Evaluation of Eurocode 7
Example 2.6 PILE IN SAND
ETC 10

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General
Designing in four steps:

1. Assessing of ground conditions, bearing layer, minimal embedment of a pile.
2. Choice of pile type, pile loadings, characteristic and design parameters of ground layers, etc.
3. Calculations – a subject of this paper: ULS and SLS of a pile, determining of pile length for given loads or a number of piles needed.
4. Confirmation: experience, pile test loadings, monitoring of a pile construction and of a structure – the only reliable verification of a design.
General: Eurocode 7 requirements

**Limit states of a pile in compression**

Ultimate limit states (ULS)
- bearing resistance failure,
- structural failure of the pile
- excessive settlement

Serviceability limit states (SLS)
- excessive settlement
- vibrations
General: Eurocode 7 requirements

**ULS – compressive resistance from ground test results**

\[ F_{c;d} \leq R_{c;d} \]

‘Model pile’ method

\[ R_{ck} = \left( R_{b,k} + R_{s,k} \right) = \frac{R_{b,cal} + R_{s,cal}}{\xi} = \frac{R_{c,cal}}{\xi} = \min \left\{ \frac{(R_{c,cal})_{\text{mean}}}{\xi_3}, \frac{(R_{c,cal})_{\text{min}}}{\xi_4} \right\} \quad (7.8) \]

The values of the correlation factors \( \xi_3 \) and \( \xi_4 \) depend on the number of profiles of tests, \( n \).

They may be set by the National annex, the recommended values are given in Table A.10 of EC 7–1.
General: Eurocode 7 requirements

**ULS – compressive resistance from ground test results**

‘Alternative’ method

\[ R_{b;k} = A_b q_{b;k} \quad \text{and} \quad R_{s;k} = \sum A_{s;i} q_{s;i;k} \quad (7.9) \]

\( q_{b;k} \) and \( q_{s;i;k} \) are characteristic values of base and shaft resistance

Popular in several countries

*may need to be corrected by a model factor larger than 1.0*
General: Eurocode 7 proposals

Example models in EN 1997-2 in informative Annex D

D.6: Correlation between compressive resistance of a single pile and cone penetration resistance $q_c$
Empirical data on $q_b$ and $q_s$ versus $q_c$ resistance for piles in coarse-grained soils (from German Standard and EA Pfähle – 2007)

D.7: Method to determine the compressive resistance of a single pile from cone penetration resistance $q_c$
Formulae and tables of empirical data on $q_b$ and $q_s$ versus $q_c$ resistance for piles in sands and gravelly sands and for clay, silt and peat (Dutch or Belgian method?)
Description of the Example 2.6
Fig. 1. Data for pile design

Fig. 2. Boring log and CPT resistance profile
Description of the Example 2.6

- 450 mm diameter piles bored with temporary casing
- founded in a medium dense to dense sand
- characteristic vertical loads: permanent of 300 kN and variable of 150 kN.
- small project – will be no load testing
- settlement will not govern the design

Using Eurocode 7, determine the design length of the pile
Results of Questionnaire

Example 2.6
Results of Questionnaire Example 2.6

• 1st Phase:
  12 solutions from five European countries (Germany 3, Italy 4, Poland 3, Portugal 1 and UK 1); one from Japan

• 2nd Phase (with the unified ‘benchmark’ $q_c$ profile):
  6 solutions (Germany 2, Italy 2, Poland 1, Portugal 1), only two changed the results

Number of answers less than expected by the ETC 10.
Results of Questionnaire Example 2.6

Main question was the pile length. It depends on:
- ground properties, pile shaft and base resistances
- safety factors (partial, correlation and model)
- calculation model
- choice of characteristic values of geotechnical parameters

Pile length:
- average 18.7m
- range 4.0m: min 17.0m (-9%), max 21.0m (+12%)
## Results of Questionnaire Example 2.6

Characteristic resistances: CPT $q_c$, shaft $q_s$ and base $q_b$; pile lengths

<table>
<thead>
<tr>
<th>ID</th>
<th>CPT qc resistance at depth</th>
<th>Unit shaft resistance $q_s$ at depth</th>
<th>Unit base resist. $q_b$</th>
<th>Pile length</th>
<th>DsgnForce</th>
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<td>Mean</td>
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</table>

