

# Pile Design to BS EN 1997-1:2004 (EC7) and the National Annex

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# What am I going to talk about?

- Concentrate on Practical Applications
- Brief Review of theTraditional Design Approach
- What is Different in EC7?
- EC7 – Geotechnical Design: Part 1: Chapter 7 – Piles
- UK National Annex:  Model Factor
- EC7 Design Method and Partial Factors



# What am I going to talk about?

- Other Aspects of Pile Design
  - Negative Shaft Friction
  - Horizontal Load
  - Structural Design
- Worked Example for a Site In Suffolk
- Conclusions



# Some History & Background

- 1974-1975:

  First proposal to develop international codes
- 1990:

  CEN (European Committee for Standardisation) set up
- 2004:

  BS EN 1997-1 (Eurocode 7, Part 1) and its UK National Annex were published

# Some History & Background

- Other Eurocodes important for piling:

  BS EN 1997-1 – Geotechnical Design

  BS EN 1990 – Basis of Structural Design

  BS EN 1991-1-1 – Actions on Structures

  BS EN 1992-1-1 – Design of Concrete Structures

  Plus Execution Codes

# Some History & Background

- April 2010:

  Most geotechnical standards and Codes of Practice were withdrawn

  Eurocodes became the current standards

  The use of Eurocodes mandatory on public sector work

- October 2013:

  Part A of Building Regulations updated to refer to Eurocodes (England)



# Some History & Background

- June 2015:

  British Standards re-issued:

  BS8004 – Foundations

  BS8002 – Retaining Structures

  BS8081 – Grouted Anchors

  Now fully compliant with Eurocodes

  [It was not originally intended to re-write these standards!]



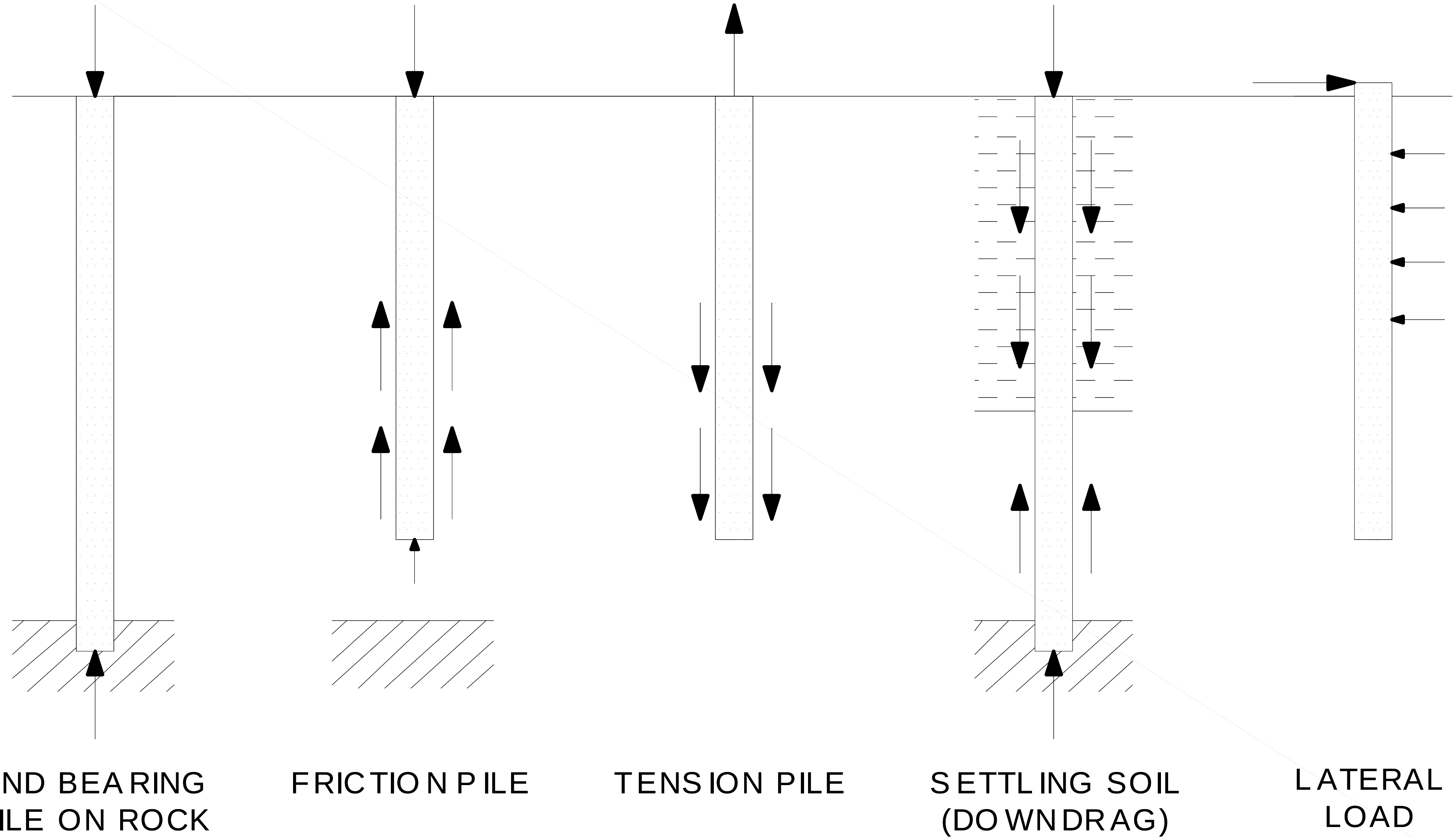
# Some History & Background

- Today:

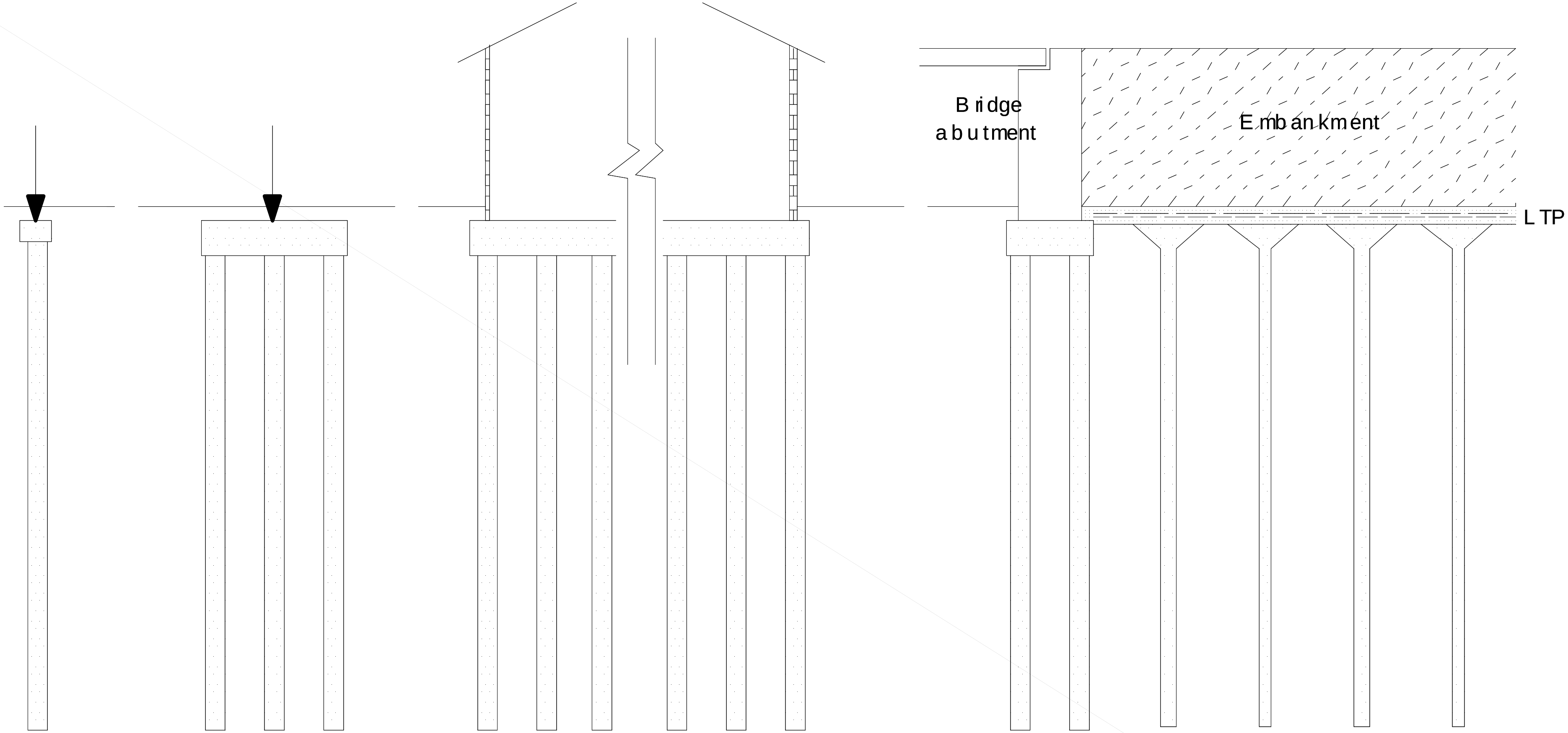
  All public sector and most private sector construction schemes are designed to Eurocodes

  The UK piling industry has taken on board the use of Eurocodes but with some reluctance

# Behaviour of Piles








SINGLE PILE BELOW COLUMN

GROUP OF PILES BELOW COLUMN

PILED RAFT TO BUILDING

PILED BRIDGE ABUTMENT AND APPROACH EMBANKMENT

# Piling Methods – Driven




# Piling Methods – Rotary Bored or CFA




# Traditional Pile Design to BS 8004

- In the past, piles were driven to a refusal
- Self-evident that the pile resistance is proportional to the drive energy
- Every driven pile has some sort of test – drive blows

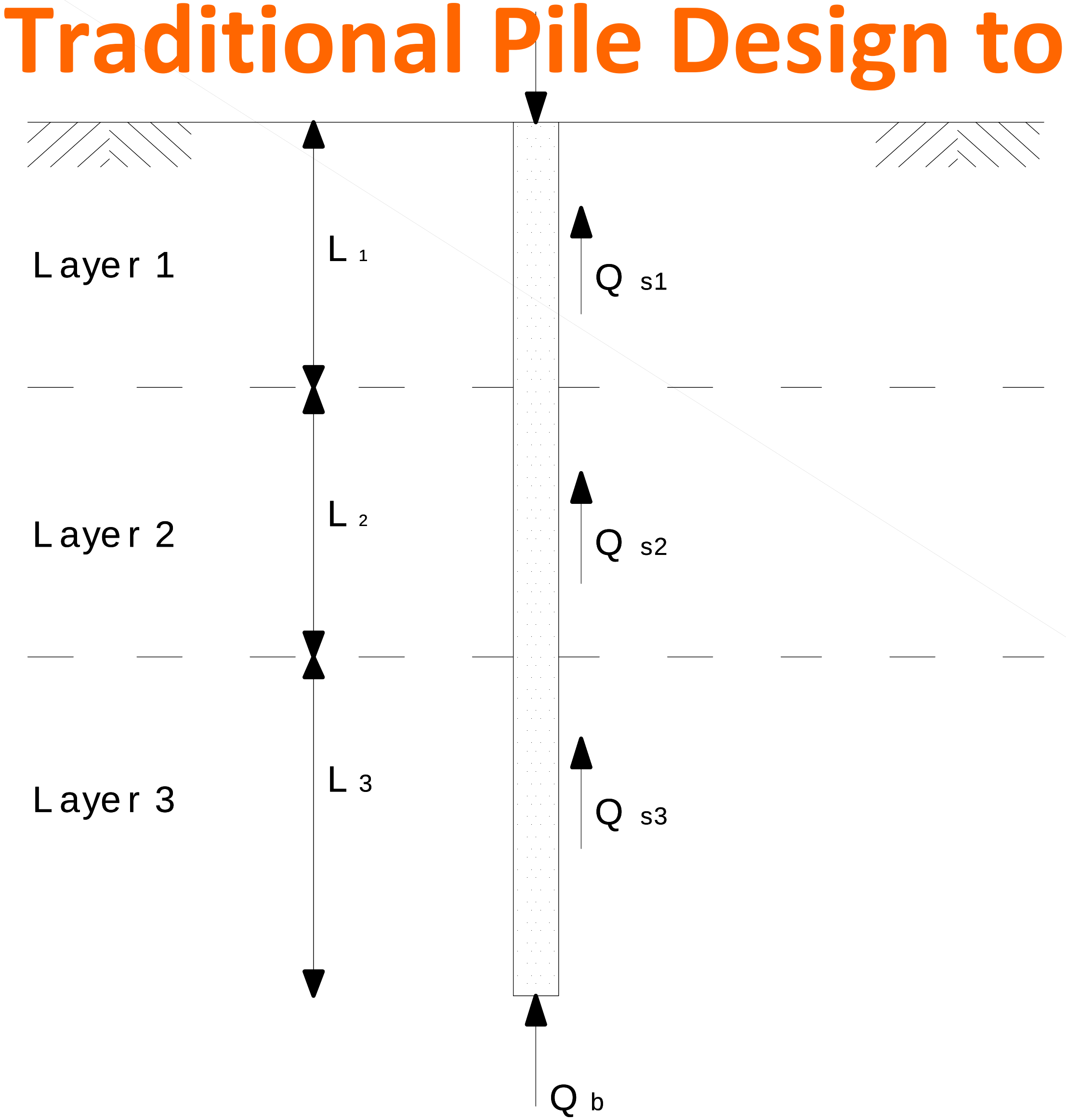
- But this does not work for bored or drilled piles as there is no feedback from installation



# Traditional Pile Design to BS 8004

- Static load testing is very attractive for design
- But testing can be uneconomic and time consuming:
  - Complex variable ground conditions
  - Variable loading
  - Difficult to deal with NSF
  - Difficult to deal with changes to vertical stress
- Pile designers therefore looked at calculation based on theoretical soil mechanics

# Traditional Pile Design to BS 8004




Ultimate pile resistance

$$Q_u = \sum Q_s + Q_b$$



# Traditional Pile Design to BS 8004

- The usual approach is to divide the ground into layers and assign ground parameters to each layer
- For bearing capacity, this is just φ', c', Cu and UCS
- From these we get Nc, Nγ and Nq for bearing capacity



# Traditional Pile Design to BS 8004

- Basic calculation method:

$$\text{Ultimate Capacity } Q_{ult} = Q_s + Q_b$$

$$\text{Shaft Capacity } Q_s = q_s \, A_s$$

$$\text{Base Capacity } Q_b = q_b \, A_b$$



# Traditional Pile Design to BS 8004

- Factor of Safety varied between 2.0 and 3.0 for compression loads and ≥ 3.0 for tension
- Actual FoS dependent on quality of GI, prior knowledge of ground conditions and whether preliminary non-working load tests or contract proof load tests were carried out

$$\text{Applied Load} \leq \frac{\text{Ultimate Capacity}}{\text{FoS}}$$

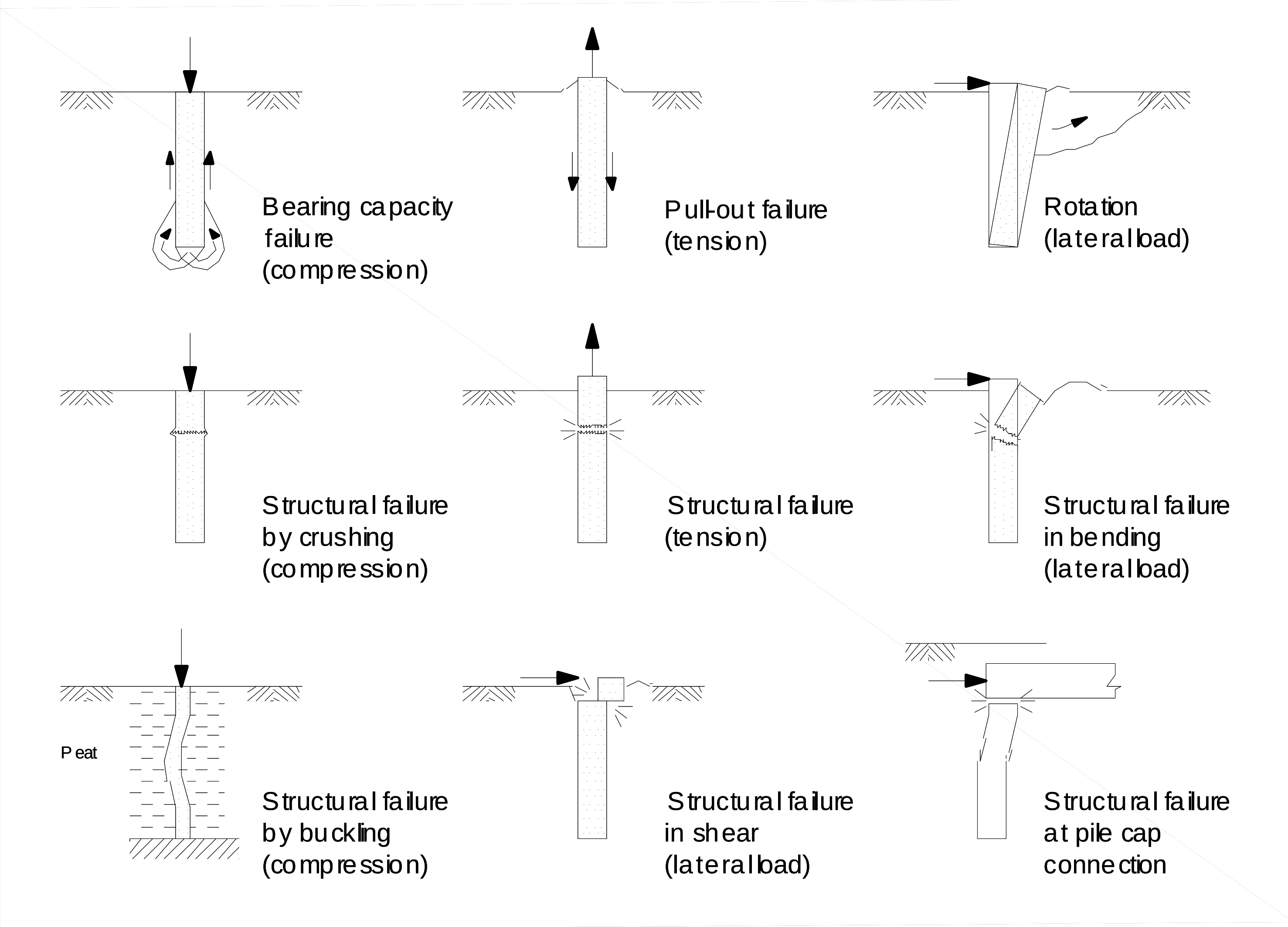


# Pile Design to EC7

- So what is different?
- EC7 method is a Limit State Design method:
  - Ultimate Limit State (ULS)
    - States associated with collapse, structural failure, excessive deformation or loss of stability of the whole of the structure or any part of it
  - Serviceability Limit State (SLS)
    - States that correspond to conditions beyond which specified service requirements are no longer met



# Some Ultimate Limit States for Piles



# Some Serviceability Limit States

- Settlement
- Tilting
- Cracking
- Uneven floor settlement



# EC7 Limit States

- EC7 Adopts five distinct ultimate limit states:
  - EQU – Loss of equilibrium (tilt or rotation)
  - STR – Internal failure or excessive deformation
    [Strength of structural material is significant]
  - GEO – Failure or excessive deformation of the ground
    [Strength of soil or rock is significant]
  - UPL – Uplift or buoyancy
  - HYD – Hydraulic heave, erosion or piping
- STR and GEO most important for pile design

# EC7 Design Approach

- Separation of ULS and SLS condition
- Permanent and variable actions
- Favourable and unfavourable actions
- Use of characteristic ground properties
- Use of several partial factors
- Partial factors avoid failure but not necessarily movement



# EC7 Design Approach

- Basic inequality to be checked:

$$E_d \leq R_d$$

- $E_d$ is the design value of the effect of all the actions
- $R_d$ is the design value of the corresponding resistance of the ground or structure
- For pile design, this inequality compares the design action $F_d$ (usually load) against the design resistance $R_d$

$$F_d \leq R_d$$



# EC7 Design Approach

- Design values of Ed, Rd are obtained by applying sets of partial factors to their characteristic values, Ek, Rk
- EC7 allows three design approaches which use different partial factor sets
- Each country specifies its design approach in its NA
  - DA1: UK, Portugal
  - DA2: France, Germany, Poland, Spain ..........
  - DA3: Denmark & Netherlands
- Some countries allow more than one approach (Ireland, Italy)

# UK National Annex

- UK has adopted Design Approach 1 - DA1
- This requires two calculations:
  - A1 + R1 + M1 Combination 1
  - R4 + A2 + M1/M2 Combination 2

(Use M1 for calculating resistances and M2 for unfavourable actions such as NSF)

- For Combination 1, partial factors > 1.0 are applied to the actions only - this does not usually control pile length
- For Combination 2, partial factors > 1.0 are applied to resistances with smaller factors applied to variable actions



# Design Actions $F_d$

- $F_d$ is the design action

$$F_d = \gamma_F \, F_{rep}$$

- $F_{rep}$ is the representative action (usually load)

$$F_{rep} = G_k + \psi \, Q_k + A_k$$

$$\psi = 1.0 \text{ for leading action or } = \psi_0, \psi_1 \text{ or } \psi_2$$

  - $G_k$ is the characteristic permanent action
  - $Q_k$ is the characteristic variable action
  - $A_k$ is the characteristic accidental action
  - $\psi$ is the factor for combination of variable actions



# Effect of Actions $E_d$

- $E_d$ is the design value of the effect of all the actions:

$$E_d = E\left\{\gamma_F F_{rep} \quad \frac{X_k}{\gamma_m} \quad a_d\right\}$$

- $F_{rep}$ is the representative action (usually load)
- $X_k$ is the characteristic value of the material property
- $a_d$ is the design value of a geometrical property
- $\gamma_F$ and $\gamma_m$ are relevant partial factors



# Effect of Actions $E_d$

- Design values:

$$F_d = \gamma_F F_{rep} \qquad X_d = \frac{X_k}{\gamma_m} \qquad a_d = a_{nom} \mp \Delta a$$

- $F_{rep}$ is the representative action (usually load)
- $X_k$ is the characteristic value of the material property
- $a_d$ is the design value of a geometrical property
- $\gamma_F$ and $\gamma_m$ are relevant partial factors



# UK National Annex

- Local requirements specified in the UK National Annex
- In the UK this involves two separate calculations with different combinations of partial factors:
  - Combination 1: Partial factors applied to actions; Ground strengths and resistances are not factored
  - Combination 2: Partial factors applied to ground strengths, resistances and variable actions; Permanent actions are unfactored
- <u>NOTE</u> for pile design, we factor ground resistances and not ground strengths



# Partial Factors on Actions

| Action | | UK NA Factor Set | | EC7 Factor Set | |
|---|---|---|---|---|---|
| | | A1 | A2 | A1 | A2 |
| Permanent | Unfavourable | 1.35 | 1.0 | 1.35 | 1.0 |
| | Favourable | 1.0 | 1.0 | 1.0 | 1.0 |
| Variable | Unfavourable | 1.5 | 1.3 | 1.5 | 1.3 |
| | Favourable | 0 | 0 | 0 | 0 |

Notes:

1. Factors can be applied to Actions or the Effect of Actions.
2. Factors given above are for buildings which remain unchanged from EC7 values
3. Combination factors for actions that can exist simultaneously are given in the UK NA to BS EN 1990.
4. There are a wider range of factors for bridges.



