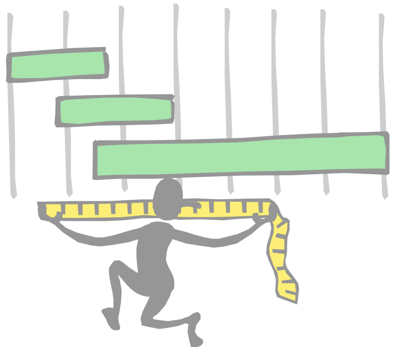
Evaluation of Eurocode 7
Example 2.6 PILE IN SAND
ETC 10

Bolesław Kłosiński
Road & Bridge Research Institute
Warsaw, Poland

General

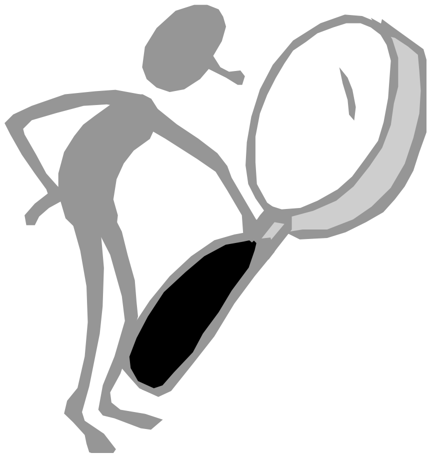


General

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. <u>Calculations – a subject of this paper</u>: 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 compresion

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

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

<u>'Model pile' method</u>

$$R_{c;k} = \left(R_{b;k} + R_{s;k}\right) = \frac{R_{b;cal} + R_{s;cal}}{\xi} = \frac{R_{c;cal}}{\xi} = \mathrm{Min}\left\{\frac{\left(R_{c;cal}\right)_{mean}}{\xi_3}; \frac{\left(R_{c;cal}\right)_{min}}{\xi_4}\right\} \quad (7.8)$$

The values of the correlation factors ξ_3 and ξ_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

<u>'Alternative' method</u>

$$R_{b;k} = A_b \, q_{b;k} \quad \text{and} \quad R_{s;k} = \Sigma A_{s;i} \, q_{s;i;k} \qquad (7.9)$$

$q_{b;k}$ 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 gravely sands and for clay, silt and peat (Dutch or Belgian method?)

Description of the Example 2.6

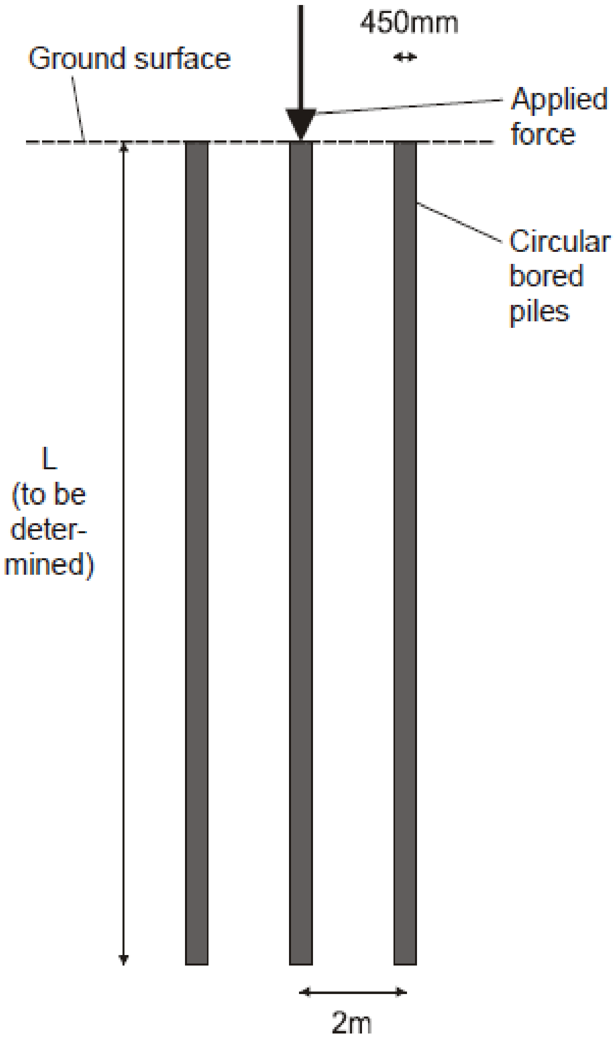
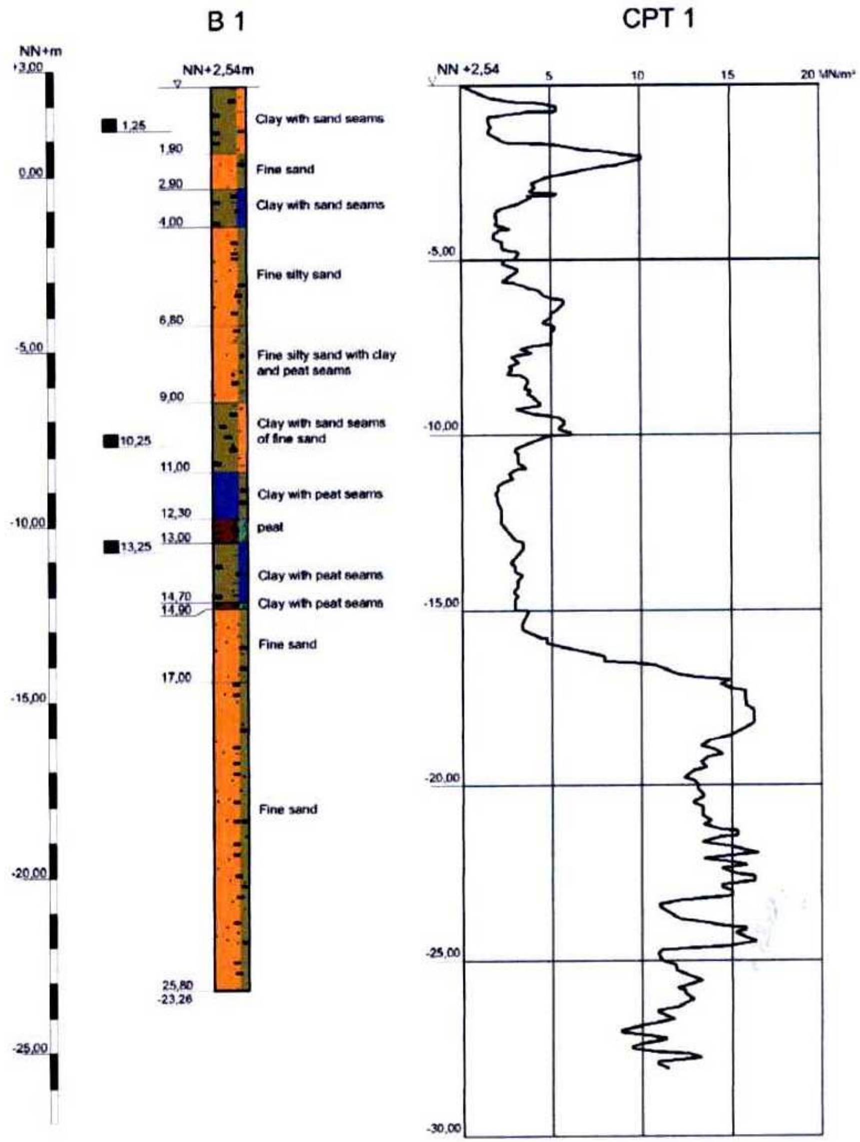


