approaches

Annex D, Eqn. D.2:

$$R_{d;d}/A' = (c'_d N_{c;d} b_{c;d} s_{c;d} i_{c;d} + q'_d N_{q;d} b_{q;d} s_{q;d} i_{q;d} + 0.5\ \gamma'_d\ B'\ N_{\gamma;d} b_{\gamma;d} s_{\gamma;d} i_{\gamma;d}) / \gamma_R$$

Where all parameters are **design values** and c terms ignored as c' = 0:

A' = effective foundation area (reduced area with load acting through its centre)

$N_{q;d} = e^{\pi \tan\phi'_d} \tan^2(\pi/4 + \phi'_d/2)$

$N_{\gamma;d} = 2\ (N_q - 1) \tan\phi'_d$

$s_{q;d} = 1 + \sin\phi'_d$

$s_{\gamma;d} = 0.7$

$$R_d = A'\ (q'_d N_{q;d} s_{q;d} + 0.5\ \gamma'_d B' N_{\gamma;d}\ s_{\gamma;d}) / \gamma_R$$

$\phi'_d = \tan^{-1}(\tan\phi'_k) / \gamma_M = \tan^{-1}(\tan 35/1.25) = 29.3^o$

Bearing resistance checked for ground water level at ground surface. If γ_w = 9.81 kN/m^3:

γ'_d = (22.0 x 1.0 – 9.81) x 1.0 = 12.19 kN/m^3

$q'_d = \gamma'_d d$ = 12.19 x 1.0 x 0.8 = 9.75 kPa

Design for DA1 – Drained Conditions

Design Approach 1 – Combination 1

Check $V_d \leq R_d$ for a **1.62 m x 1.62 m pad**

- Design value of the vertical action

$$\mathbf{V_d} = \gamma_G (G_k + \gamma_c' A\ d) + \gamma_Q Q_k$$

$$= 1.35\ (900 + (24.0 - 9.81) \times 1.62^2 \times 0.8 + 1.5 \times 600 = \underline{\mathbf{2155.2\ kN}}$$

Note: Submerged weight of foundation used. Alternatively could use total weight and subtract uplift force due to water pressure under foundation

- Design value of the bearing resistance

$$\mathbf{R_{d;d}} = A\ (q'\ N_{q;d} s_{q;d} + 0.5\gamma'_d B' N_{\gamma;d}\ s_{\gamma;d}) / \gamma_R$$

$$= 1.62^2\ (9.75 \times 33.3 \times 1.57 + 0.5 \times 12.19 \times 1.62 \times 45.23 \times 0.7) / 1.0 = \underline{\mathbf{2158.2\ kN}}$$

The ULS design requirement $\mathbf{V_d \leq R_d}$ **is fulfilled** as 2155.2 kN < 2158.2 kN.

Design Approach 1 – Combination 2

Check $V_d \leq R_d$ for a **2.08m x 2.08 m pad**

- Design value of the vertical action

$$\mathbf{V_d} = \gamma_G (G_k + \gamma_c' A\ d) + \gamma_Q Q_k = 1.0\ (900 + (24.0 - 9.81) \times 2.08^2 \times 0.8) + 1.3 \times 600 = \underline{\mathbf{1729.1\ kN}}$$

- Design value of the bearing resistance

$$R_d = 2.08^2\ (9.75 \times 16.92 \times 1.49 + 0.5 \times 12.19 \times 2.08 \times 17.84 \times 0.7) / 1.0 = \underline{\mathbf{1748.4\ kN}}$$

The ULS design requirement $\mathbf{V_d \leq R_d}$ **is fulfilled** as 1729.1 kN < 1748.4 kN

b = 2.08m for **DA1.C2 >** b = 1.62m for **DA1.C1**

DA1 Design Width – Drained Conditions: DA1 = 2.08m - given by DA1.C1

Designs for DA2 and DA3 – Drained Conditions

Design Approach 2

Check $V_d \le R_d$ for a **1.87 m x 1.87 m pad**

- Design value of the vertical action

$V_d = \gamma_G (G_k + \gamma_c' A\ d) + \gamma_Q Q_k$

$\mathbf{V_d}$ = 1.35 (900 + (24.0 – 9.81) x 1.87² x 0.8) + 1.5 x 600 = **2168.6 kN**