# Pile Design to EC7

- Static load tests
- Ground tests (using direct correlations), e.g. CPT or PMT
- Dynamic impact tests, e.g. CAPWAP
- Statistical corrections required to account for number of test results (correlation factor)
- EC7 concentrates on pile design by testing.
- There is little reference to design by calculation – the normal UK approach!



# Pile Design Methods Covered by EC7

| Design method | Information used | Constraints |
|---|---|---|
| Testing | Static load tests | Validity must be demonstrated by calculation or other means |
| | Ground test results | Validity must be demonstrated by static load tests in comparable situations |
| | Dynamic load tests | |
| Calculation | Empirical or analytical calculation methods | |
| Observation | Observed performance of comparable piled foundations | Must be supported by the results of site investigation and ground testing |



# Pile Design to EC7

- The most common method for design method in the UK is design by calculation
- Pile load testing is used mostly for verification of the design
- Ground tests are used to select soil properties



# Calculation Based on Soil Parameters

- Design can be based on measured φ', c', Cu and UCS usually from laboratory testing of undisturbed samples

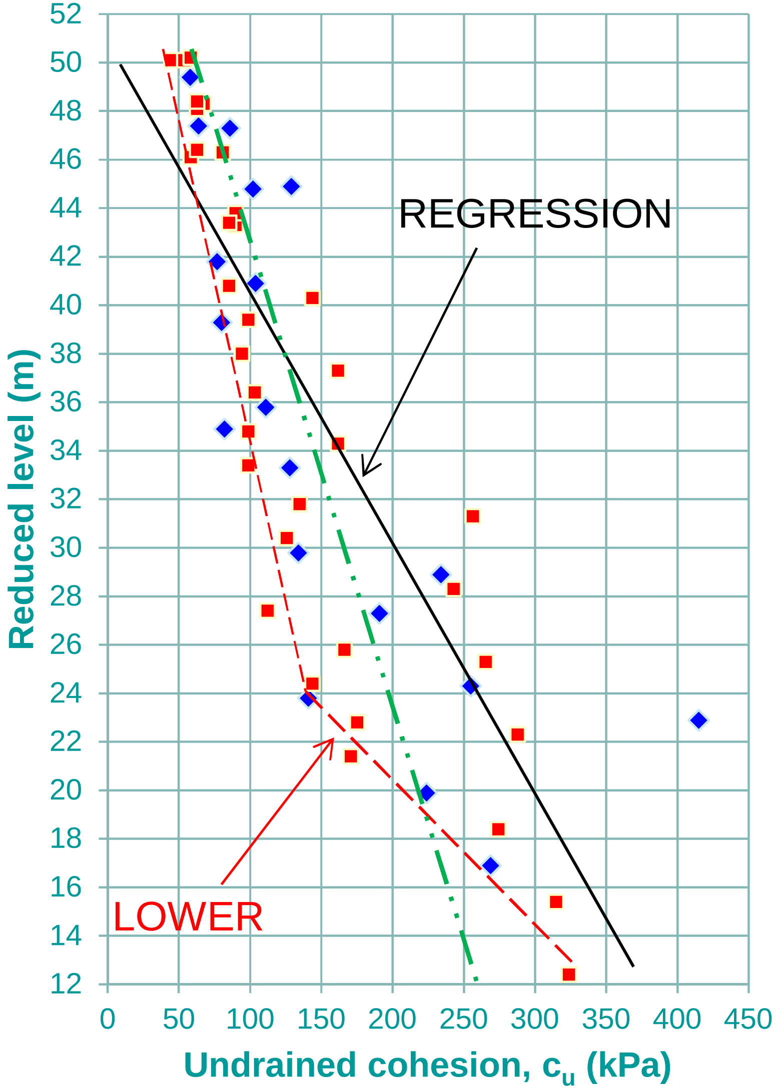
- More common to use empirical relationships between insitu CPT, SPT, PMT and other measurements to estimate these parameters

- We can measure G, Eu and E' in the laboratory, but again it is more common to use empirical relationships

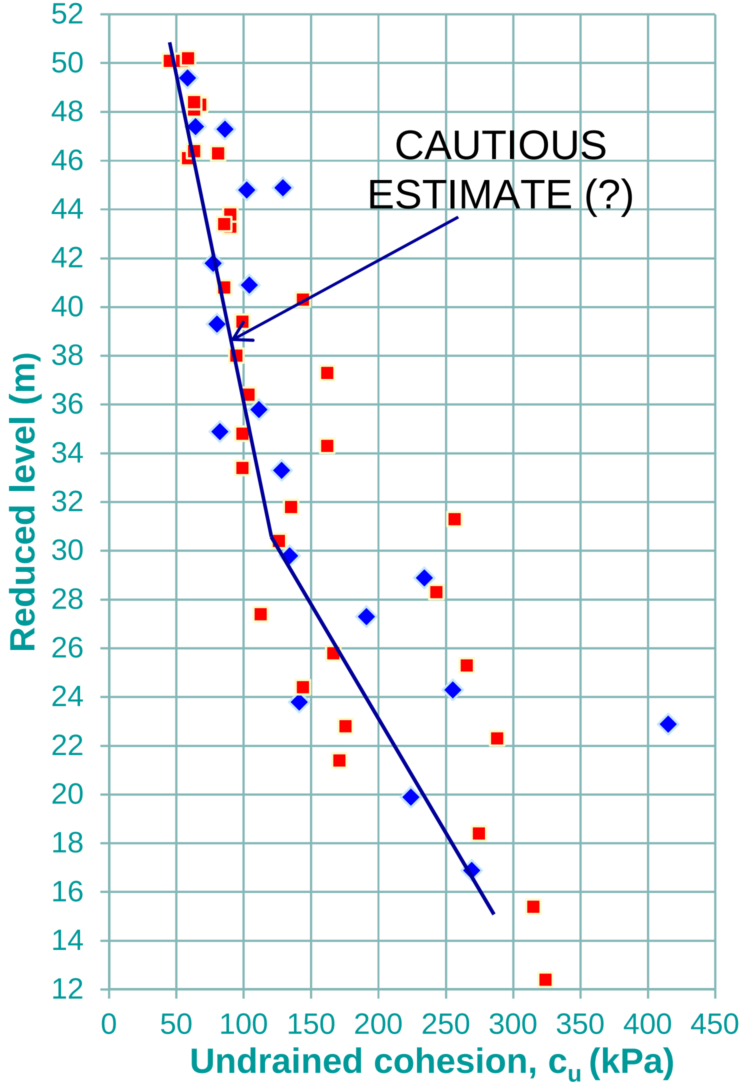
# Ground Characterisation

- EC7 says a lot about determining characteristic or representative soil properties
- Cautious estimate affecting the occurrence of the limit state
  - Similar to BS 8002 and CIRIA 104
  - Most engineers already adopt cautious estimates
  - Engineering judgement required
  - Statistics can be applied, but is difficult because of the usual limited number of samples and test data
  - For pile design, not a great deal of difference between soil parameters for EC7 design compared to BS 8004 design

## London Clay, cohesion v depth




## London Clay cohesion v depth





# Calculation Based on Soil Parameters

- Design is based on fundamental geotechnical ground parameters such as c’, φ’, G, E’, but could also include Cu, UCS and Eu for clays and rocks
- These extend into derived parameters such as Nc, Nγ and Nq for bearing capacity, Kq and Kc factors for horizontal loads on piles or Ka, Kac, Kp and Kpc for ground retention
- But we also need some empirical factors such as Ks for granular, α for clay, β for Chalk

# So how do we estimate pile shaft friction and end bearing from ground parameters?

- Effective Stress Approach

  Granular Soils

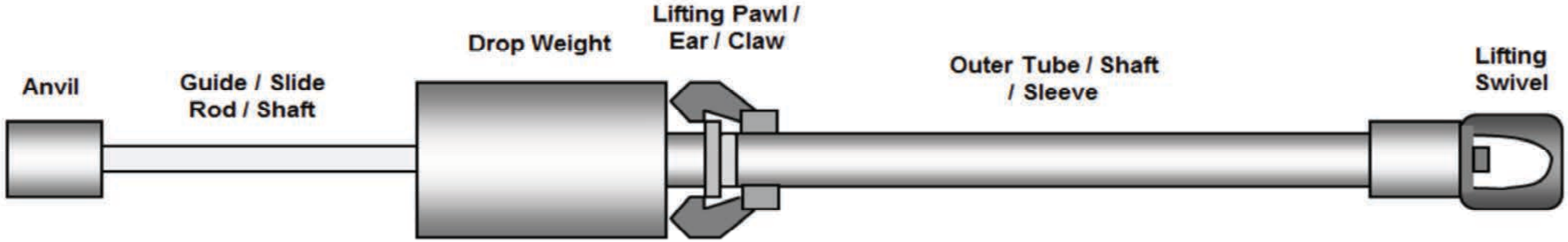
$$q_s = \sigma'_v \; k_s \; \tan\delta$$

- Total Stress Approach

  Cohesive or Rock (Weak Mudstone)

$$q_s = \alpha \; c_u$$

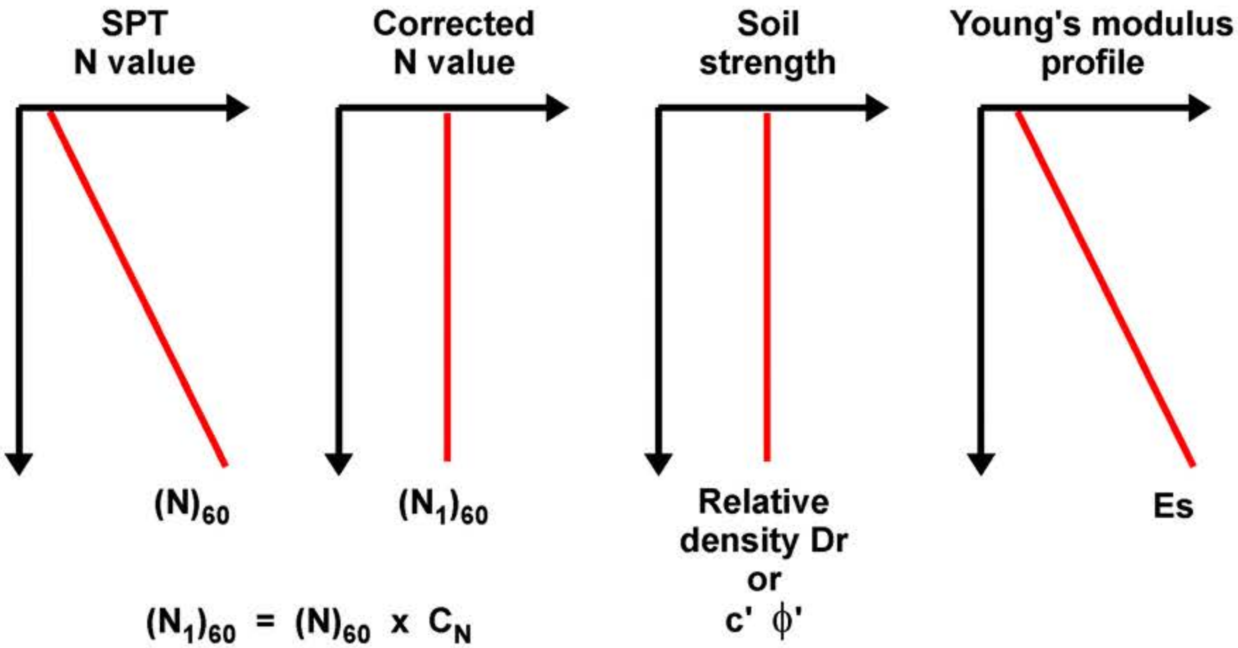
# Standard Penetration Test – Granular Soils

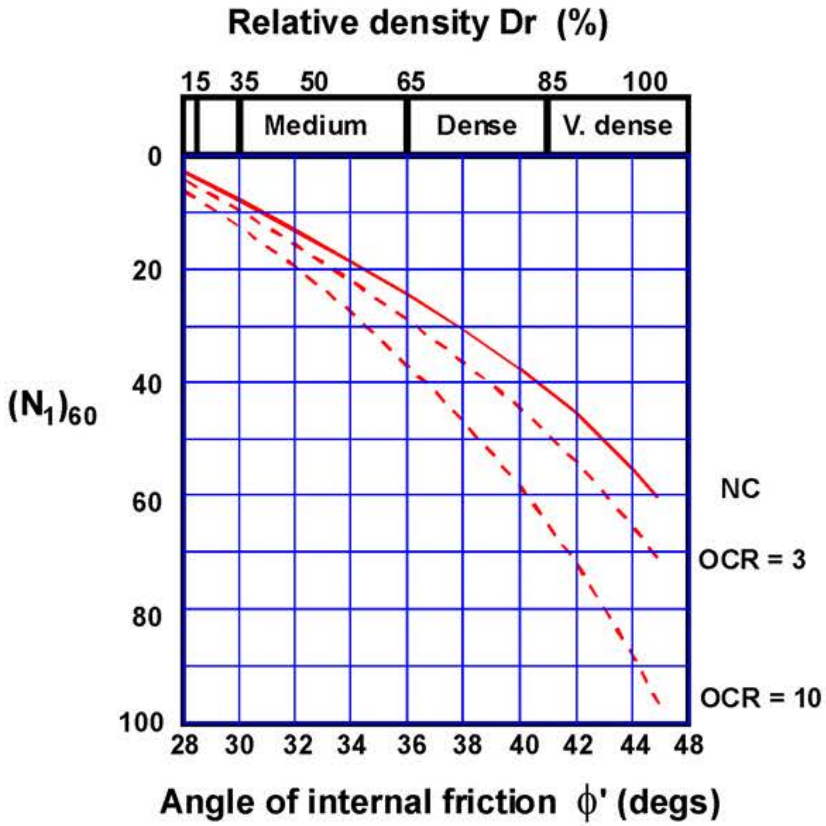



Diagrams from Equipe Group Geotechnica

SPT undergoing calibration

# Standard Penetration Test – Granular Soils



# Standard Penetration Test – Clay Soils

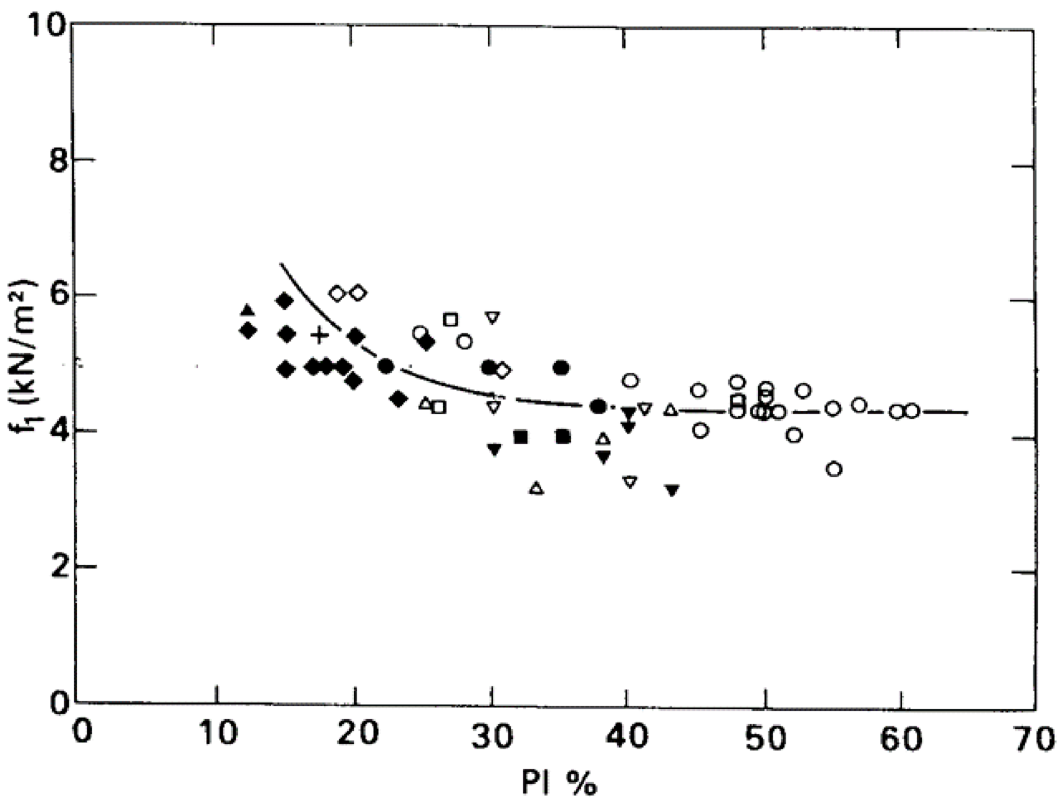


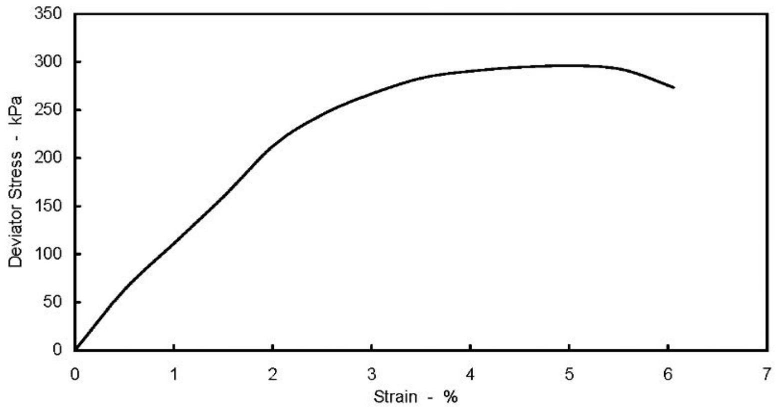

Fig 19 Variation of $f_1 = c_u/N_{60}$ with plasticity index for overconsolidated clays (after Stroud and Butler, 1975)