Total = 174.5 181.6

Mean = 14.54 13.97

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Results of Questionnaire Example 2.6

• CPT $q_c$ resistance:
  - in upper layers – large scatter, in many cases = 0;
    max values: 8MPa for 2.5m, 4 for 7.5m, 5 for 12.5m
  - for 17.5m $q_c$ = 12 to 16; mean = 14.5MPa
  - for 22.5m $q_c$ = 11.9 to 16.5; mean = 14.0MPa

How did assessed these values?
• By eye – 8 cases 61.5%
• by statistical analysis – 3 cases 23%
• from a previous design – 1 case 8%
• other (average, Excell calc.) – 4 cases 31%
Results of Questionnaire Example 2.6

What correlations did you used for soil parameters?

- unit weights of soils, relative density $I_D$, relation $q_c$ to $N_{SPT}$, $q_c$ to friction angle, $q_c$ to $s_u$,

- selected sources: Standards BS, DIN, PN; German EA Pfähle; Manual (Kulhawy & Mayne); Robertson & Campanella 1983; Lunne, Robertson & Powell; Japan Specs for Highway Bridges and Public Works Research Institute; Viggiani
Results of Questionnaire Example 2.6

- **Unit shaft resistance** $q_s$:
  - in upper layers – large scatter, in many cases $= 0$;
  - max values: 74kPa for 2.5m, 52 for 7.5m, 111 for 12.5m
  - for 17.5m $q_s = 60$ to 142kPa
  - for 22.5m $q_s = 60$ to 191kPa

- **Unit base resistance** $q_b$:
  - for 17.5m $q_b = 1622$ to 6600kPa
  - for 22.5m $q_b = 1189$ to 8000kPa
Results of Questionnaire Example 2.6

Calculation model for shaft and base resistance

- Annex D.6 from EN 1997–2 2 cases 15%
- Annex D.7 from EN 1997–2 3 cases 23%
- Alternative in national annex/stand. 3 cases 23%
- Other (CPT, Bustamante–Gianeselli, static formula, Japan Highway Specs) 5 cases 38%
Results of Questionnaire Example 2.6

- **Which country’s National Annex was used?**
  GB, German, Italian, Polish, Portugal

- **Which Design Approach was used?**

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<tr>
<th>Design Approach</th>
<th>Cases</th>
<th>Percentage</th>
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<tbody>
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<td>DA1 Comb 2 only</td>
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<td>8%</td>
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<td>DA2</td>
<td>3</td>
<td>23%</td>
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<tr>
<td>DA2* (for piles = DA2)</td>
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<td>15% total 38%</td>
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<td>DA3</td>
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<tr>
<td>Reliability Based Design RDB</td>
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Results of Questionnaire Example 2.6
Partial safety factors, correlation and model factors

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<th>Correlation factors</th>
<th>Model factor</th>
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<td>1.35</td>
<td>1.5</td>
<td>-</td>
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</table>

Some of values given were not used in calculations
Values of partial factors

- **Actions**
  most to EC7-1 Ann. A: $\gamma_G = 1.35 \gamma_Q = 1.5$ 8 cases 62%

- **Ground resistances**
  $\gamma_f = 1 \ (5)$ or $1.25 \ (3)$
  $\gamma_c = 1 \ (5), 1.25 \ (1), 1.5 \ (1)$
  $\gamma_{cu} = 1 \ (4), 1.4 \ (1)$

- **Shaft resistance**
  $\gamma_s = 1$ to 1.6

- **Base resistance**
  $\gamma_b = 1$ to 1.7

- **Total resistance**
  $\gamma_t = 1$ to 1.6

- **Correl. Factors**
  $\xi_3 = 1$ to 1.7, $\xi_4 = 1$ to 2

- **Model Factor (2 cases)**
  $\gamma_{Rd} = 1.4 \ (1), 1.5 \ (1)$
Results of Questionnaire Example 2.6

Design compressive forces $F_{cd}$

$F_{cd} = 630$ kN (7 cases)