- Design value of the bearing resistance

$\mathbf{R_d}$ = 1.87² (9.75 x 33.3 x 1.57 + 0.5 x 12.19 x 1.87 x 45.23 x 0.7) / 1.4 = **2174.6 kN**

The ULS design requirement $\mathbf{V_d \le R_d}$ **is fulfilled** as 2178.6 kN < 2203.6 kN.

DA2 Design Width for Undrained Conditions: DA2 = 1.57m

Design Approach 3

Check $V_d \le R_d$ for a **2.29 m x 2.29 m pad**

- Design value of the vertical action

$V_d = \gamma_G(G_k + \gamma_c' A\ d) + \gamma_Q Q_k$ = 1.35 (900 + (24.0 – 9.81) x 2.29² x 0.8) + 1.5 x 600 = **2195.4 kN**

- Design value of the bearing resistance

R_d = 2.29² (9.75 x 16.92 x 1.49 + 0.5 x 12.19 x 2.29 x 17.84 x 0.7)/1.0 = **2203.1 kN**

The ULS design requirement $\mathbf{V_d \le R_d}$ **is fulfilled** as 2195.4 < 2203.1 kN

DA3 Design Width for Undrained Conditions: DA3 = 2.29m

SLS Design

- Calculate settlement using **adjusted elasticity method**

$$s = p\,B\,f\,/\,E_m$$

- E_m = design value of the modulus of elasticity
- f = settlement coefficient
- p = bearing pressure

- Assume $E_m = E' = 1.5N = 1.5 \times 40 = 60$ MPa
- $f = (1 - \nu^2)\,I$ where $\nu = 0.25$ and $I = 0.95$ for square foundation
- Then $f = (1 - 0.25^2) \times 0.95 = 0.89$
- $p = (G_k + Q_k)/B^2 = (900 + 600) / 2.08^2 = 346.7$ kPa for smallest foundation
- Hence settlement:

$$s = p\,B\,f\,/\,E_m = 346.7 \times 2.08 \times 0.89 \times 1000 / 60000 = 10.7 \text{ mm}$$

- As $s < 25$ mm, **SLS condition satisfied**

Summary of Designs

	Undrained width (m)	Drained width (m)	$R_{u,k}$ / F_k ratio
DA1.C1	(1.32)	(1.62)	
DA1.C2	1.39	**2.08**	2.3
DA2	1.57	**1.87**	2.0
DA3	1.56	**2.29**	2.9

- **ULS design:** For each Design Approach, the **drained condition** determines the **foundation width** for this design situation
- **SLS design:** The calculated settlement of the smallest foundation of width 2.08m, under the characteristic load is 11 mm, which is less than the allowable settlement of 25mm, so that the **SLS condition is satisfied** in this example
- The ratio $R_{u,k}$ / F_k is **less than 3** and **greater than 2** for all the Design Approaches, hence the **settlement** should be **calculated**

Conclusions

- **Section 3** provides the requirements for the **collection, evaluation and presentation of geotechnical data** as an integral part of the geotechnical design process
- **Section 6** provides a **comprehensive framework** with the **principles** for design of spread foundations
- The **designer** of spread foundations is **explicitly required** to:
  - Consider all relevant limit states
  - Consider both ULS and SLS
  - Consider both drained and undrained conditions (where relevant)
  - Distinguish between actions on the foundation and resistances
  - Treat appropriately:
    - Forces from supported structure (permanent or variable)
    - Forces due to water pressure (actions not resistances)
- Since **overall factors of safety** for ULS design are **generally lower** than traditionally used for foundation design, it is likely that settlement considerations and hence **SLS requirements** will **control** more **foundation designs**, particularly on cohesive soils and when using DA1


Thank You