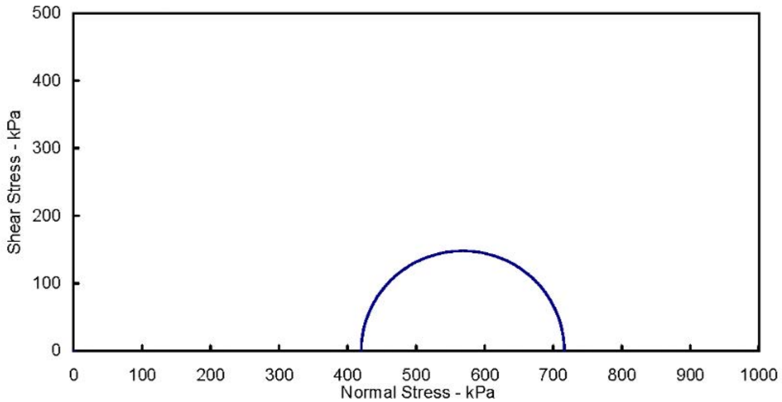
$C_u = f_1 \times (N)60$

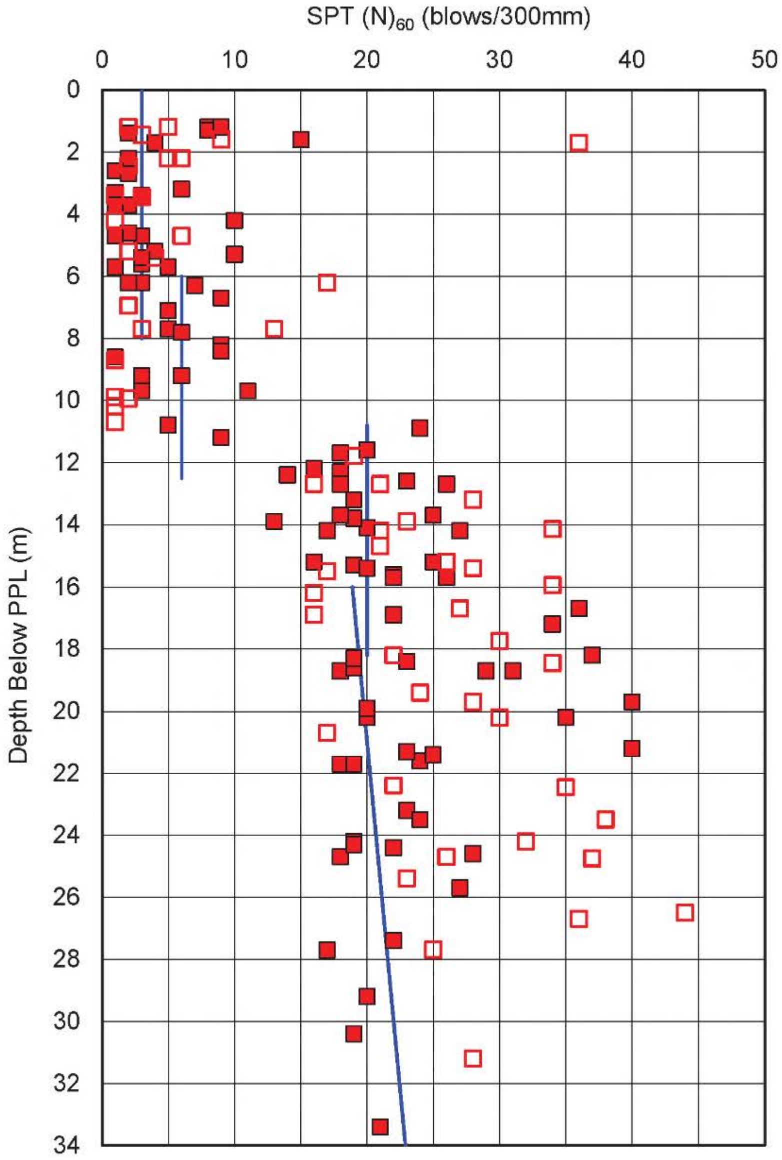
$f_1 = 4.0$ to $6.0$

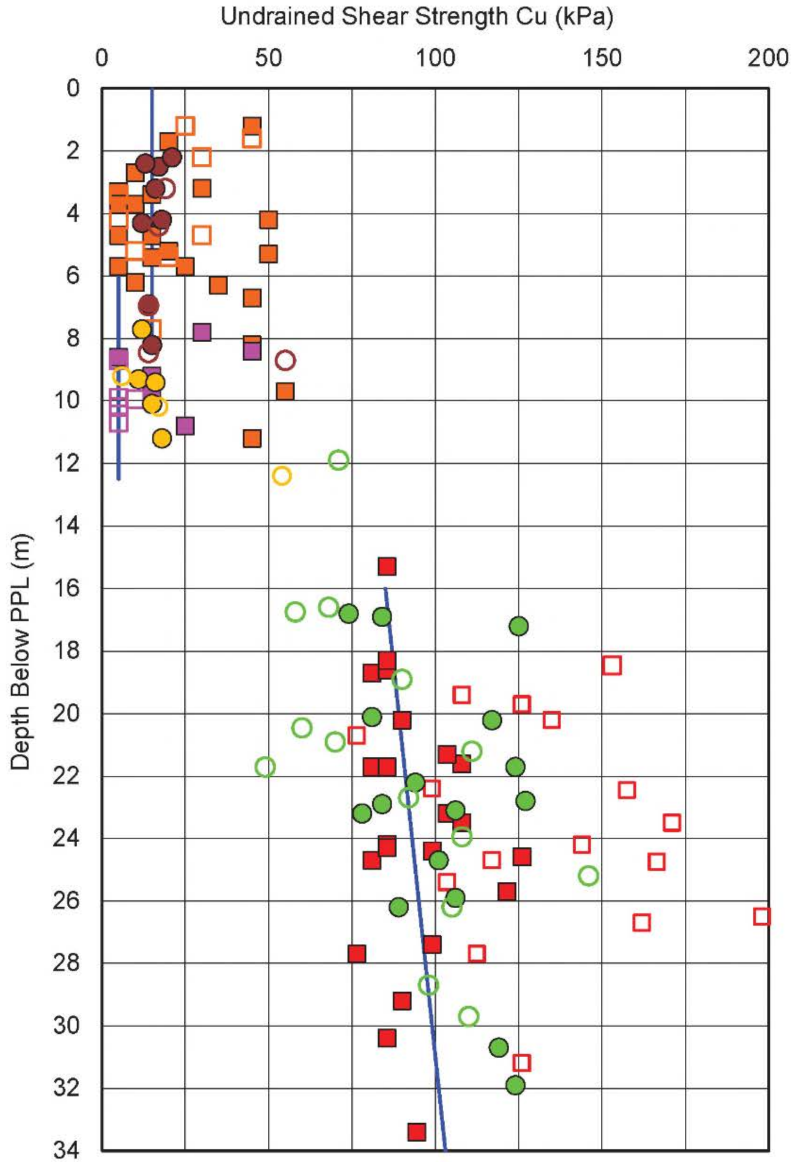
# Laboratory – Undrained Shear Strength

## Triaxial Testing



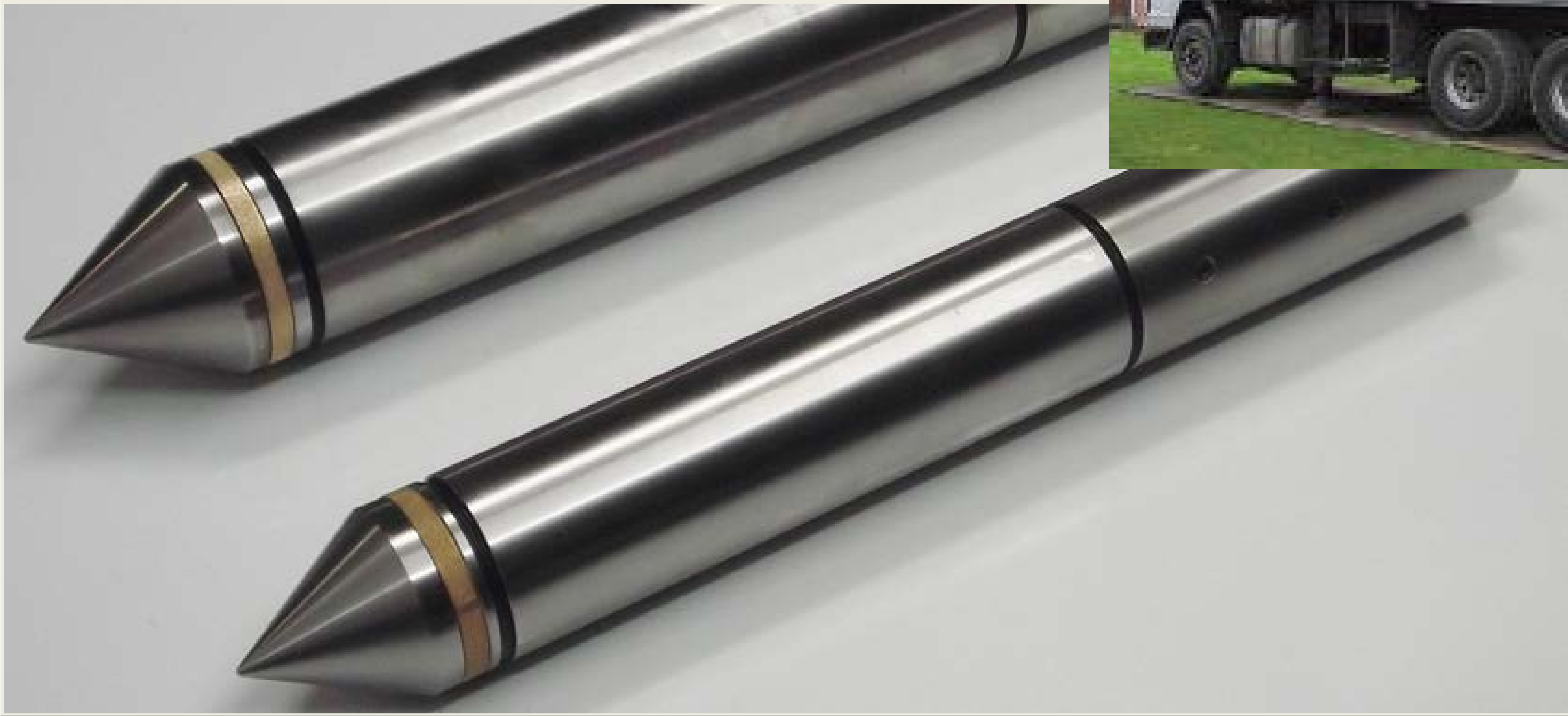





SPT $(N)_{60}$ (blows/300mm)
0
10
20
30
40
50
Depth Below PPL (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34


Undrained Shear Strength Cu (kPa)
0
50
100
150
200
Depth Below PPL (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34

# Insitu Testing – CPT

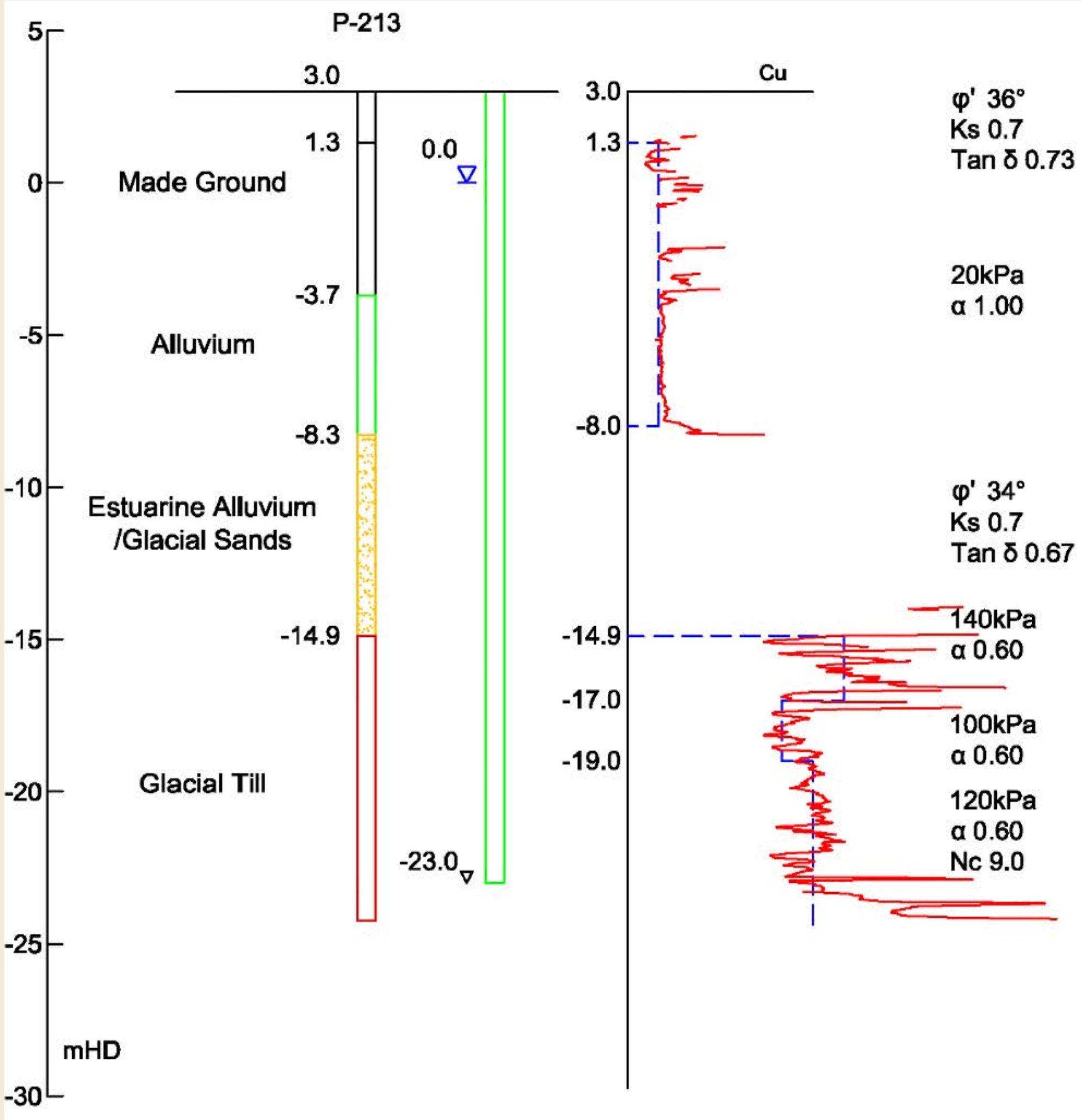
Cu in clays
Φ' in granular soils

# GI Using CPT

$C_u = q_c / N_k$
$N_k = 15$ to $30$

$N_k = 20$ taken for Glacial Till in this example





# Pile Shaft Friction

- Beta Method

  Soft Soils or Chalk

$$q_s = \sigma'_v \ \beta \qquad \beta = k_s \tan\delta \qquad \beta = 0.45 \text{ to } 0.80 \text{ for Chalk}$$

- UCS Method

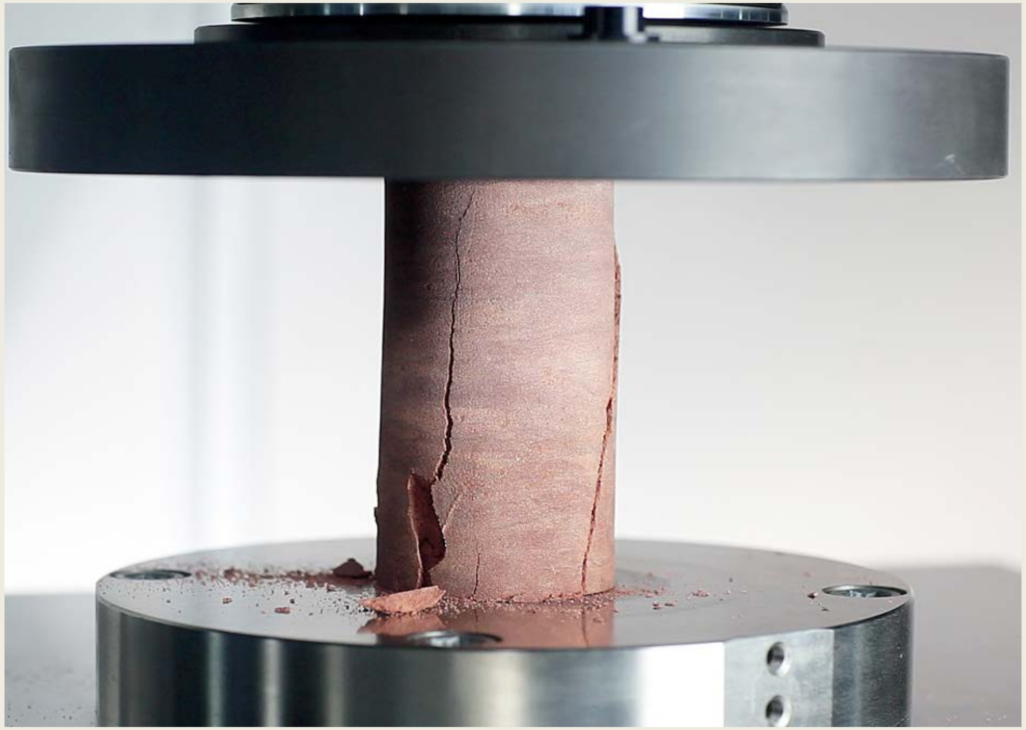
  Sandstone, Limestone or Strong Mudstone

$$q_s = a\,\mathrm{UCS}^b \qquad a = 200 \rightarrow 450 \quad b = 0.4 \rightarrow 0.6$$

# Rock Testing

Point Load Testing


Uniaxial Compression Test



# Pile End Bearing

- Effective Stress Approach

  Granular

$$q_b = \sigma'_v \, N_q$$

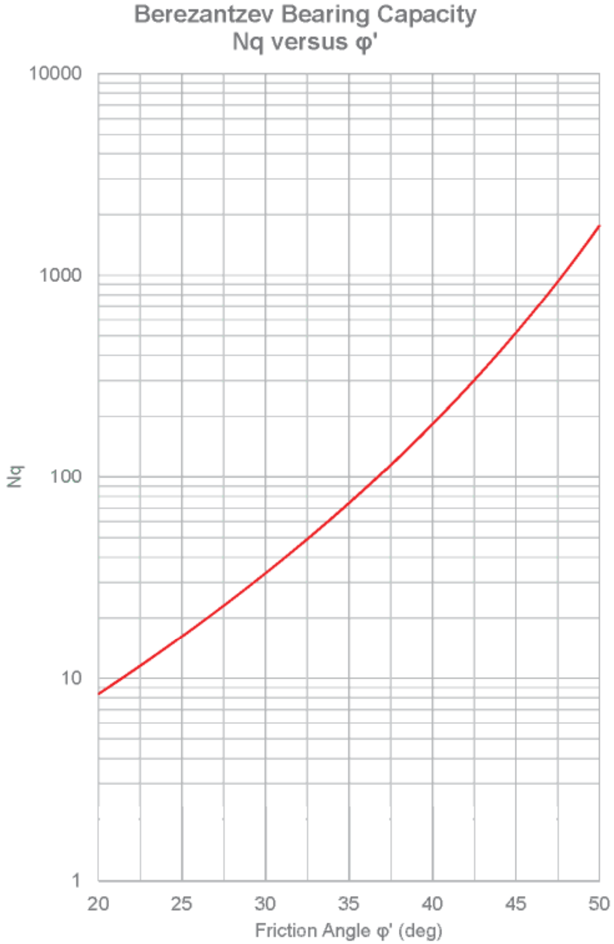
- Total Stress Approach

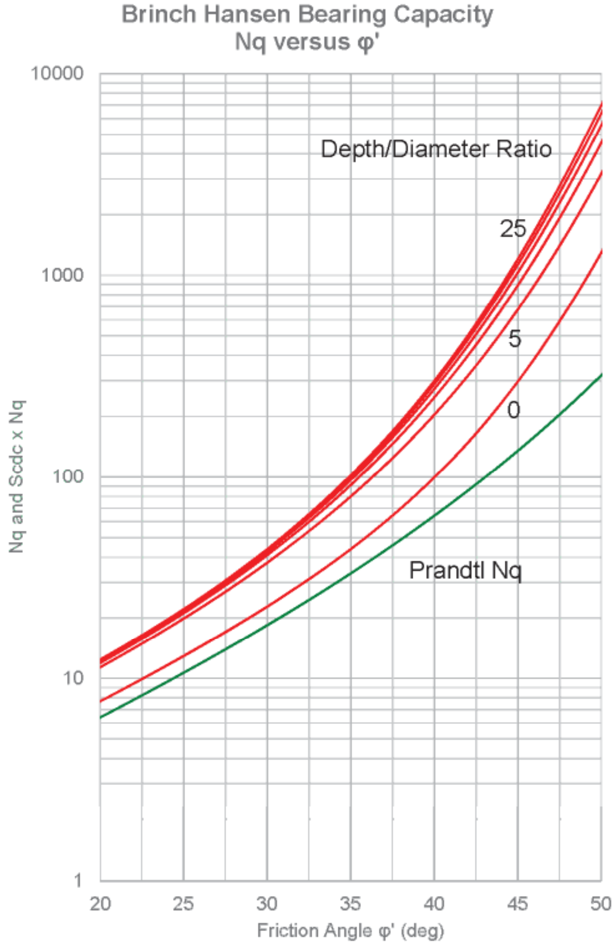
  Cohesive or Rock (Weak Mudstone)

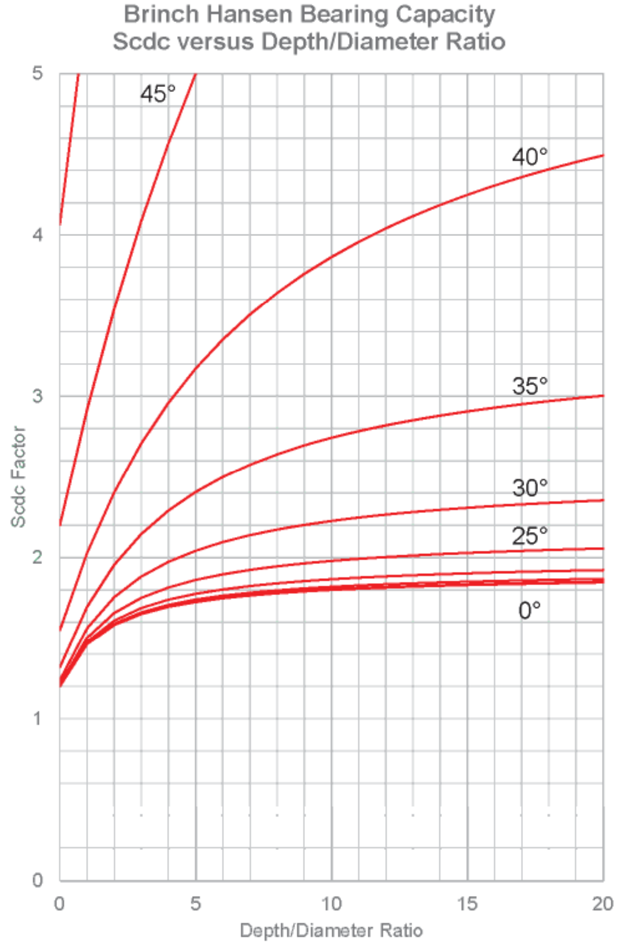
$$q_b = c_u \, N_c$$



# Pile End Bearing





# Pile End Bearing

- SPT Method

  Chalk

$$q_b = 200 \text{ to } 300 \times \text{ SPT N}$$

- UCS Method

  Sandstone, Limestone or Strong Mudstone

$$q_b = \frac{UCS}{2} N_c$$



# Design Soil Parameters

- Design values obtained by dividing the characteristic or representative property by a partial factor

$$X_d = \frac{X_k}{\gamma_m}$$

- Usual properties to be factored are strength [but stiffness may need to be factored for horizontal load design]
- Either effective stress strength, c' and φ', or undrained shear strength $c_u$, or unconfined compressive strength UCS for rocks
- For pile design to the UK National Annex, factored design soil parameters are not used except for negative shaft friction



# Partial Factors on Soil Parameters

| Soil Property | UK NA Factor Set | | EC7 Factor Set | |
|---|---|---|---|---|
| | M1 | M2 | M1 | M2 |
| Friction Angle tan ϕ' | 1.0 | 1.25 | 1.0 | 1.25 |
| Effective Cohesion c' | 1.0 | 1.25 | 1.0 | 1.25 |
| Undrained Shear Strength Cu | 1.0 | 1.4 | 1.0 | 1.4 |
| Unconfined Strength UCS | 1.0 | 1.4 | 1.0 | 1.4 |
| Unit Weight γ | | | 1.0 | 1.0 |

UK NA gives no factor for unit weight so presume 1.0; other factors remain unchanged.

For pile design to the UK National Annex, factored design soil parameters are not used except for negative shaft friction



# Pile Design to EC7 Based on Resistances

- For pile design, it is necessary to compare the design action $F_d$ (usually load) against the design resistance $R_d$

$$F_d \leq R_d$$

- But note that this is now in terms of compression or tension load and compression or tension resistance:

$$F_{c;d} \leq R_{c;d} \qquad F_{t;d} \leq R_{t;d}$$

- As is usual, the design resistance $R_{c;d}$ can be assumed to be the sum of the end bearing and shaft design resistances:

$$R_{c;d} = R_{b;d} + R_{s;d}$$



# Pile Design to EC7 Based on Resistances

- The design resistances $R_{c;d}$ or $R_{t;d}$ are obtained from the characteristic end bearing and shaft friction by using partial resistance factors

$$R_{c;d} = \left[\frac{R_{b;k}}{\gamma_b} + \frac{R_{s;k}}{\gamma_s}\right] \text{ or } \left[\frac{R_{c;k}}{\gamma_t}\right] \qquad R_{c;k} = R_{b;k} + R_{s;k}$$



# Pile Design to EC7 Based on Resistances

- The characteristic end bearing and shaft friction can be computed using existing and recognisable methods either by:
  - Calculation
  - Static load testing
  - Dynamic load testing
  - Correlation with CPT or other insitu ground testing
  - Design charts based on experience (e.g. EA-Pfähle used in Germany)



# Pile Design by Calculation

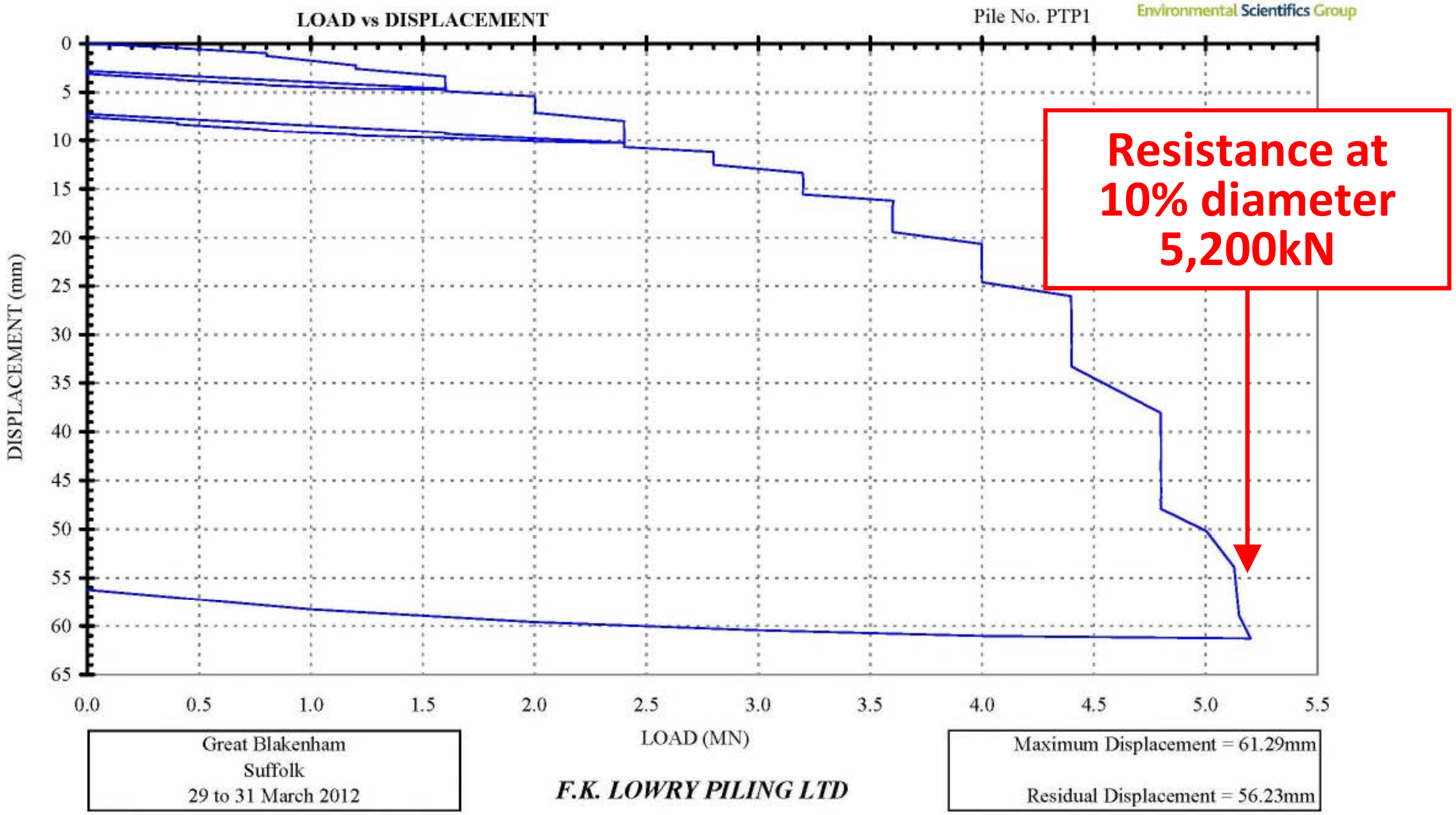
- The characteristic base resistance and shaft resistance can be calculated from the characteristic end bearing and shaft friction stresses as follows:

$$R_{b;k} = \frac{A_b \, q_{b;k}}{\gamma_{Rd}} \qquad R_{s;k} = \frac{\sum A_{s;i} \, q_{s;i;k}}{\gamma_{Rd}}$$