- 615 kN (2 cases)
- 495 kN (2 cases)
- n.a. (2 cases)

In Germany

$F_{cd} = 675$ kN for structural design (acc. to EC2)
Results of Questionnaire Example 2.6

- How conservative is your previous national practice?
  - Conservative: 8 cases (61.5%)
  - About right: 1 case (8%)
  - Unconservative: 1 case (8%)
  - Very unconservative: 1 case (8%)

- How conservative is EC7 with your National Annex?
  - Conservative: 6 cases (46%)
  - About right: 4 cases (31%)
  - Very unconservative: 1 case (8%)
Results of Questionnaire Example 2.6

• How does your EC7 design compare with your previous national practice?
  More conservative 2 cases 15%
  About the same 6 cases 46%
  Less conservative 3 cases 23%

• Having completed your design to EC7, how confident are you that design is sound?
  Unsure 4 cases 31%
  Confident 7 cases 54%
  Very confident 2 cases 15% Σ=69%
Discussion of Results of Example 2.6
Discussion of Results of the Example 2.6

**Pile shape and length**

- 450 mm diameter piles bored with casing are rather not typical, in many countries CFA piles or piles with larger diameter would be used

- A pile should be embedded in a ‘competent layer’ at least e.g. 2.5m (EA Pfähle) or 3.0m (PL Standard) Therefore a pile shorter than 18m (17.5m?) may be regarded as not safe.
Discussion of Results of the Example 2.6

_Pile length:_ average 18.7m
range 4.0m: min 17.0m (−9%), max 21.0m (+12%)

The scatter is small, considering variety of assumptions, Design Approaches, calculation methods, safety factors etc.

Probably most people would intuitively just by looking at the CPT result say, that the piles should penetrate the stiffer layer after 16 m a couple of meters. So would the scatter be (much) higher, if the cpt profile would have been more constant?

_But bearing in mind the results of the Workshop in Dublin (2005) – range of pile length ±62%, the final result seems surprisingly better than one may expect…_
Discussion of Results of the Example 2.6

- **Unit shaft resistance** $q_s$ **in softer upper layers**
  In several answers the shaft resistance in upper layers was fully disregarded or reduced.
  An experienced designer would assume there $q_s = 0$.

**Calculation model for shaft and base resistance**
In several solutions – ‘model pile method’
In some cases – ‘Alternative method’
  – from EN 1997–2 Annex D.6 and D.7
  – from national annex or standards
Other methods based on the CPT (e.g. Bustamante–Gianeselli)

Reliability Based Design RBD to Japan Highway Specs
Discussion of Results of the Example 2.6

- **Design Approaches**
- DA chosen according to National Annexes
  - Almost equal use of DA1 and DA2
  - DA3 – only 1 case

**Partial & Model Factors**
Partial factors to EC7–1 Annex A or to National Annexes.
In two cases – low PFs compensated by Model Factor
  \[ (= 1.5 \text{ and } 1.4) \]

**Japan answer:** Reliability Based Design – not to Eurocode but results very similar
Discussion of Results of the Example 2.6

*Benchmark soil data*
- Fixing the benchmark soil profile data did not change much the results.
- In 2\textsuperscript{nd} phase only in 2 (of 6) answers the pile length was changed by 0.5m.

*Settlement of the pile in SLS*
Only four answers: 6.4, 13.7, 20 and 20.5 mm
Only the first two are probable, others are rather overestimated.

\[ s = 20 \text{ mm} = \text{ca. 4.4\% of pile diameter} \]
seems not probable in SLS
Conclusions

Example 2.6
Conclusions

• Eurocodes should unify structural designing in EU. It is a long way to achieve this goal...
• In fact “pile designing to Eurocode” does not exist. There is much freedom in use of rules of Eurocodes.
  • The reasons of discrepancy of results are: different understanding of characteristic values, three Design Approaches, various design models, various traditions and specific features resulting in National Annexes of particular countries, etc.
• It is a good task for European geotechnical community: if not reach unified all calculations, then at least achieve a comparable level of safety (and economy!) of designs.
Thank you for your attention!