- These are similar to the approach used for BS 8004 but include an additional model factor $\gamma_{Rd}$ to 'correct' the partial resistance factors (applied to the characteristic resistances to obtain the design resistance $R_{c;d}$)

# Pile Load Testing

- Pile Load Tests – Preliminary – To ULS




- Load test to ULS allows a lower model factor $\gamma_{Rd}$ to be used



# Pile Shaft Friction

- Effective Stress Approach – Granular

$$q_s = \sigma'_v \; k_s \; \tan\delta$$

- Total Stress Approach – Cohesive or Rock (Weak Mudstone)

$$q_s = \alpha \, c_u$$

- Beta Method – Soft Soils or Chalk

$$q_s = \sigma'_v \; \beta \qquad \beta = k_s \tan\delta \qquad \beta = 0.45 \text{ to } 0.80 \text{ for Chalk}$$

- UCS Method – Sandstone, Limestone or Strong Mudstone

$$q_s = a \, UCS^b \qquad a = 200 \rightarrow 450 \quad b = 0.4 \rightarrow 0.6$$



# Pile End Bearing

- Effective Stress Approach – Granular

$$q_b = \sigma'_v \; N_q$$

- Total Stress Approach – Cohesive or Rock (Weak Mudstone)

$$q_b = c_u \, N_c$$

- SPT Method – Chalk

$$q_b = 200 \text{ to } 300 \times \text{ SPT N}$$

- UCS Method – Sandstone, Limestone or Strong Mudstone

$$q_b = \frac{UCS}{2} N_c$$

# Partial Resistance Factors

- The design resistance $R_d$ is obtained from the characteristic end bearing and shaft friction by using partial resistance factors

$$R_{c;d} = \left[\frac{R_{b;k}}{\gamma_b} + \frac{R_{s;k}}{\gamma_s}\right] \text{ or } \left[\frac{R_{c;k}}{\gamma_t}\right]$$

- The partial resistance factors in the UK National Annex have been modified to take account of the type of pile and whether the serviceability behaviour is to be determined either by load test or a rigorous and reliable calculation



# Partial Resistance Factors for Driven Piles

| Component | UK NA Factor Set | | | EC7 Factor Set | | | |
|---|---|---|---|---|---|---|---|
| | R1 | R4 (No SLS) | R4 (SLS) | R1 | R2 | R3 | R4 |
| Base | 1.0 | 1.7 | 1.5 | 1.0 | 1.1 | 1.0 | 1.3 |
| Shaft | 1.0 | 1.5 | 1.3 | 1.0 | 1.1 | 1.0 | 1.3 |
| Total | 1.0 | 1.7 | 1.5 | 1.0 | 1.1 | 1.0 | 1.3 |
| Tension | 1.0 | 2.0 | 1.7 | 1.25 | 1.15 | 1.1 | 1.6 |

Main differences for resistance factors relate to:

1. Factor set R4 where different values depend on whether SLS behaviour is verified or not (test or calculation).
2. Model factor to be applied to ground properties to derive characteristic values or directly to the calculated shaft or end bearing capacities.
3. Model factor 1.4, but can be reduced to 1.2 if a load test is completed to calculated unfactored ultimate resistance (ULS check).



# Partial Resistance Factors for Bored Piles

| Component | UK NA Factor Set | | | EC7 Factor Set | | | |
|---|---|---|---|---|---|---|---|
| | R1 | R4 (No SLS) | R4 (SLS) | R1 | R2 | R3 | R4 |
| Base | 1.0 | 2.0 | 1.7 | 1.25 | 1.1 | 1.0 | 1.6 |
| Shaft | 1.0 | 1.6 | 1.4 | 1.0 | 1.1 | 1.0 | 1.3 |
| Total | 1.0 | 2.0 | 1.7 | 1.15 | 1.1 | 1.0 | 1.5 |
| Tension | 1.0 | 2.0 | 1.7 | 1.25 | 1.15 | 1.1 | 1.6 |

Main differences for resistance factors relate to:

1. Factor set R4 where different values depend on whether SLS behaviour is verified or not (test or calculation).
2. Model factor to be applied to ground properties to derive characteristic values or directly to the calculated shaft or end bearing capacities.
3. Model factor 1.4, but can be reduced to 1.2 if a load test is completed to calculated unfactored ultimate resistance (ULS check).

# Partial Resistance Factors for CFA Piles

| Component | UK NA Factor Set | | | EC7 Factor Set | | | |
|---|---|---|---|---|---|---|---|
| | R1 | R4 (No SLS) | R4 (SLS) | R1 | R2 | R3 | R4 |
| Base | 1.0 | 2.0 | 1.7 | 1.1 | 1.1 | 1.0 | 1.45 |
| Shaft | 1.0 | 1.6 | 1.4 | 1.0 | 1.1 | 1.0 | 1.3 |
| Total | 1.0 | 2.0 | 1.7 | 1.1 | 1.1 | 1.0 | 1.4 |
| Tension | 1.0 | 2.0 | 1.7 | 1.25 | 1.15 | 1.1 | 1.6 |

Main differences for resistance factors relate to:

1. Factor set R4 where different values depend on whether SLS behaviour is verified or not (test or calculation).
2. Model factor to be applied to ground properties to derive characteristic values or directly to the calculated shaft or end bearing capacities.
3. Model factor 1.4, but can be reduced to 1.2 if a load test is completed to calculated unfactored ultimate resistance (ULS check).



# Equivalent Lumped FoS

| Pile Type | Actions | Resistance Factors | | Model Factor | Lumped FoS |
|---|---|---|---|---|---|
| | A2 | R4 (No SLS) | R4 (SLS) | | |
| Driven End Bearing | 1.1 | 1.7 | 1.5 | 1.4 | 2.6/2.3 |
| | | | | 1.2 | 2.2/2.0 |
| Driven End & Shaft | 1.1 | 1.7/1.5 | 1.5/1.3 | 1.4 | 2.5/2.0 |
| | | | | 1.2 | 2.1/1.9 |
| Bored Shaft Friction | 1.1 | 1.6 | 1.4 | 1.4 | 2.5/2.2 |
| | | | | 1.2 | 2.1/1.9 |

1. Partial factor on actions assumes 70% permanent and 30% variable.
2. British Standard BS 8004 lumped FoS ranged from 2.0 to 3.0.
3. Model factor 1.2 requires load test to be completed to unfactored ultimate resistance.
4. Lower value for resistance factors dependent on SLS behaviour being verified (by load test or reliable calculation).



# Pile Design From Static Load Tests

- The design resistance $R_{c;d}$ can also be obtained directly from static load testing by applying correlation factors ξ and the same partial resistance factors γ given above

$$R_{c;d} = \left[\frac{R_{c;k}}{\gamma_t}\right]$$

- The characteristic resistance is obtained from the static load test data using the following

$$R_{c;k} = \text{Min}\left[\frac{\text{Mean } R_{c;m}}{\xi_1}\right] \text{ or } \left[\frac{\text{Minimum } R_{c;m}}{\xi_2}\right]$$



# Pile Design From Static Load Tests

- Values for $\xi_1$ and $\xi_2$ depend on the number of static load tests with values decreasing as the number of load tests increases

| Static Pile Load Tests (n = number of tested piles) | | | | | |
|---|---|---|---|---|---|
| ξ for n = | 1 | 2 | 3 | 4 | ≥ 5 |
| $\xi_1$ | 1.55 | 1.47 | 1.42 | 1.38 | 1.35 |
| $\xi_2$ | 1.55 | 1.35 | 1.23 | 1.15 | 1.08 |

For stiff & strong structures use $\frac{\xi}{1.1} \not< 1.0$ for redistribution



# Pile Design From Dynamic Impact Tests

- The characteristic resistance can also be obtained from dynamic impact test data using the following similar relationship:

$$R_{c;k} = \text{Min}\left[\frac{\text{Mean } R_{c;m}}{\xi_5}\right] \text{ or } \left[\frac{\text{Minimum } R_{c;m}}{\xi_6}\right]$$

- An additional model factor $\gamma_{Rd}$ is also required:
  - 0.85 when using signal matching (CAPWAP)
  - 1.10 when the test includes pile head displacement
  - 1.20 if no measurement of pile head displacement



# Pile Design From Dynamic Impact Tests

- Values for $\xi_5$ and $\xi_6$ depend on the number of dynamic impact tests with values decreasing as the number of tests increases

| Dynamic Impact Tests (n = number of tested piles) | | | | | |
|---|---|---|---|---|---|
| ξ for n = | ≥ 2 | ≥ 5 | ≥ 10 | ≥ 15 | ≥ 20 |
| $\xi_5$ | 1.94 | 1.85 | 1.83 | 1.82 | 1.81 |
| $\xi_6$ | 1.90 | 1.76 | 1.70 | 1.67 | 1.66 |

An additional model factor $\gamma_{Rd}$ is also required:

0.85 when using signal matching (CAPWAP)

1.10 when the test includes pile head displacement

1.20 if no measurement of pile head displacement

# Pile Design From Ground Test Results

- The characteristic resistance can also be obtained from empirical relationships with ground test results (such as CPT) using the following similar relationship:

$$R_{c;k} = \text{Min}\left[\frac{\text{Mean } R_{c;cal}}{\xi_3}\right] \text{ or } \left[\frac{\text{Minimum } R_{c;cal}}{\xi_4}\right]$$

- Values for $\xi_3$ and $\xi_4$ depend on the number of ground test results with values decreasing as the number of profiles increases

# Correlation Factors for Ground Tests

| Ground Test Results (n = number of profiles) | | | | | | | |
|---|---|---|---|---|---|---|---|
| $\xi$ for n = | 1 | 2 | 3 | 4 | 5 | 7 | 10 |
| $\xi_3$ | 1.55 | 1.47 | 1.42 | 1.38 | 1.36 | 1.33 | 1.30 |
| $\xi_4$ | 1.55 | 1.39 | 1.33 | 1.29 | 1.26 | 1.20 | 1.15 |

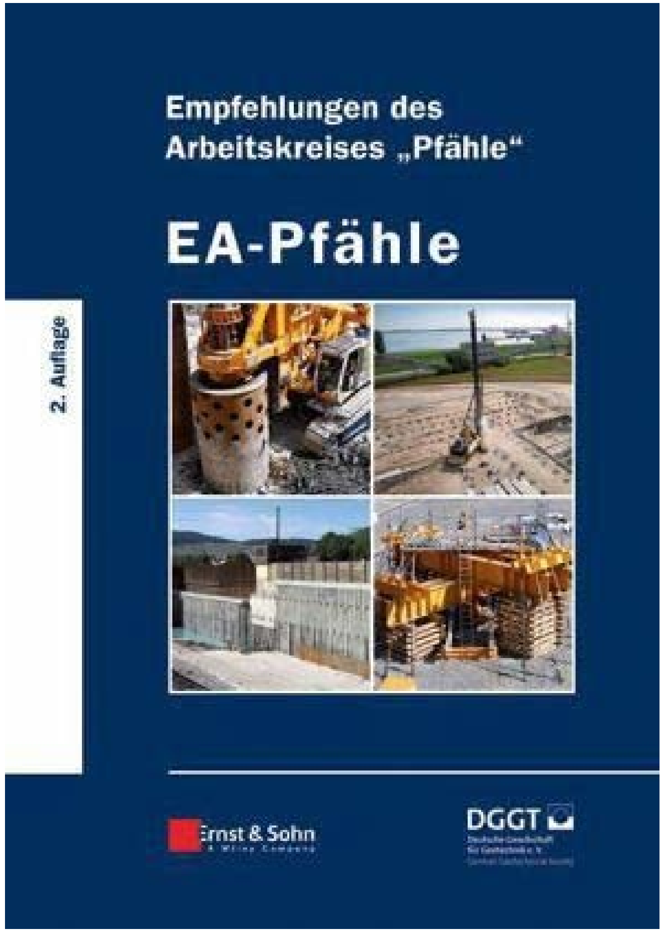
For stiff & strong structures use $\frac{\xi}{1.1} \nless 1.0$ for redistribution

- EC7 requires that the method used to determine the pile characteristic resistance from ground test results should be established from pile load tests and comparable experience
- These correlation factors were intended to be used with CPT profiles or pressuremeter data
- However, EC7 includes the 'alternative procedure' or calculation method within section 7.6.2.3 covering ground test results



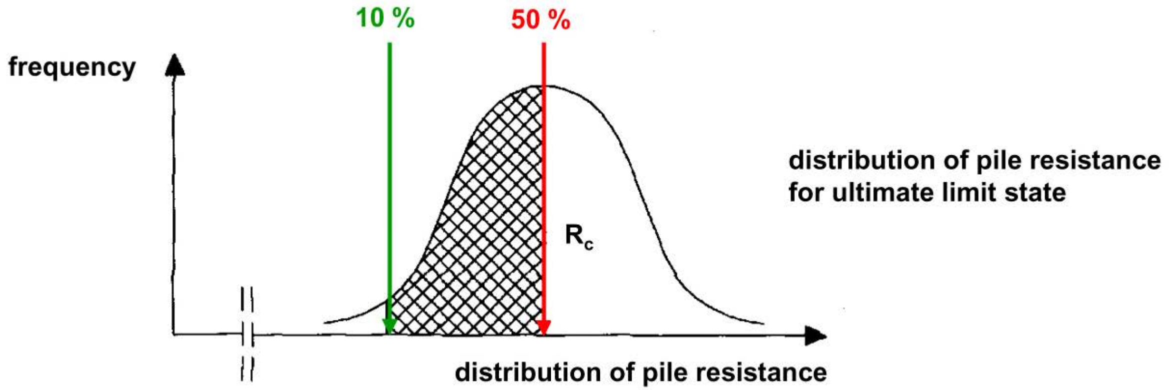
# Pile Design From Design Charts [Experience]

- The characteristic resistance can also be obtained from published design charts (such as those given in EA-Pfähle used in Germany)
- Design charts based on a statistical analysis of static pile load tests



# Pile Design From Design Charts [Experience]

- Tables give characteristic shaft friction and end bearing for different pile types and ground conditions correlated to CPT cone resistance or undrained shear strength
- Charts give 10% or 50% percentiles. EA-Pfähle recommends using the 10% value



# Pile Design From Design Charts [Experience]

**in non-cohesive soils**

| settlement of pile head $s/D_s$ bzw. $s/D_b$ | ultimate base resistance $q_b$ [kN/m²] for a mean tip resistance $q_c$ of a CPT [MN/m²] | | |
|---|---|---|---|
| | 7.5 | 15 | 25 |
| 0,02 | 550 – 800 | 1,050 – 1,400 | 1,750 – 2,300 |
| 0,03 | 700 – 1,050 | 1,350 – 1,800 | 2,250 – 2,950 |
| 0.10 (= $s_g$) | 1,600 – 2,300 | 3,000 – 4,000 | 4,000 – 5,300 |

Intermediary values can be interpolated linearly.
For bored piles with foot enlargement values to be reduced to 75 %.

**in non-cohesive soils**

| mean tip resistance $q_c$ of a CPT [MN/m²] | ultimate skin friction $q_{s1,k}$ [kN/m²] |
|---|---|
| 7,5 | 55 – 80 |
| 15 | 105 – 140 |
| ≥ 25 | 130 – 170 |

Intermediary values can be interpolated linearly.

**in cohesive soils**

| settlement of pile head $s/D_s$ bzw. $s/D_b$ | ultimate base resistance $q_b$ [kN/m²] undrained shear strength $c_{u,k}$ [kN/m²] | | |
|---|---|---|---|
| | 100 | 150 | 250 |
| 0,02 | 350 – 450 | 600 – 750 | 950 – 1,200 |
| 0,03 | 450 – 550 | 700 – 900 | 1,200 – 1,450 |
| 0.10 (= $s_g$) | 800 – 1,000 | 1,200 – 1,500 | 1,600 – 2,000 |

Intermediary values can be interpolated linearly.
For bored piles with foot enlargement values to be reduced to 75 %.

**in cohesive soils**

| undrained shear strength $c_{u,k}$ [kN/m²] | ultimate skin friction $q_{s1,k}$ [kN/m²] |
|---|---|
| 60 | 30 – 40 |
| 150 | 50 – 65 |
| ≥ 250 | 65 – 85 |

Intermediary values can be interpolated linearly.

Tables 5.12 to 5.15 for Bored Piles – Recommended 10% percentiles given in green



# Pile Settlement

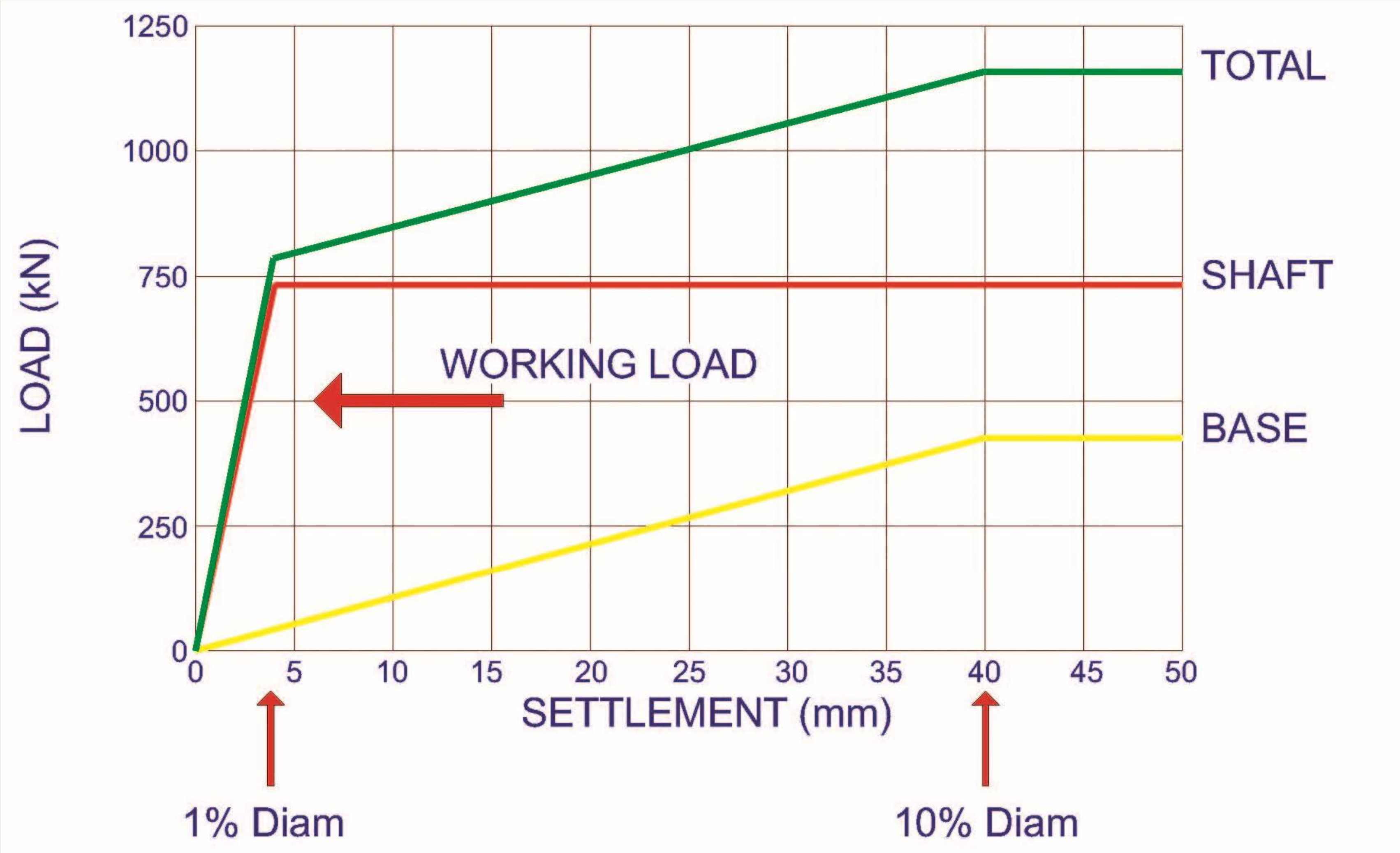
- EC7 has been written with much more emphasis on SLS behaviour regarding pile settlement and horizontal movement
- EC7 adopts lower partial factors but on the understanding that movements are considered
- The partial resistance factors in the UK National Annex have therefore been modified to take account of the type of pile and whether the serviceability behaviour is to be determined either by load test or a rigorous and reliable calculation



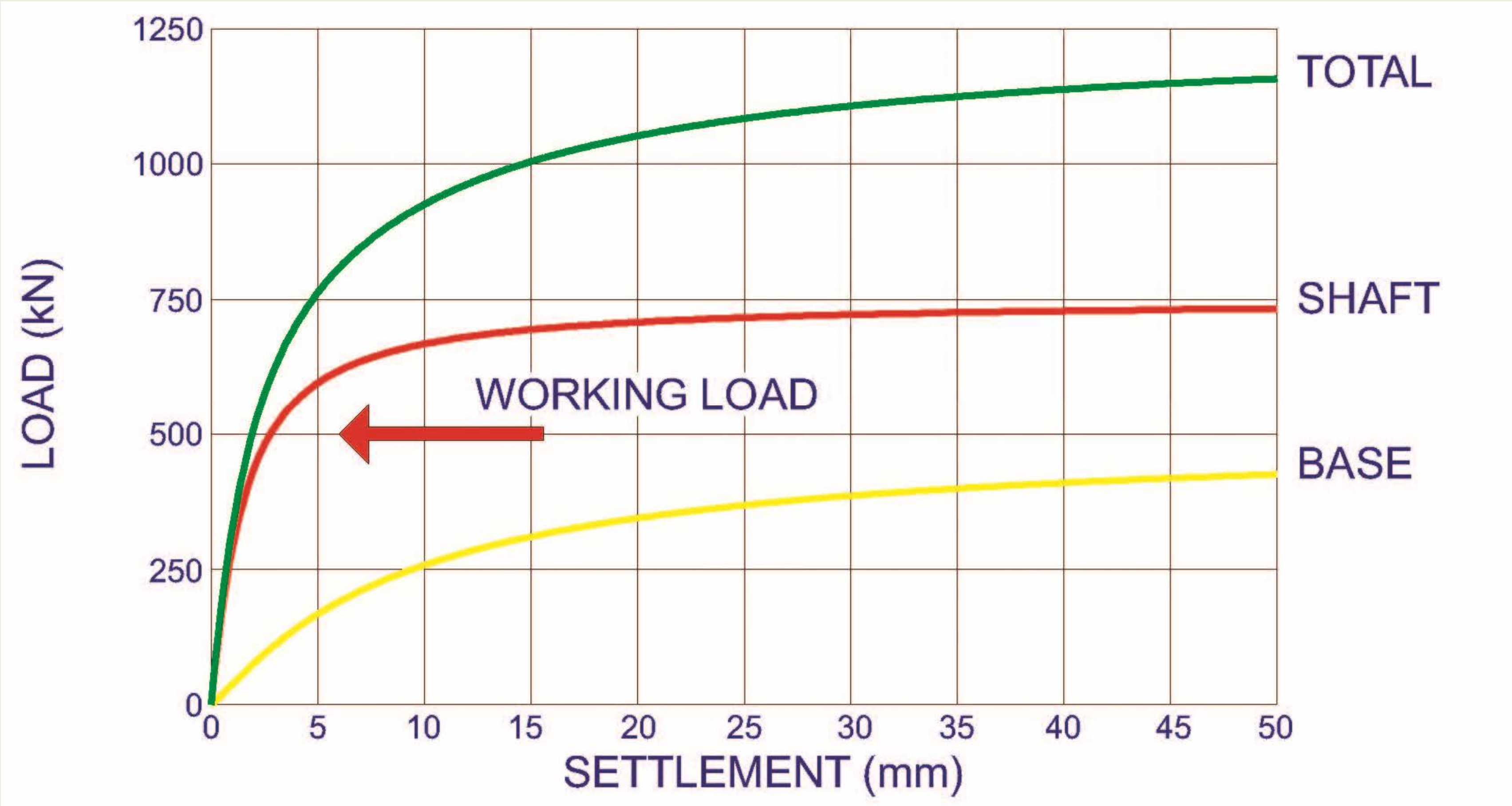
# Pile Settlement

- Empirical method: Pile settlements are dependent on the stiffness properties of the founding soil or rock, the pile geometry, and the mechanism of load transfer to the ground.
- Typically:
  - Shaft friction is mobilised at a movement equal to about 1% of the pile diameter
  - End bearing is mobilised at a movement equal to about 10% of the pile diameter
- Good for understanding behaviour but not rigorous

# Pile Settlement



# Pile Settlement



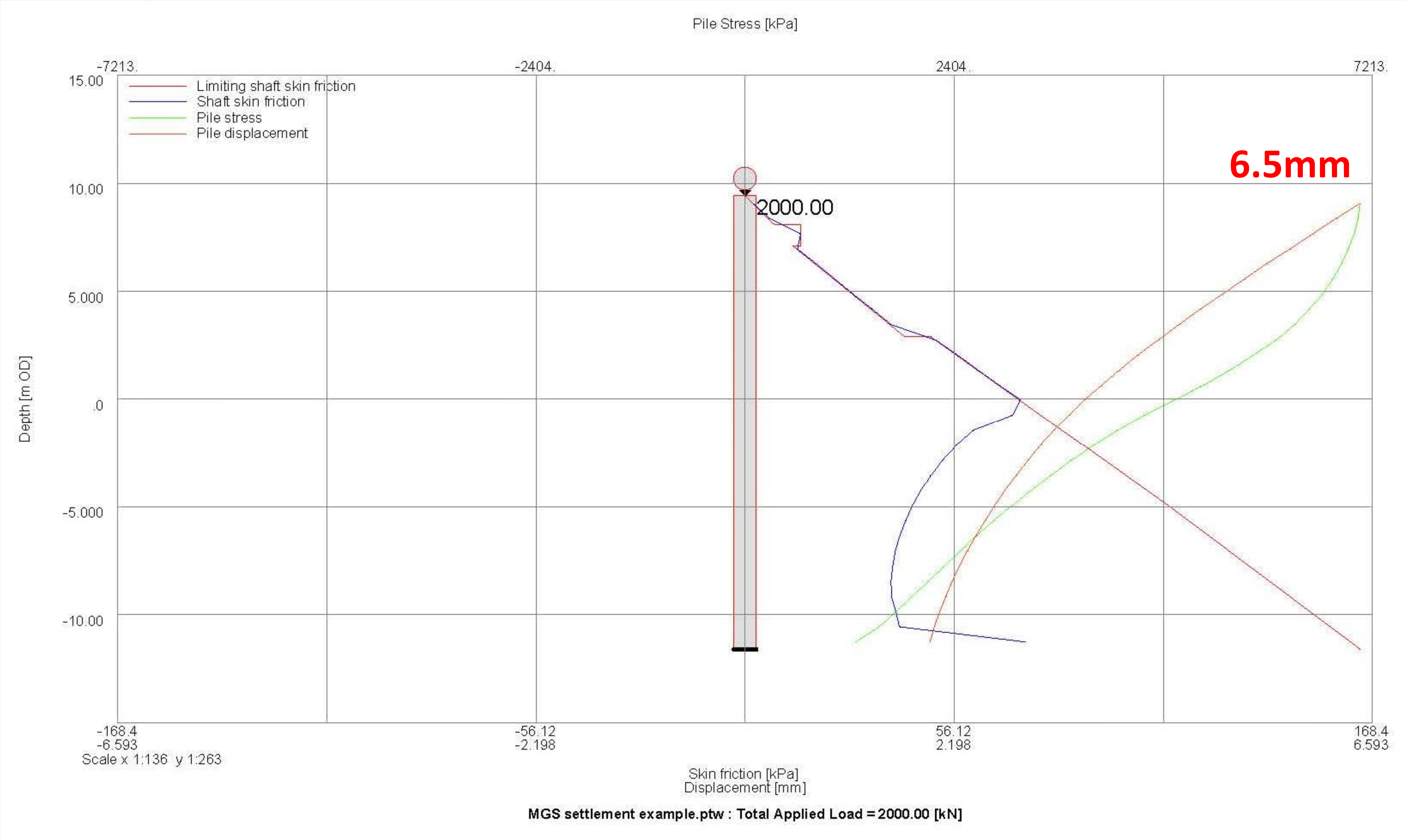


# Pile Settlement

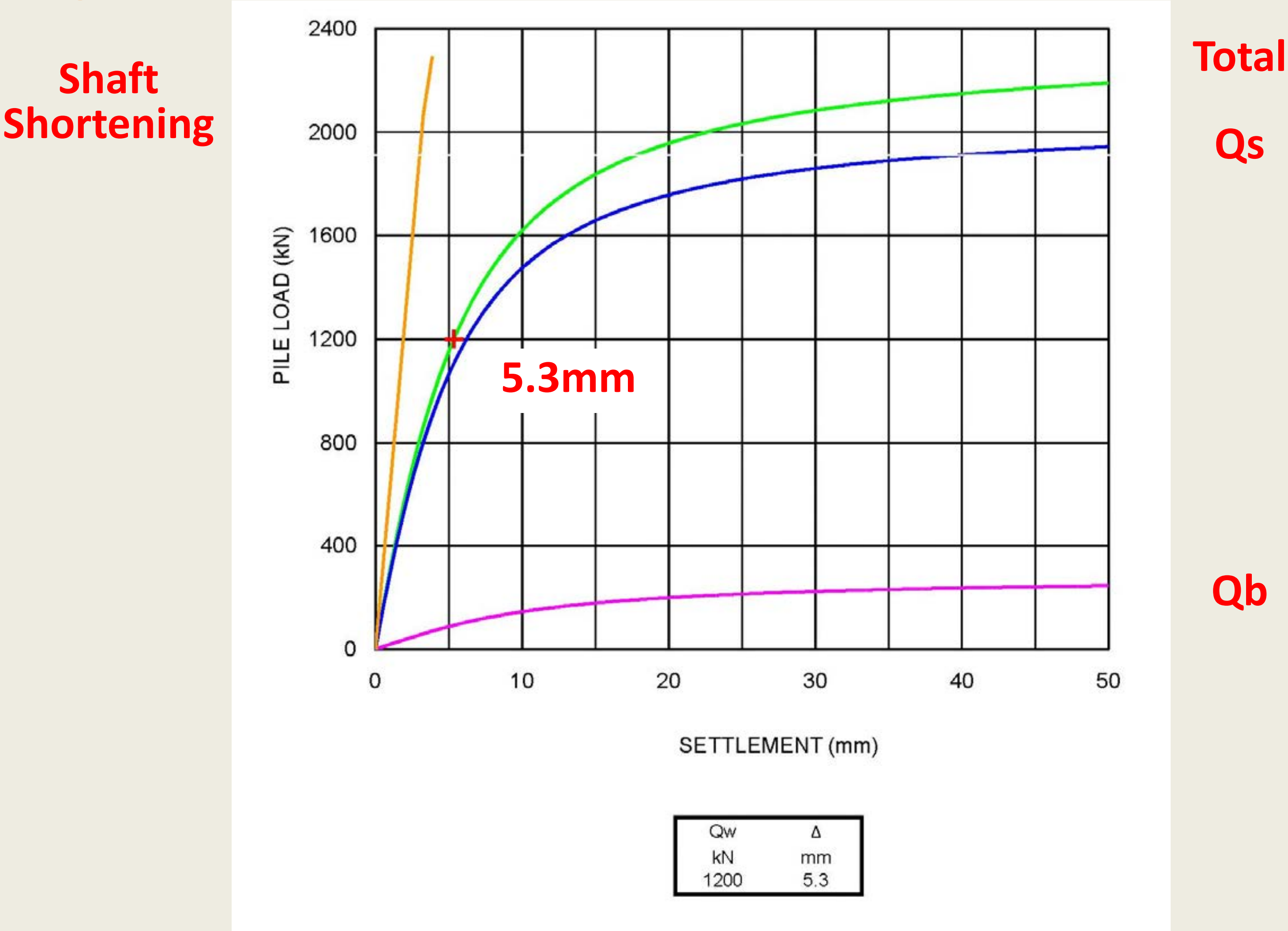
- Computational approaches for assessing pile settlements are now available for use in the commercial design office in the form of computer programs:
  - PIGLET Closed form elastic continuum equations
    Randolph (1980)
  - CEMSET Simplified hyperbolic functions for the pile base and shaft
    Fleming (1992)
  - PILSET Iterative approach based on Mindlin equations
    Poulos & Davis (1980) - Oasys Limited
  - REPUTE Based on boundary elements



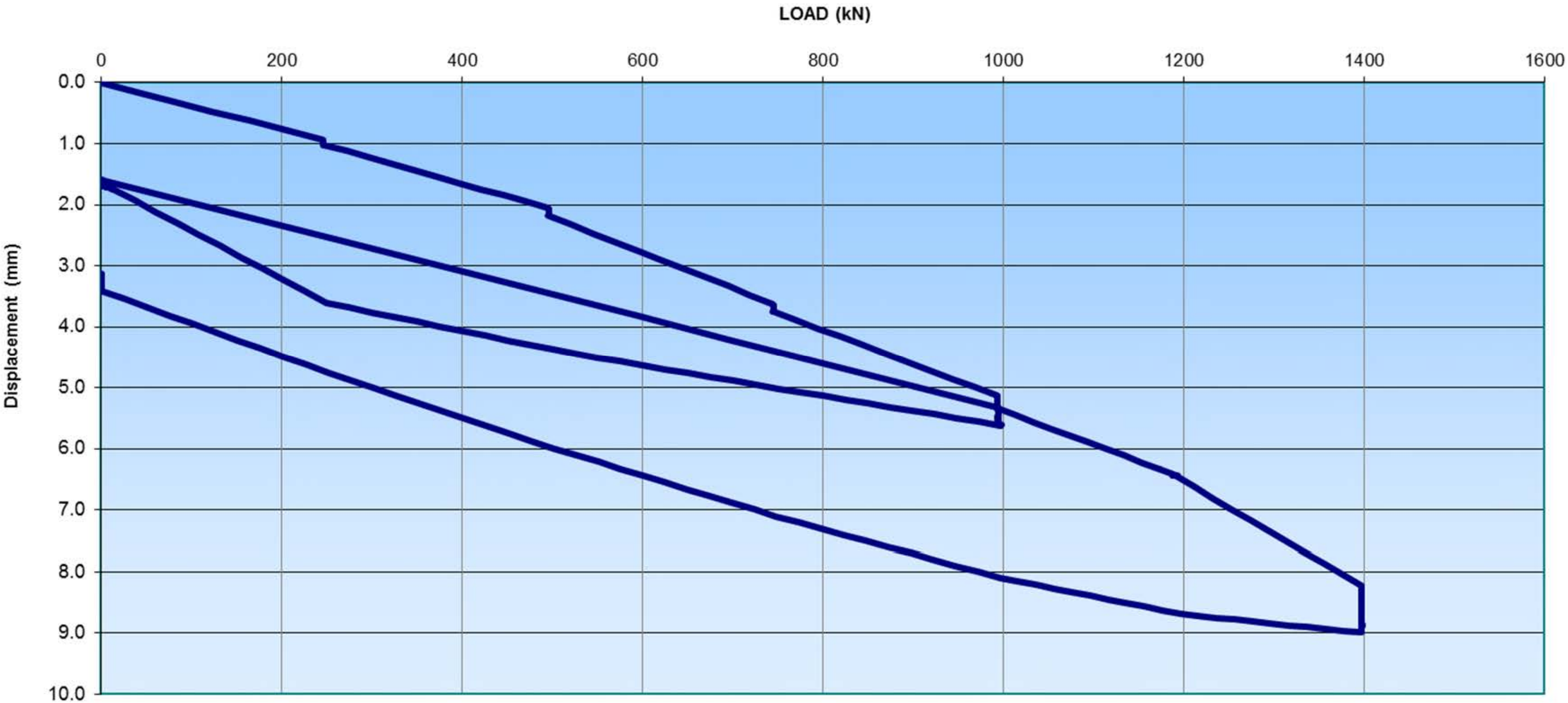
# Example PILE Settlement Calculation



# Example CEMSET Settlement Calculation




# Pile Load Test – Working to DVL + 50%





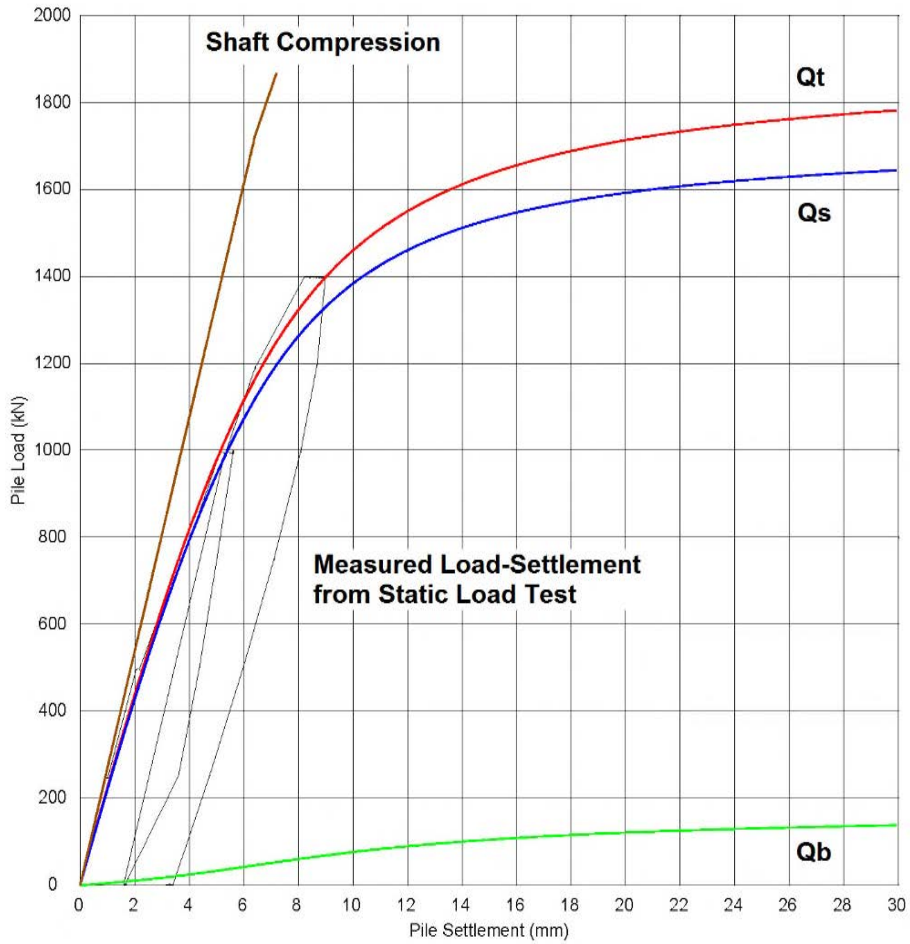
# Load Test Back Analysis

Bearing capacity calculation based on soil parameters and CEMSET settlement calculation used to back analyse load test

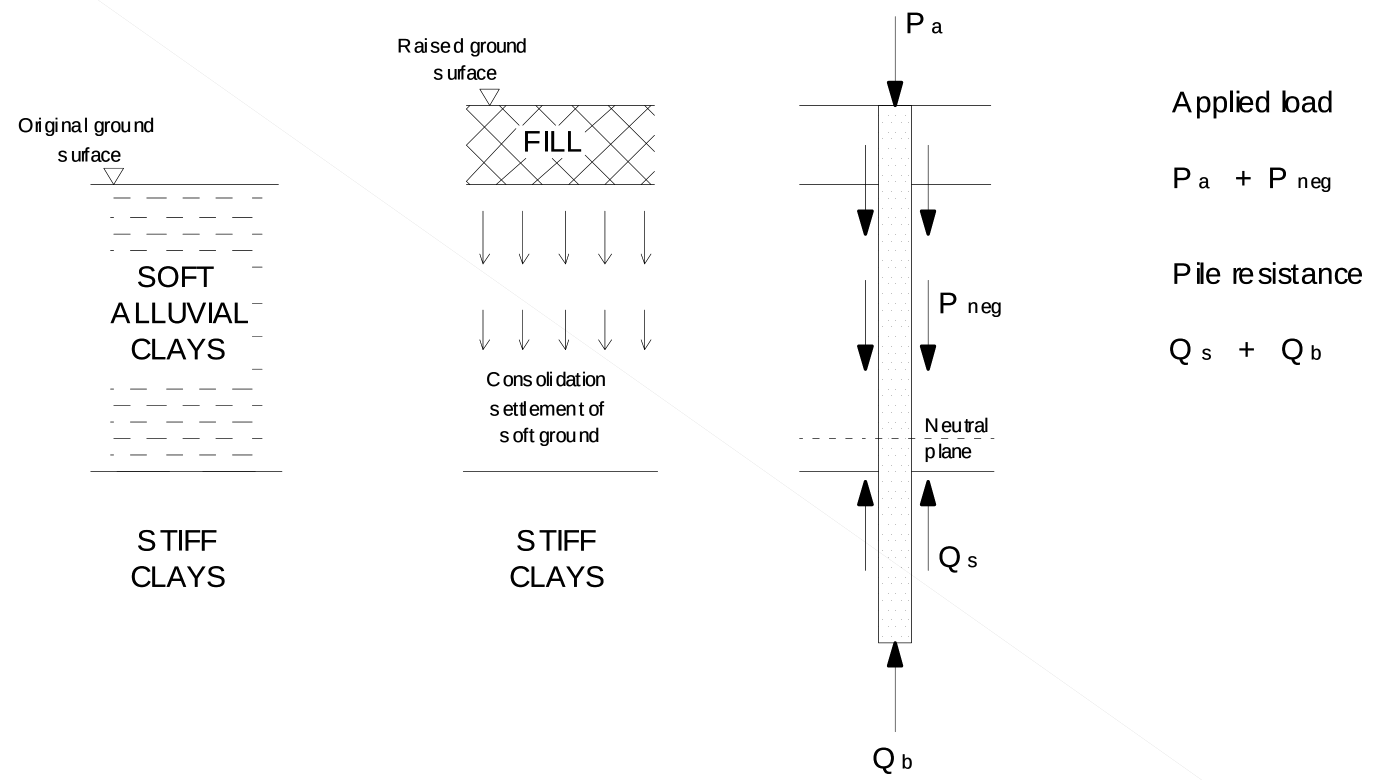
Very good match

Design program to compute pile settlement behaviour. Program based on:
A new method for single pile settlement prediction and analysis.
W.G.K.Fleming, (1992). Géotechnique 42, No. 3, 411-425.

| | | | |
|---|---|---|---|
| Pile System | Cfa bored | Friction free length | 11.00 m |
| Equivalent shaft diameter | 450 mm | Shaft friction length | 15.00 m |
| Equivalent base diameter | 450 mm | Shaft flexibility factor | 0.0025 |
| Ultimate shaft capacity | 1724 kN | End bearing Young's modulus | 40000 kPa |
| Ultimate base capacity | 172 kN | Pile Shaft Young's modulus | 30000000 kPa |
| Overall pile length | 26.00 m | Effective column length factor | 0.45 |



# Negative Shaft Friction



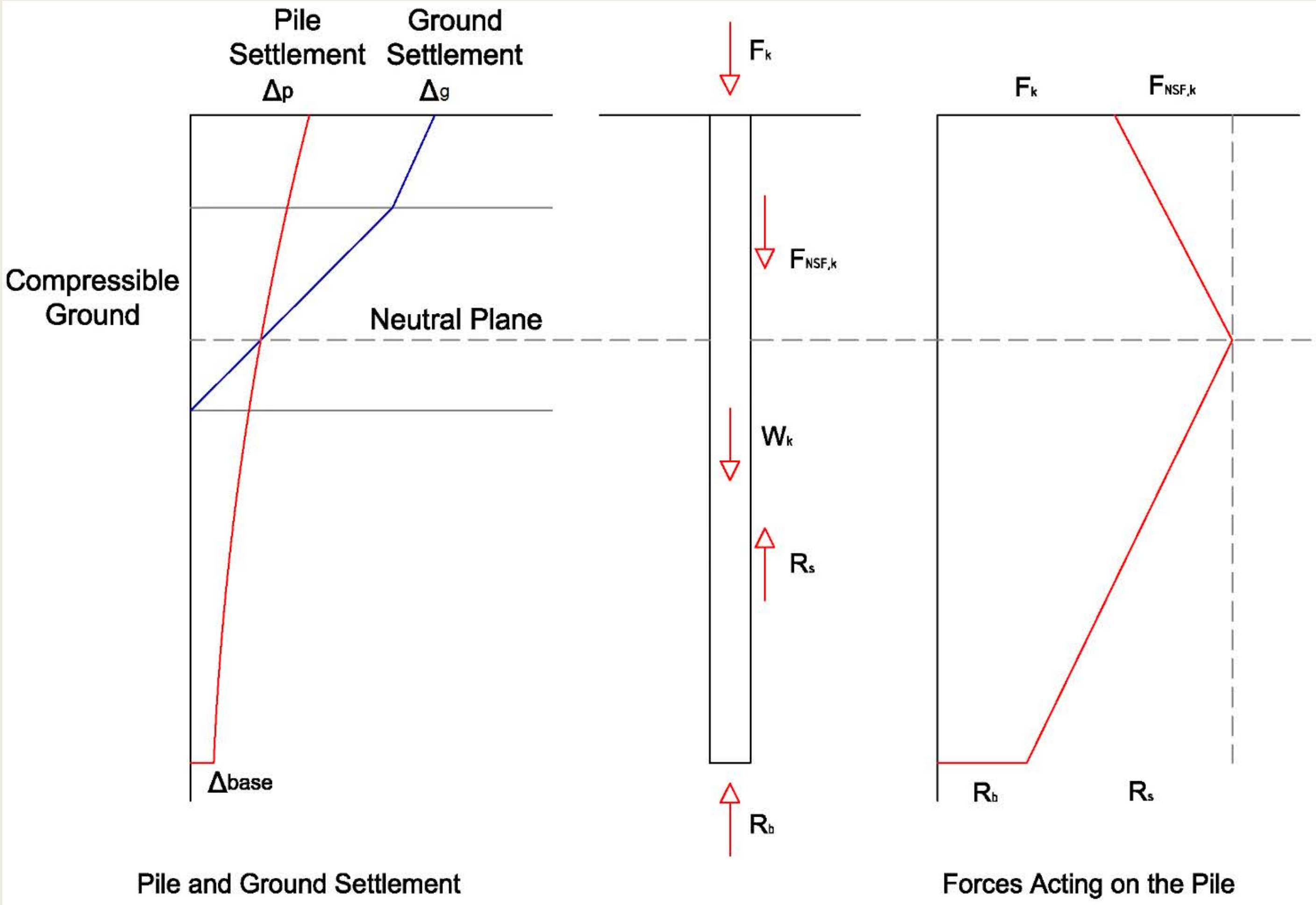


# Negative Shaft Friction

NSF occurs when ground settlement exceeds pile settlement at any point

Complex problem that cannot be designed by load test

Need soil-structure interaction software





# Negative Shaft Friction

- EC7 has little to say about NSF
- No consensus between Designers
- Two possible approaches:
- An SLS problem
  - Analyse the effect of ground settlement on the pile and estimate pile settlements and stresses
  - Complex analysis
  - Requires suitable software
  - Time consuming



# Negative Shaft Friction

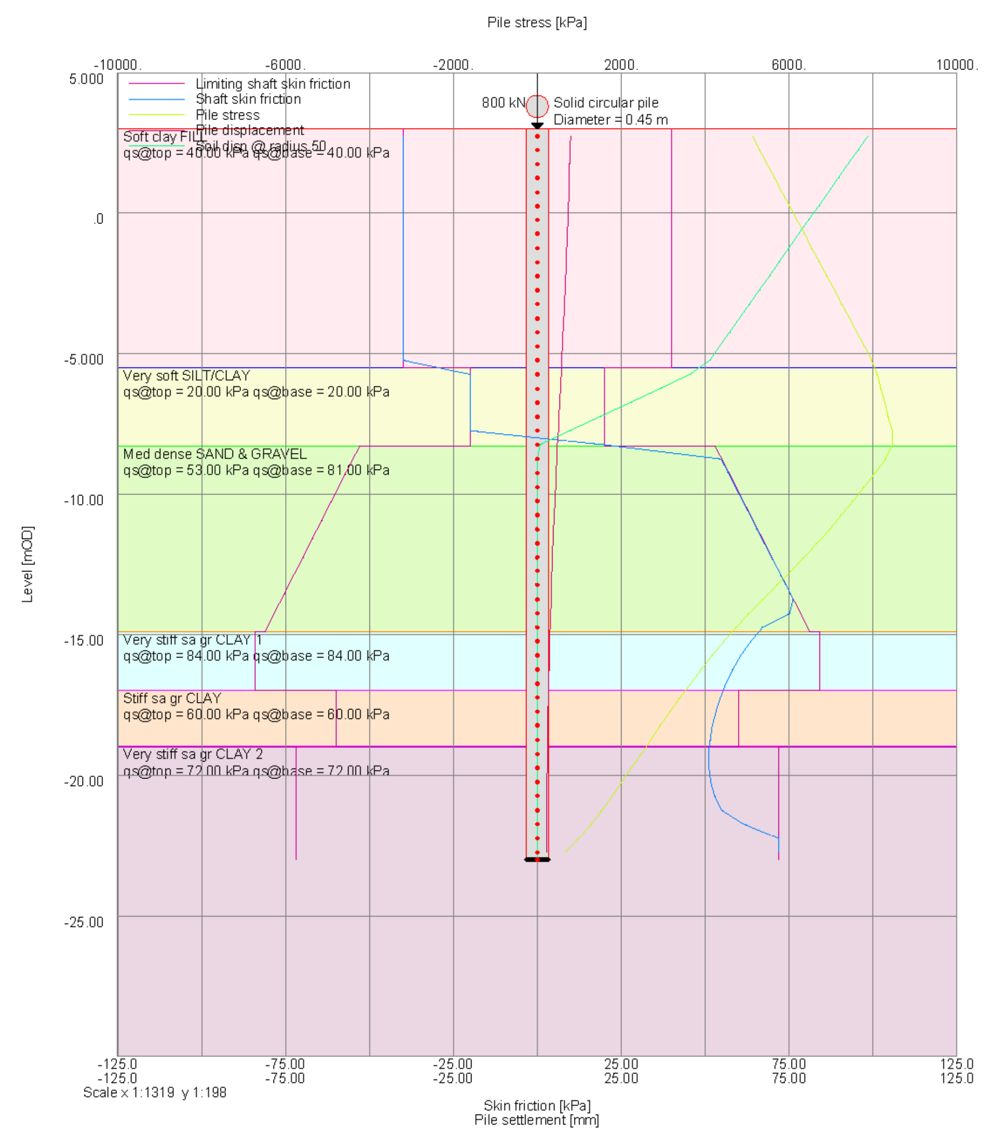
- A ULS problem
  - Estimate the potential additional load due to the settling soil
  - Treat as an extra permanent load
  - Simple calculation but not really correct
  - Most common method
- Does it comply with EC7?



# Negative Shaft Friction

Typical software output for SLS analysis:

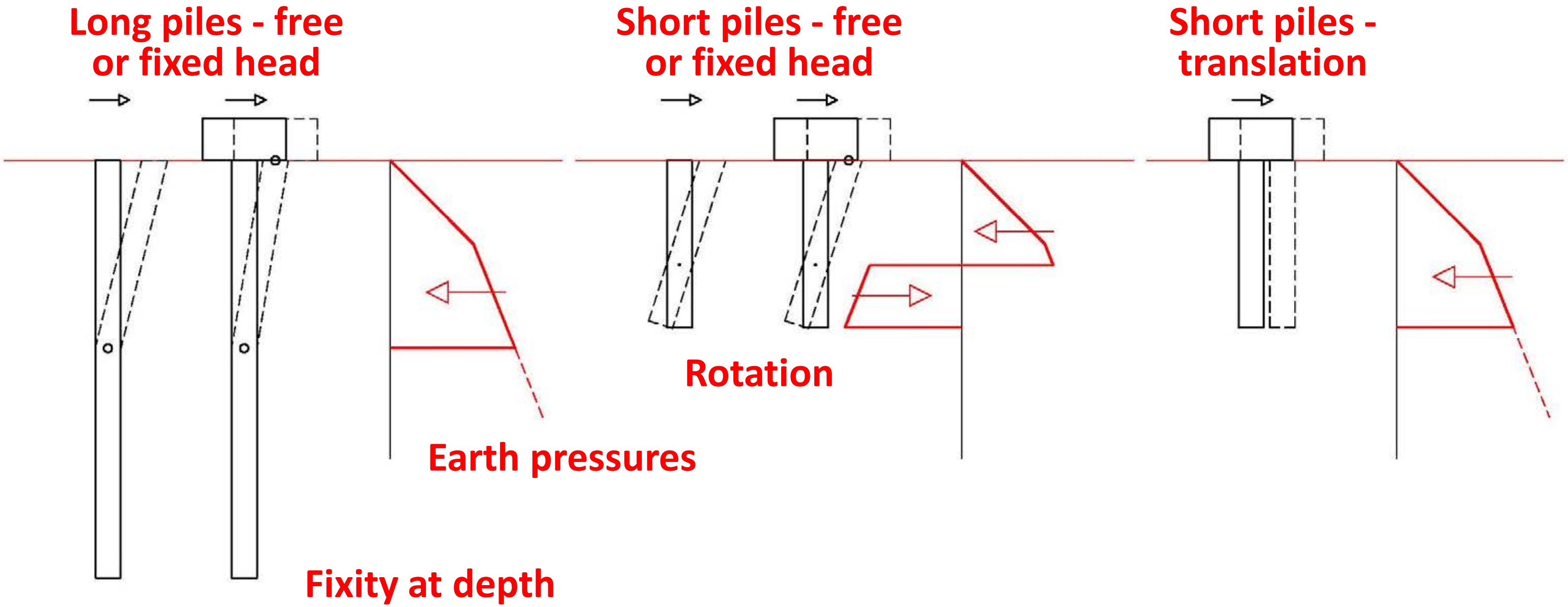
100mm ground settlement
10mm pile settlement





# Horizontal Loading

- It is possible to carry out ULS horizontal load analyses but these depend on the assumed mechanism of behaviour





# Horizontal Loading

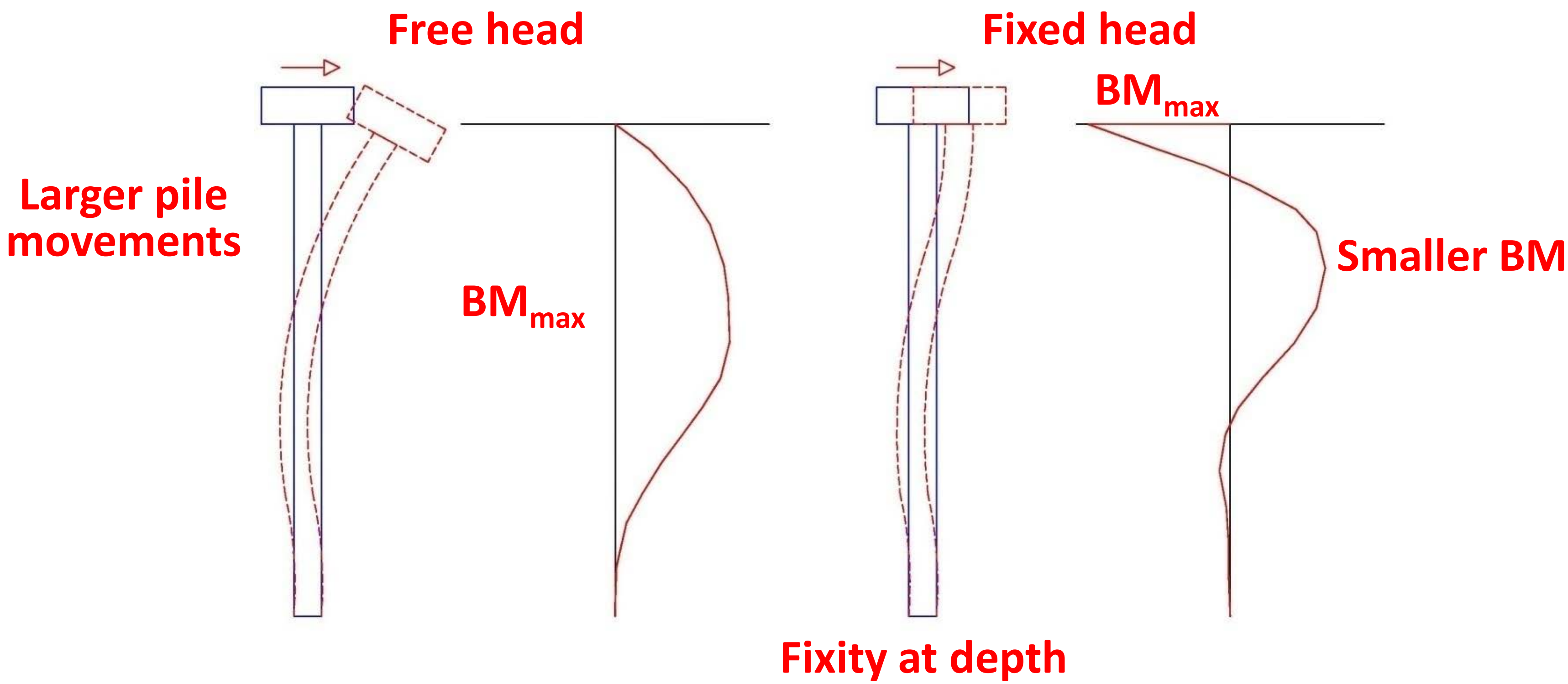
- Resistance to horizontal load:
  - Short piles: Lateral resistance of ground
  - Longer piles: Combination of ground strength & stiffness, pile stiffness and restraint conditions
- EC7 gives only general guidance:
  - Check inequality:
  - Ed is the horizontal load action effect
  - Rd is the resistance to horizontal load
- Not much practical help

# Horizontal Loading

- For horizontal load design, STR limit state usually governs – the capacity of the pile section to carry bending moments
- Many Designers use equilibrium methods (Broms)
- Recent BS8004 (2015) promotes this approach but this is a poor model of the behaviour of most piles and it ignores SLS
- Soil-structure interaction software (e.g. ALP or WALLAP)
- Traditional approach: SLS analysis (unfactored)
- Apply partial factor to moments and shear forces, typically 1.4 to 1.5 and compare with structural strength

# Horizontal Loading

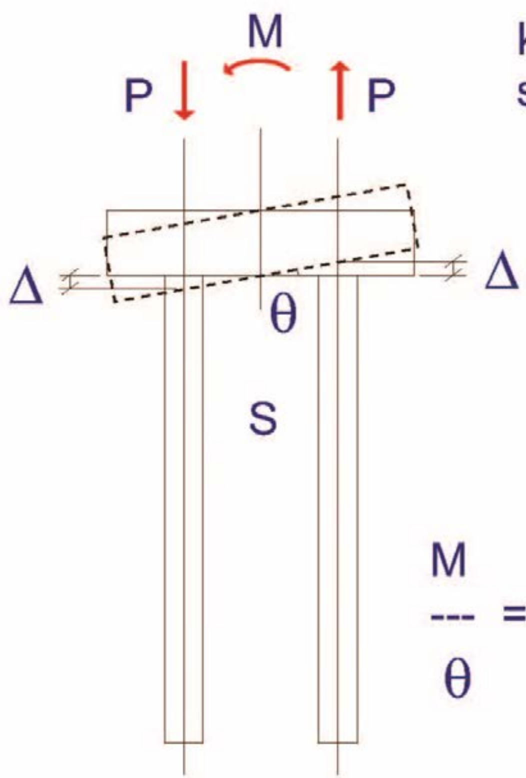
- Note that real piles have flexural stiffness (EI)
- Horizontal behaviour is controlled by head fixity at the cap





# Horizontal Loading – Head Fixity

- Head fixity can be modelled as shown
- Larger pile groups have much larger fixity
- Bending moment is usually maximum at the connection to the pile cap




Two Pile Cap Head Fixity

k is the pile axial stiffness in kN/m

$M = P\,S$

$\Delta = \theta\,S/2$

$P = k\,\Delta$

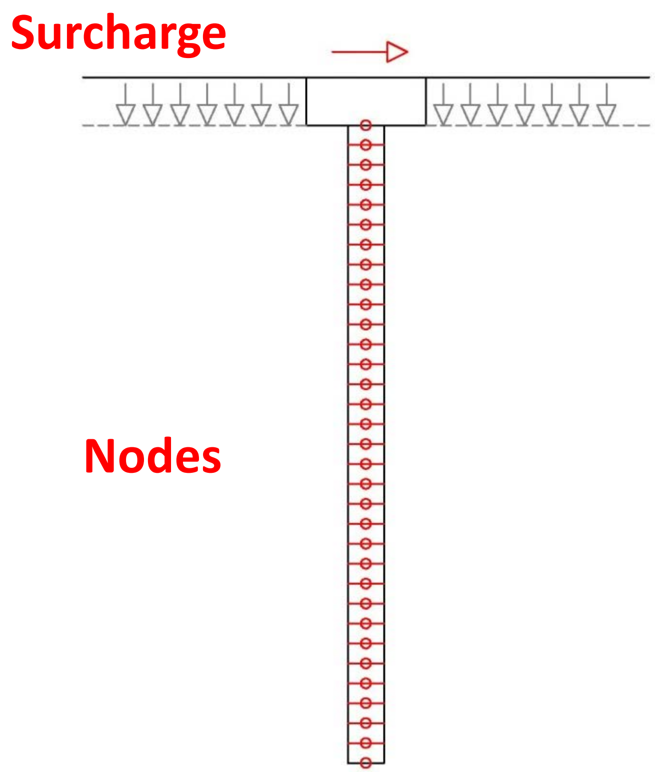
Combine to give moment stiffness per pile.

$$\frac{M}{\theta} = \frac{k\,S^2}{4} \text{ kNm/radian}$$



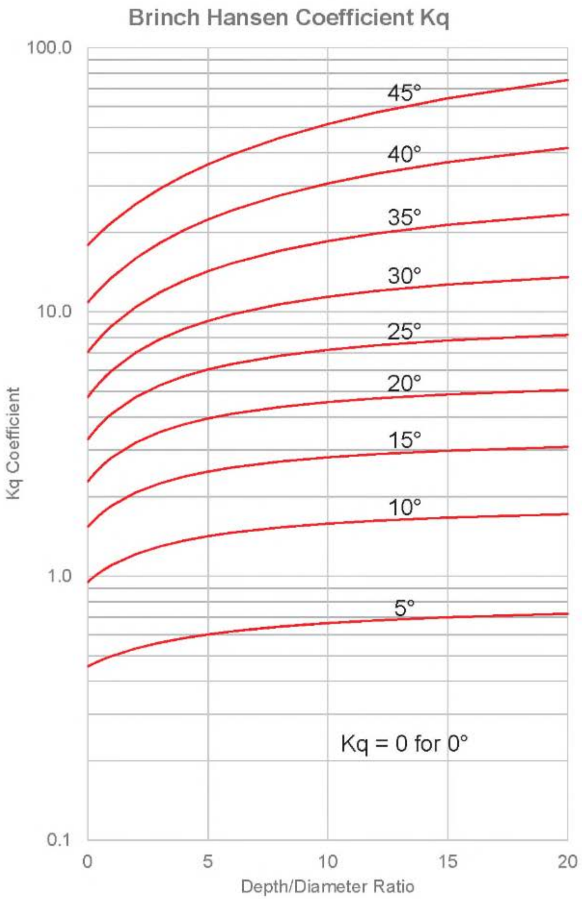
# Horizontal Loading

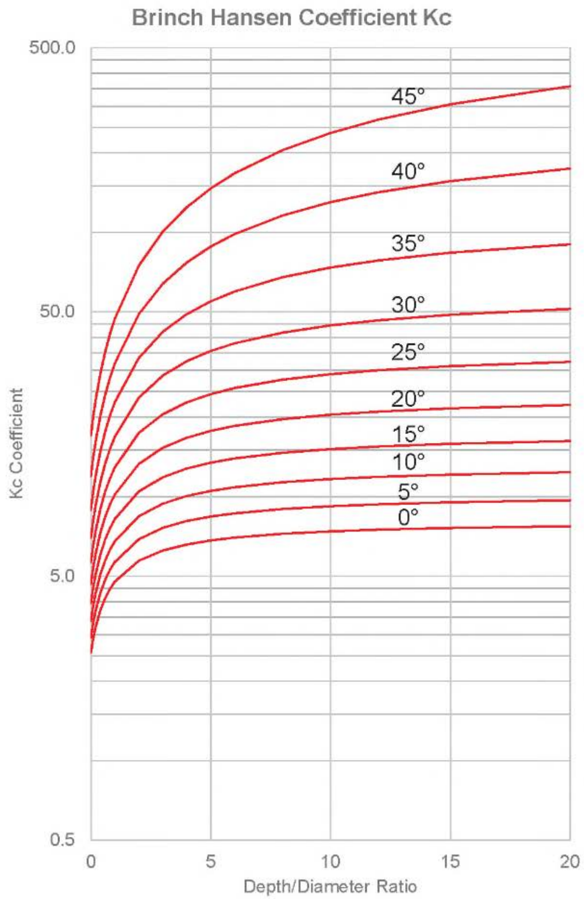
- EC7 allows soil-structure interaction software to be used:
  - Options in UK are ALP or WALLAP
  - Pile is modelled as beam elements
  - Ground is modelled as springs
  - Analysis can be based on factored horizontal actions or factored soil strength (and stiffness)
  - Best to analyses without factors
  - Apply partial factors to BM & SF



# Horizontal Loading

- ALP uses Brinch Hansen $k_q$ and $k_c$ coefficients



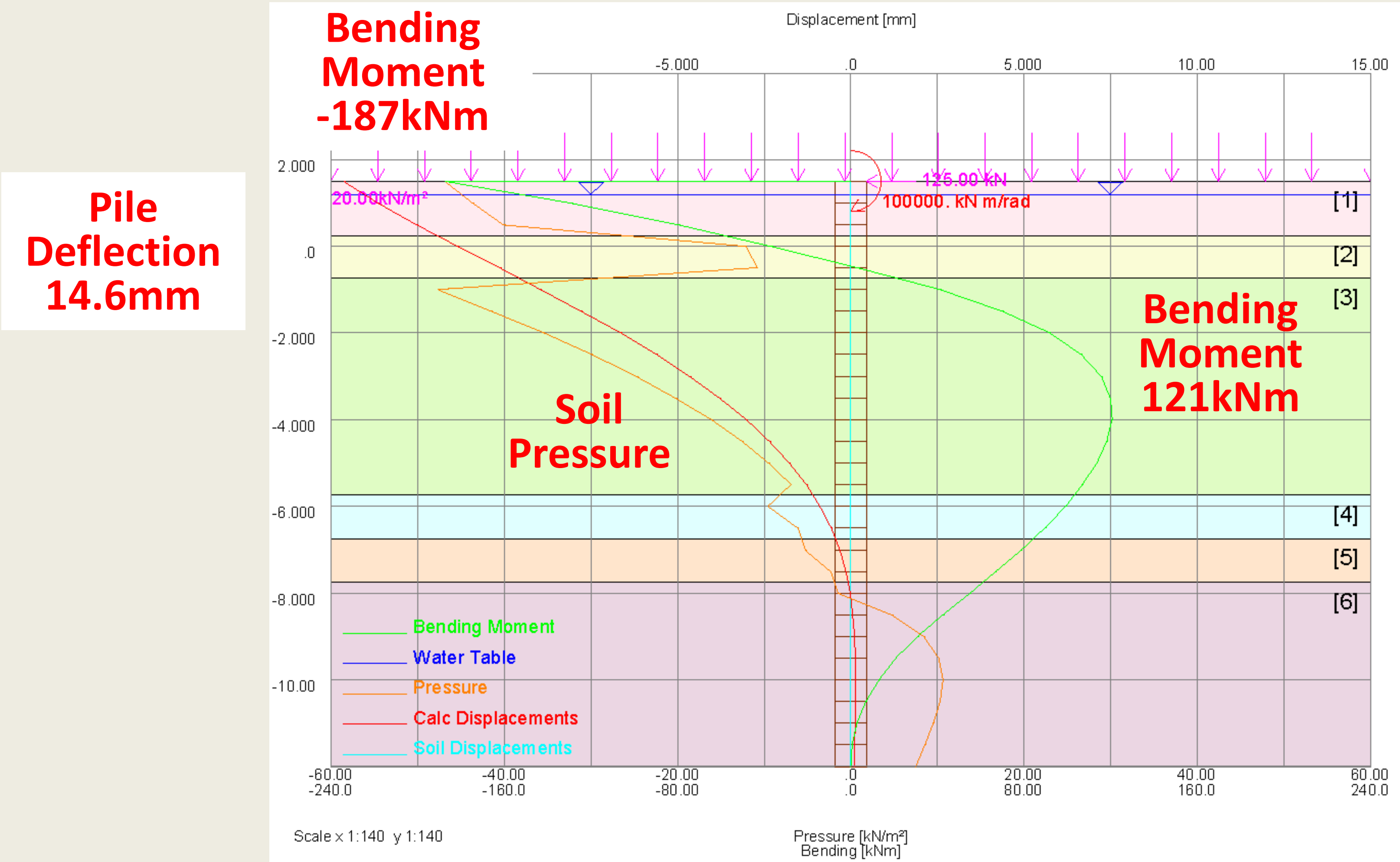





# Horizontal Loading

- How do we apply EC7 to these types of analysis?
- Strictly, to comply with EC7, three analyses are required:
    - ULS combinations 1 & 2 – calculate design bending moments and shear forces
    - SLS – consider pile deflection
- ULS combination 2 requires factored soil strength
- How do we deal with soil stiffness when using factored soil strength?
- Risk of large number of analyses

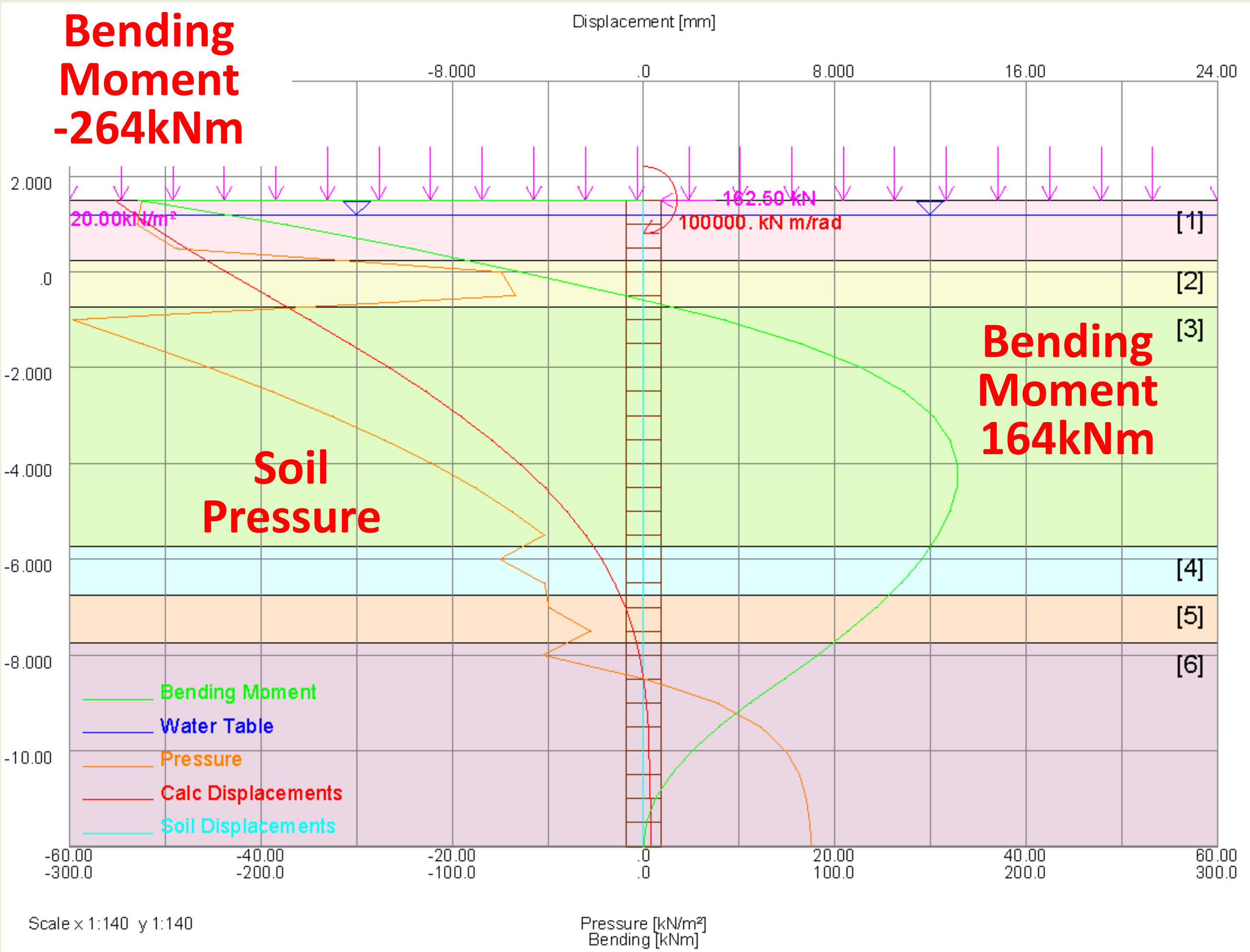
# Example ALP Horizontal Load Analysis




## SLS - Unfactored

# Example ALP Horizontal Load Analysis

**Pile Deflection 22.1mm**

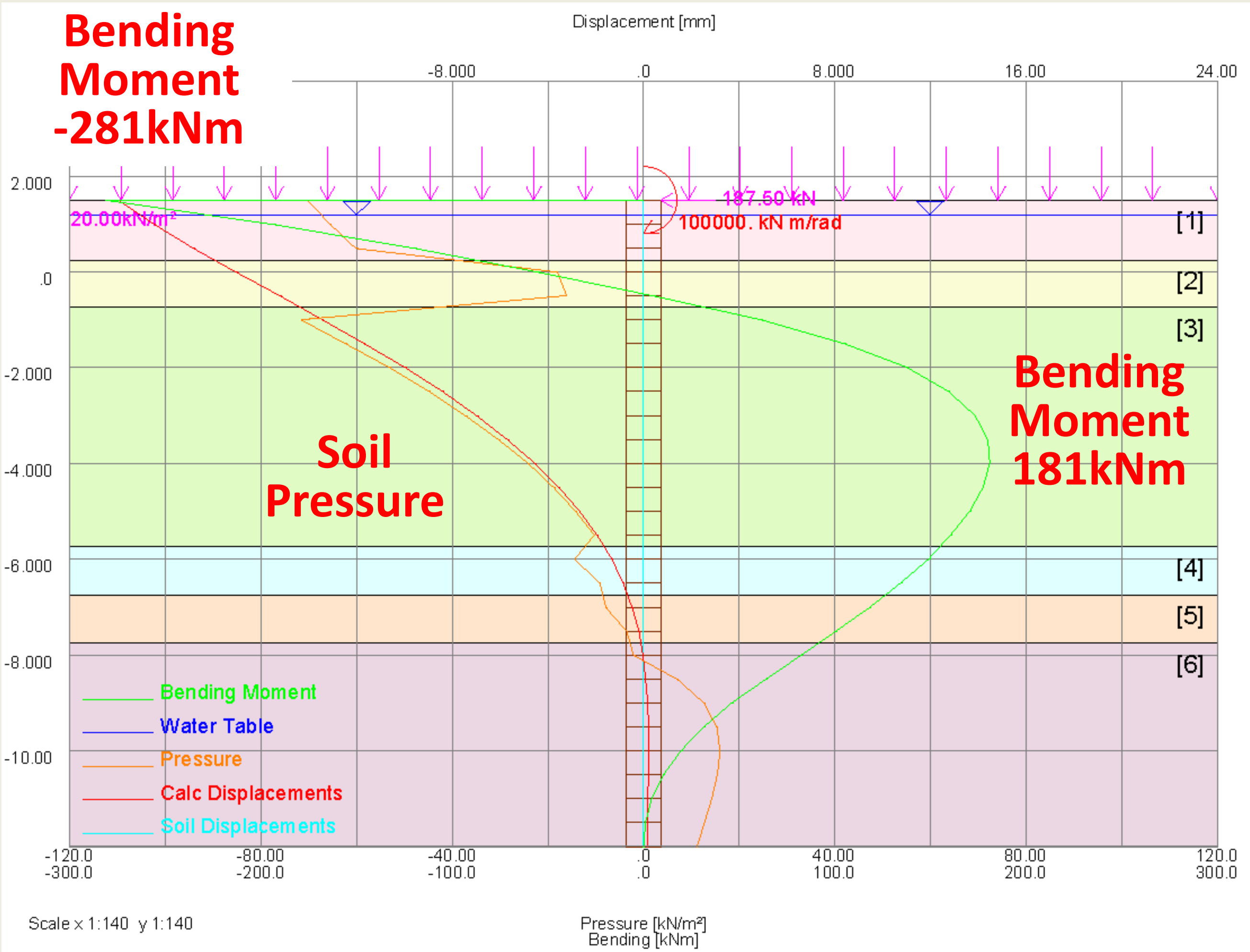



## ULS – A2/M2 Factor Sets



# Example ALP Horizontal Load Analysis

**Pile Deflection 22.0mm**




## ULS – A1/M1 Factor Sets



# Example ALP Horizontal Load Analysis

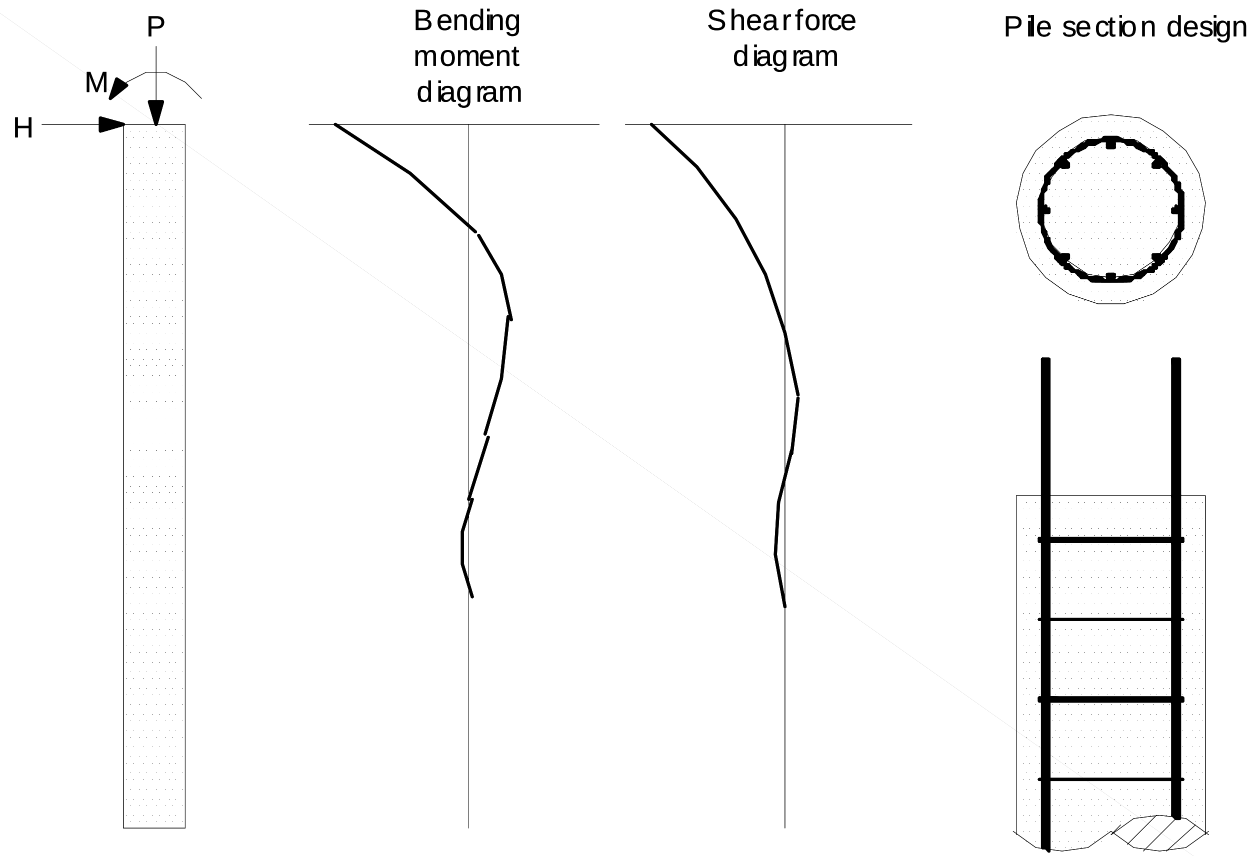
| | SLS No factors | ULS A2/M2 | ULS A1/M1 | ULS A1/M1* | |
|---|---|---|---|---|---|
| Material Factor $\gamma_m$ | | 1.25 | 1.0 | 1.0 | |
| Horizontal $G_k$ | 0 | 0 | 0 | 0 | kN |
| Horizontal $Q_k$ | 125 | 125 | 125 | 125 | kN |
| Partial Factor $\gamma_G$ | | 1.0 | 1.35 | 1.0 | |
| Partial Factor $\gamma_Q$ | | 1.3 | 1.5 | 1.0 | |
| Horizontal $G_d$ | 0 | 0 | 0 | 0 | kN |
| Horizontal $Q_d$ | 125.0 | 162.5 | 187.5 | 125.0 | kN |
| At Pile Head | | | | | |
| Calculated Moment M | -187 | -264 | -281 | -187 | kNm |
| Partial Factor $\gamma$ | | 1.0 | 1.0 | 1.5 | |
| Design Moment $M_d$ | | -264 | -281 | -281 | kNm |
| Peak at Depth | | | | | |
| Calculated Moment M | 121 | 164 | 181 | 121 | kNm |
| Partial Factor $\gamma$ | | 1.0 | 1.0 | 1.5 | |
| Design Moment $M_d$ | | 164 | 181 | 182 | kNm |

ULS A1/M1* - Partial factors applied to effect of actions



## ULS – A1/M1 Factor Sets

# Structural Design of Piles




- Not EC7 - But pile designers must be aware



# Structural Design of Piles

- Based on BS EN 1992-1-1 (EC2 Part 1.1.)
- Use the calculated design compression and tension loads combined with design bending moments and shear forces
- Compression loads are sometimes ‘favourable’
- Cast in-situ piles treated as circular columns
- Precast piles generally square columns
- In most cases the piles are fully restrained and will not fail by buckling even in soft or loose ground



# Structural Design of Piles

- EC2 contains clauses which are specific to cast in-situ piles:
  - Partial factor on concrete strength increased by 10%
  - Design pile diameter 95% of nominal pile diameter
- These clauses were not required by BS 8110 – EC 2 is more conservative!
- Shear calculation differs significantly from BS 8110
- In some cases more longitudinal steel is needed due to shear.



# Structural Design of Piles

- EC2 requirements for maximum bar spacing conflict with piling execution codes
- In some cases small diameter piles are not buildable
- Minimum 6 bars
- Not general UK practice for axially loaded piles
- Steel lap lengths can be excessive



# Design Example

- 600mm CFA bored preliminary test pile
- Installed from a reduced level dig (3.5m below original level)
- Pile bored to 20.6m depth
- Founded in very weak Chalk
- Maximum test load 5,200kN at 61.3mm (Approx 10% D)
- Example design based on:
  - Calculation
  - Static load test

# Design Actions $F_d$ for Design Example

- Example calculation

  Permanent Load $G_k = 1400\text{kN}$ Variable Load $Q_k = 600\text{kN}$

- Factor Set A1

  $$\text{EC7 Design Action } F_d = 1400 \times 1.35 + 600 \times 1.5$$

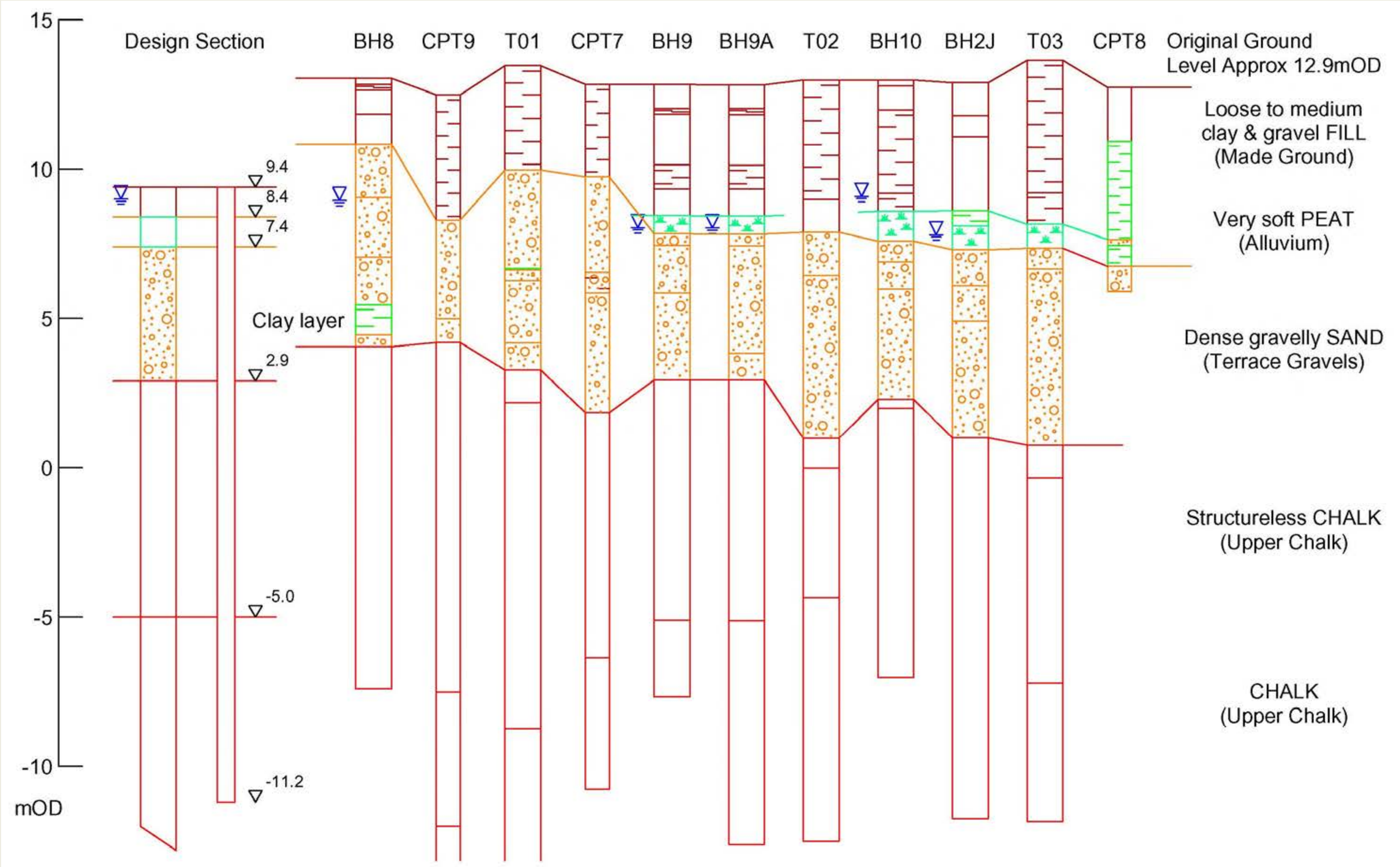
  $$\text{EC7 Design Action } F_d = 2790\text{kN}$$

- Factor Set A2

  $$\text{EC7 Design Action } F_d = 1400 \times 1.0 + 600 \times 1.3$$

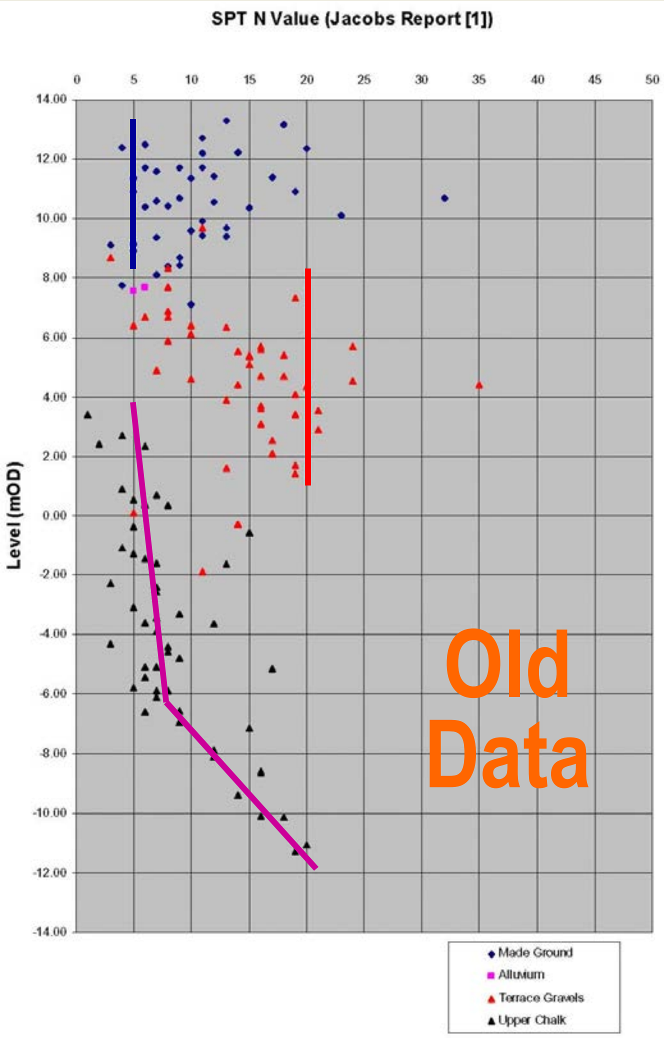
  $$\text{EC7 Design Action } F_d = 2180\text{kN}$$

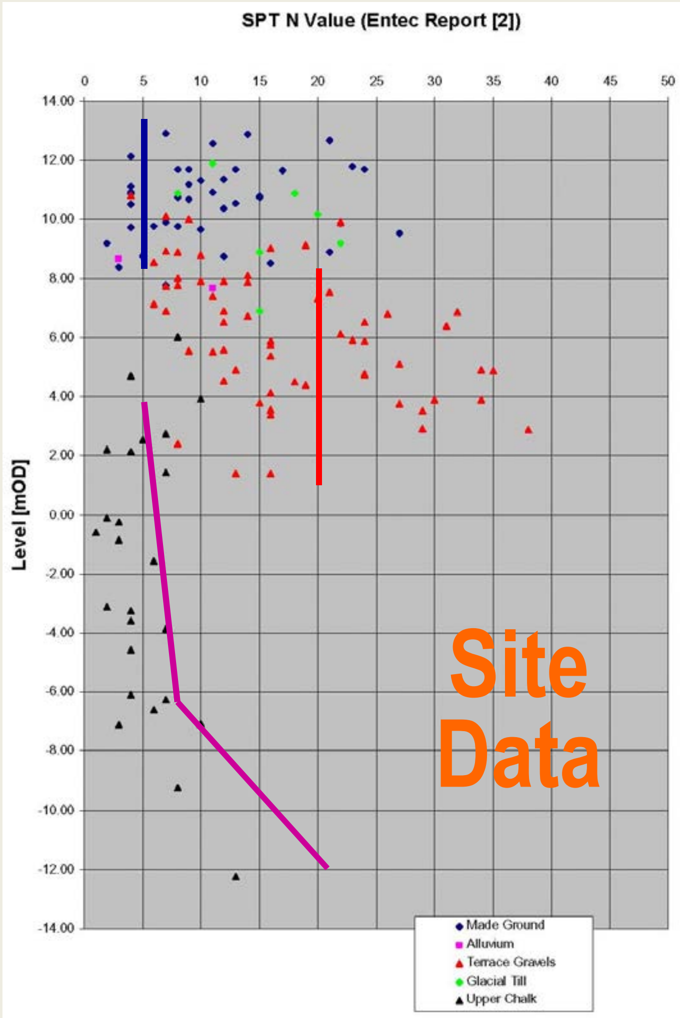


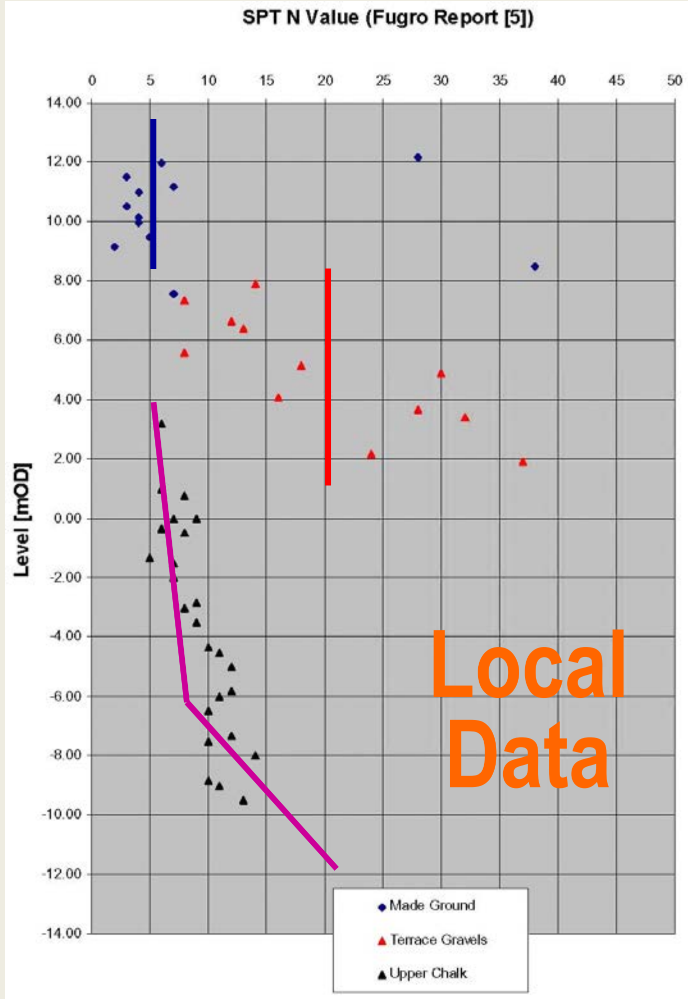




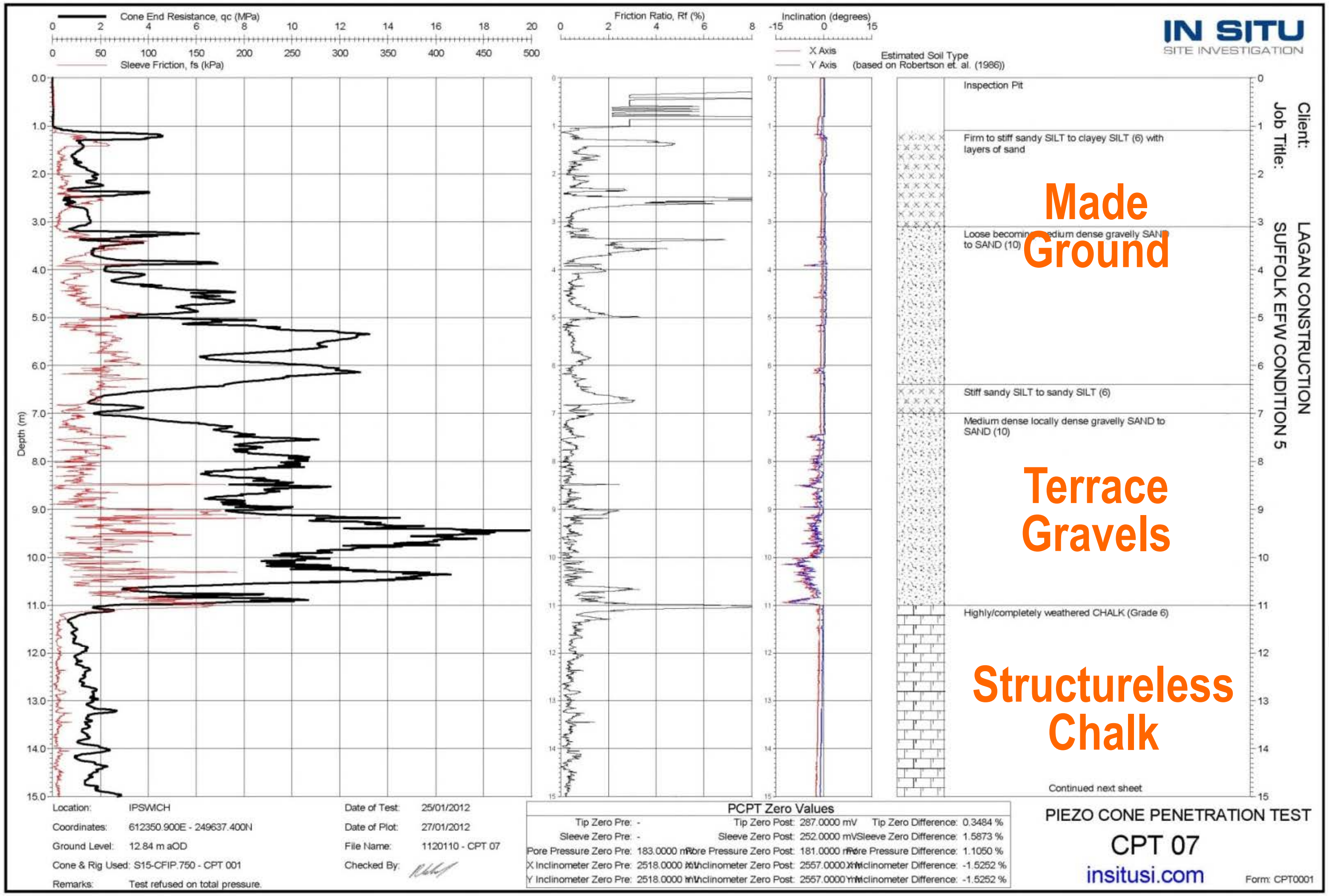

# Geological Section



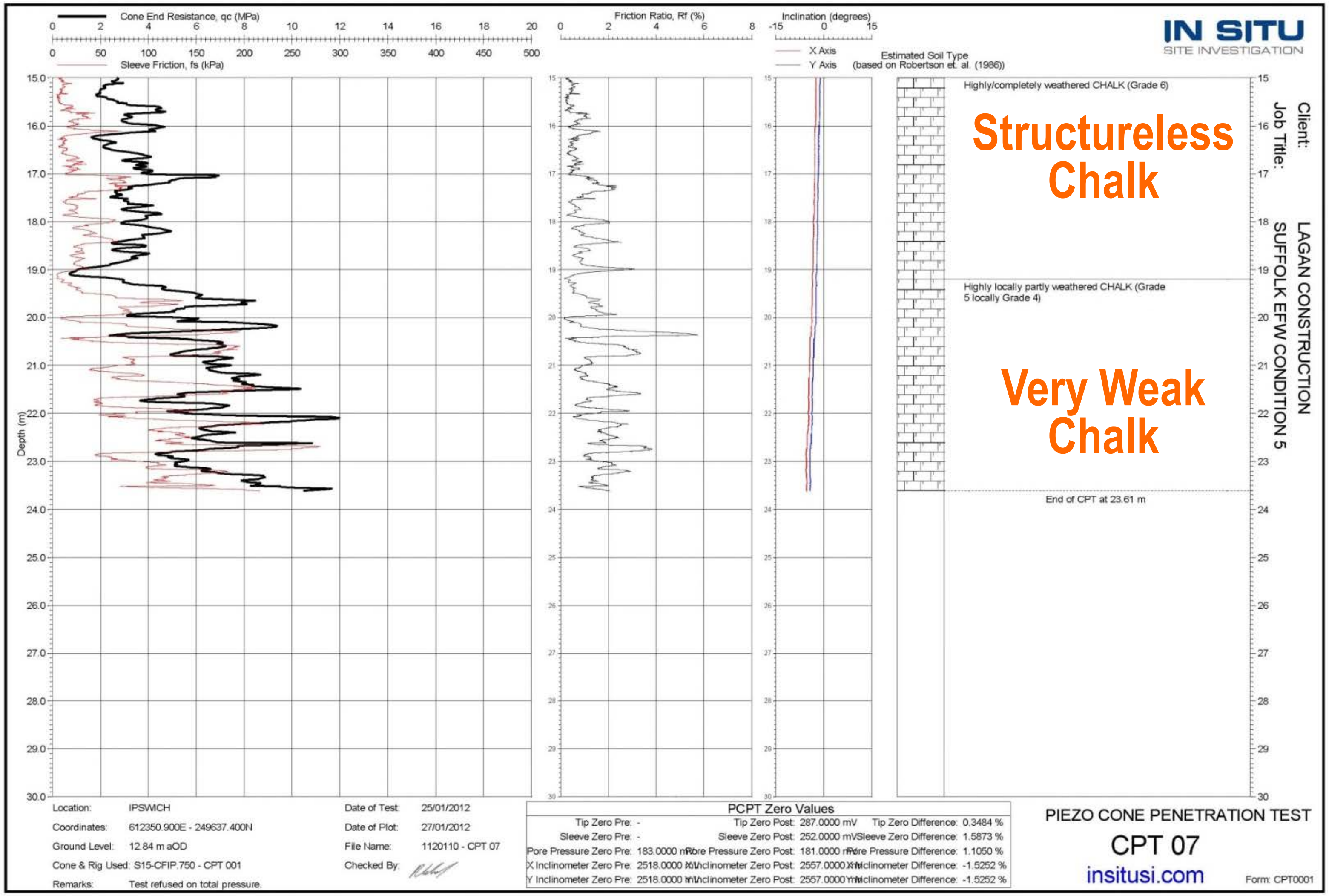




# Insitu SPT Data





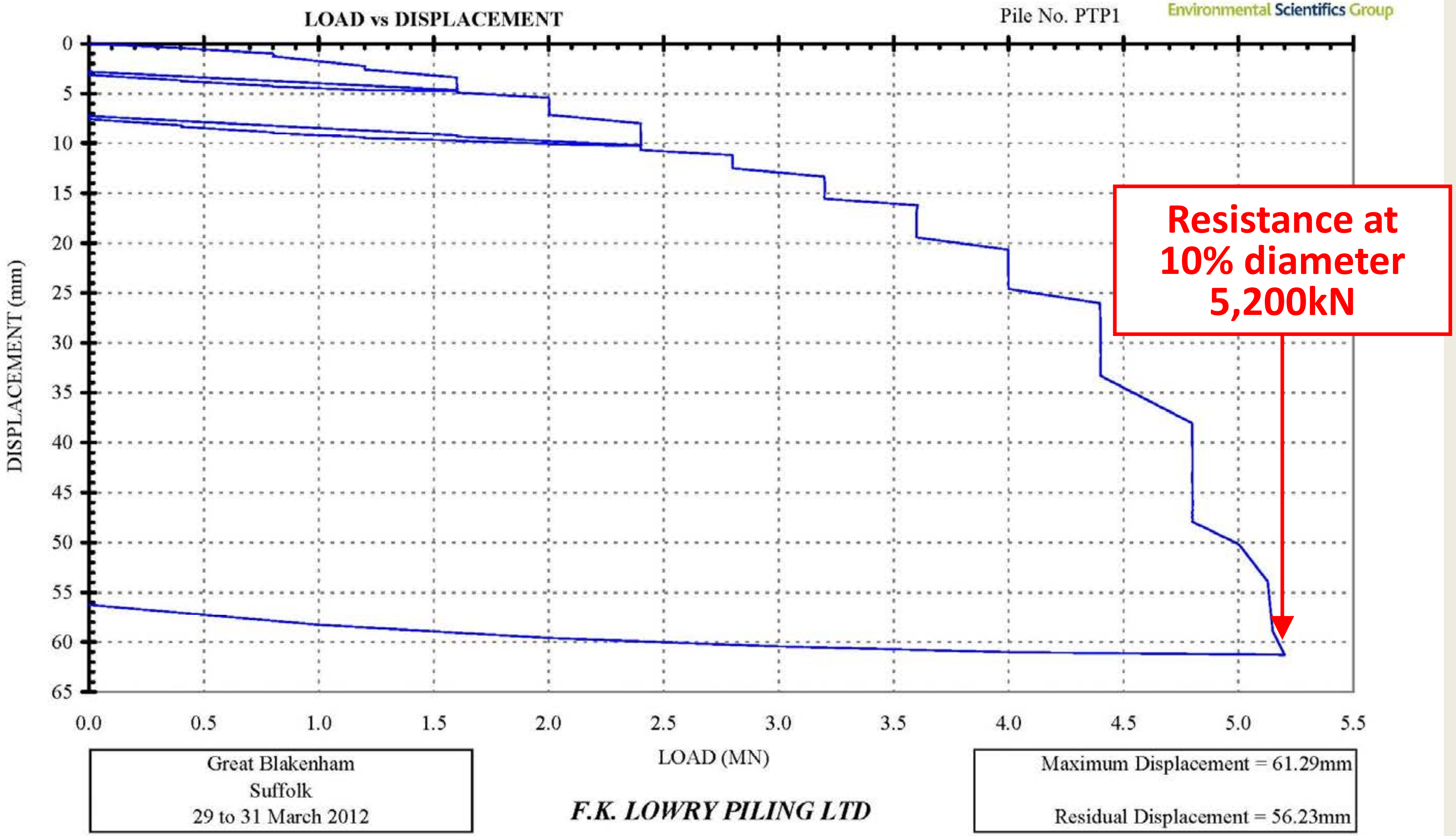

# Insitu CPT Data




# Insitu CPT Data

# Pile Load Test Results

ESG Environmental Scientifics Group





# Design Parameters for Design Example

| Soil Description | Top Level mOD | Soil Properties | Design Parameters |
|---|---|---|---|
| Granular BACKFILL | 9.4 | $\phi' = 35°$ | $\tan\delta = 0.7$  $k_s = 1.0$ |
| Very soft PEAT | 8.4 | $c_u = 25$ | $\alpha = 0.6$ |
| Dense gravelly SAND | 7.4 | $\phi' = 35°$ | $\tan\delta = 0.7$  $k_s = 1.0$ |
| Structureless CHALK | 2.9 | N = 5 bl/300mm | $q_s = \sigma_v' \beta$   $\beta = 0.8$ |
| Weak Chalk | -5.0 | N = 15 bl/300mm | $q_s = \sigma_v' \beta$   $\beta = 0.8$   $q_b = 200$ N |

| | | | |
|---|---|---|---|
| Enhanced base | | N = 40 bl/300mm | $q_b = 8{,}000$kPa |



PILE BEARING CAPACITY

Pile System Cfa bored Diameter 600 mm

| Soil Description | Top Level (mOD) | Soil Type | Shaft Stress Top (kPa) | Shaft Stress Base (kPa) | Shaft Friction (kN) |
|---|---|---|---|---|---|
| Granular BACKFILL | 9.40 | Drained | 0 | 6 | 6 |
| Very soft PEAT | 8.40 | Undrained | 15 | 15 | 28 |
| Dense gravelly SAND | 7.40 | Drained | 11 | 44 | 234 |
| Structureless CHALK | 2.90 | Chalk | 50 | 114 | 1223 |
| Very weak CHALK | -5.00 | Chalk | 114 | 165 | 1632 |

Pile Toe Level -11.20 mOD
Base stress 3000 kPa

| | |
|---|---|
| NEGATIVE SHAFT FRICTION | 0 kN |
| SHAFT CAPACITY | 3123 kN |
| END BEARING CAPACITY | 848 kN |
| ULTIMATE CAPACITY | 3971 kN |

Maintained load test to ultimate capacity EC7 Model Factor 1.2

| | |
|---|---|
| Characteristic Shaft Resistance Rsk | 2603 kN |
| Characteristic End Bearing Resistance Rbk | 707 kN |
| Characteristic Pile Resistance Rk | 3309 kN |

Settlement verified by load test

EC7 Resistance Factors

| | |
|---|---|
| Shaft Factor | 1.4 |
| End Bearing Factor | 1.7 |
| Shaft Tension Factor | 1.7 |

UK National Annex to EC7 Factor Set R4

| | |
|---|---|
| EC7 DESIGN RESISTANCE Rcd | 2275 kN |
| EC7 DESIGN TENSION RESISTANCE Rtd | 1531 kN |
| PILE LENGTH | 20.60 m |

**cf 5,200kN measured**

**Calculation still on low side**



# Bearing Capacity – β 0.80



PILE BEARING CAPACITY

Pile System Cfa bored Diameter 600 mm

| Soil Description | Top Level (mOD) | Soil Type | Shaft Stress Top (kPa) | Shaft Stress Base (kPa) | Shaft Friction (kN) |
|---|---|---|---|---|---|
| Granular BACKFILL | 9.40 | Drained | 0 | 6 | 6 |
| Very soft PEAT | 8.40 | Undrained | 15 | 15 | 28 |
| Dense gravelly SAND | 7.40 | Drained | 11 | 44 | 234 |
| Structureless CHALK | 2.90 | Chalk | 50 | 114 | 1223 |
| Very weak CHALK | -5.00 | Chalk | 114 | 165 | 1632 |

Pile Toe Level -11.20 mOD
Base stress 8000 kPa

| | | |
|---|---|---|
| NEGATIVE SHAFT FRICTION | 0 | kN |
| SHAFT CAPACITY | 3123 | kN |
| END BEARING CAPACITY | 2262 | kN |
| ULTIMATE CAPACITY | 5385 | kN |

BC calculation down to here is the same as we have always carried out

No change for EC7

Maintained load test to ultimate capacity

EC7 Model Factor 1.2

Step 1 Model Factor

| | | |
|---|---|---|
| Characteristic Shaft Resistance Rsk | 2603 | kN |
| Characteristic End Bearing Resistance Rbk | 1885 | kN |
| Characteristic Pile Resistance Rk | 4487 | kN |

Settlement verified by load test

EC7 Resistance Factors

| | |
|---|---|
| Shaft Factor | 1.4 |
| End Bearing Factor | 1.7 |
| Shaft Tension Factor | 1.7 |

Step 2 Resistance Factors

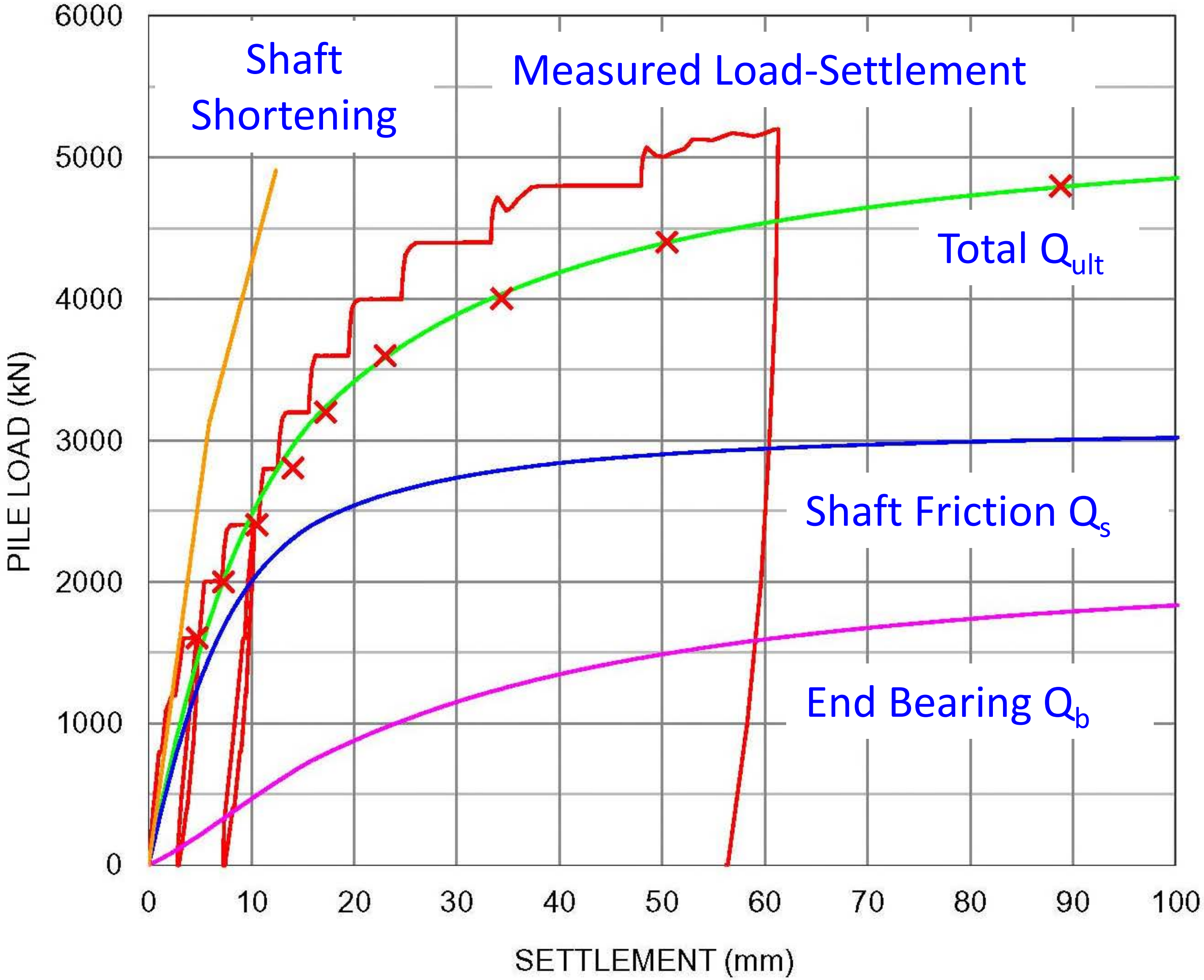
EC7 model and resistance factors applied

UK National Annex to EC7 Factor Set R4

| | | |
|---|---|---|
| EC7 DESIGN RESISTANCE Rcd | 2968 | kN |
| EC7 DESIGN TENSION RESISTANCE Rtd | 1531 | kN |
| PILE LENGTH | 20.60 | m |

$R_{c;d}$ 2,968kN

# Enhanced Base




5,385kN

3,123kN

2,262kN

# CEMSET Fit to Test Results



# Design Based on Calculation

- Calculated design resistance $R_{c;d}$

$$R_{b;k} = \frac{2,262}{1.2} = 1,885\text{kN} \qquad R_{s;k} = \frac{3,123}{1.2} = 2,603\text{kN}$$

$$R_{c;d} = \left[\frac{1,885}{1.7} + \frac{2,603}{1.4}\right] = 2,968\text{kN}$$

- Based on calculation with the best CEMSET fit to the measured load-settlement behaviour



# Design Based on Static Load Tests

- Design resistance $R_{c;d}$

$$R_{c;k} = \text{Min}\left[\frac{\text{Mean } 5{,}200\text{kN}}{1.55}\right] \text{ or } \left[\frac{\text{Minimum } 5{,}200\text{kN}}{1.55}\right]$$

$$R_{c;k} = 3{,}355\text{kN}$$

$$R_{c;d} = \left[\frac{3{,}355}{1.7}\right] = 1{,}974\text{kN}$$

- Note that this method is based on the measured resistance at 10% of the pile diameter rather than the extrapolated ultimate capacity (about 5,400kN based on CEMSET)



# Design Based on Static Load Tests

- Assuming say 3 pile load tests and a stiff/strong structure would allow a reduced correlation factor of 1.29 to be used giving $R_{c;d}$ = 2,371kN



# Comparison Between Design Methods

| | |
|---|---|
| ▪ Nominal pile load | 2,000kN |
| ▪ EC7 Design Action | 2,180kN |
| ▪ Design Resistance: | |
| ▪ Based on Calculation | 2,275kN to 2,968kN |
| ▪ Based on Static Load Test | 1,974kN to 2,371kN |



# Conclusions – 1

- EC7 does not tell the Designer how to design piles but does give rules and procedures to be followed
- EC7 has complicated pile design with the introduction of numerous partial factors; load factors, combination factors, material factors, resistance factors, model factors and correlation factors



# Conclusions – 2

- More design effort is required to design to EC7
- In some respects EC7 is more conservative
- There are some problem areas which must be resolved
- <u>BUT</u> EC7 does provides a more logical design framework
- Engineering judgement must not be suspended



# Conclusions – The Future

- Discussions are taking place on future revisions to Eurocode 7 and its UK National Annex
- So far, EC7 has failed to provide a ‘harmonized technical specification’ – three design approaches are permitted
- Can this be resolved?
- EC7 does not specify a value for the model factor $\gamma_{Rd}$
- Are the UK values too conservative?
- The shortcomings and inconsistencies are being addressed
- Next version in 2020



# Thanks for Your Attention