Fig. 1. Data for pile design

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

ID	CPT qc resistance at depth					Unit shaft resistance qs at depth					Unit base resist. qb		Pile length	DsgnForce
	2.5 m	7.5 m	12.5 m	17.5 m	22.5 m	2.5 m	7.5 m	12.5 m	17.5 m	22.5 m	17.5 m	22.5 m	m	Fcd kN
1/72	6,00	2,80	2,20	16,00	14,50	30,0	17,5	0,0	60,0	72,5	5177	7488	19,5	615
2/41	0,00	3,35	3,35	3.35	11,89	0,0	11,18	11,18	11,18	18,29	n/a	1189	20,0	630
3/69	8,00	4,00	3,00	12,00	13,00	4,5	14,5	31,3	70,0	111,1	460	590	20,5	
4/45	4,00	3,90	2,70	14,80	14,00	0,0	35,0	35,0	120,0	120,0	1800	1800	19,0	495
5/25	0,00	0,00	5,00	15,00	14,00	0,0	0,0	0,0	75,0	70,0	6580	7770	18,0	630
6/83	7,40	3,60	2,50	13,50	13,50	74,0	51,7	111,0	125,0	125,0	2490	2490	**17,0**	n/a
StdDev	2,30	1,10	0,30	1,90	1,90	11,5	16,1	15,1	32,6	32,6	651	651	-	-
7/20	0,00	0,00	0,00	14,00	13,00	0,0	0,0	0,0	132,0	132,0	3773	3773	18,0	630
8/51	5,00	4,00	2,50	13,00	13,00	12,0	22,0	0,0	75,0	75,0	3125	3125	**21,0**	630
9/116	6,85	3,90	2,50	13,30	13,30	0,0	0,0	0,0	95,0	95,0	2720	2720	20,0	630/675
		Benchmark		qc values					98,0	98,0	2810	2810	19.5	675
10/33	-	3,50	2,10	15,00	16,50	32,0	28,0	24,0	56,0	105,0	3100	-	17,5	630
11/109	2,20	2,90	2,40	14,00	14,00	13,7	41,0	27,6	142,0	191,3	1622	2280	18,0	495
		Benchmark		qc values					-	-			17.5	495
12/91	5,00	3,50	2,20	16,00	14,50	12,2	26,7	53,5	75,4	96,4	3920	4936	18,0	615
13/54	6,00	3,50	2,20	16,00	14,50	30,0	17,5	0,0	60,0	60,0	6600	8000	16,5	630
			Total =	174,5	181,6							Total =	243,0	
			Mean =	14,54	13,97							Mean =	18,69	

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 statisical 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

<u>Calculation model for shaft and base resistance</u>

- 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?**

DA1 Comb 1&2		5 cases	38%
DA1 Comb 2 only		1 case	8%
DA2	3 cases	23%	
DA2* (for piles = DA2)	2 cases	15%	total 38%
DA3		1 case	8%
Reliability Based Design RDB		1 case	8%

Results of Questionnaire Example 2.6

Partial safety factors, correlation and model factors

ID	Design Approach	Partial safety factors for ULS								Correlation factors		Model factor
		γ_G	γ_Q	γ_f	γ_c	γ_{cu}	γ_s	γ_b	γ_t	ξ_3	ξ_4	
1/72	1 Comb. 1	1,3	1,5	-	-	-	1	1,25	-	1,7	1,7	1
1/72	1 Comb. 2	1	1,3	-	-	-	1,45	1,7	1,6			
2/41	1 Comb. 1	1,35	1,5	-	-	-	1	1,25	-	-	-	1,5
2/41	1 Comb. 2	1	1,3	-	-	-	1,3	1,6	-			
3/69	1 Comb. 1	1,35	1,5	1	1	-	-	-	-	1,6	2	1,4
3/69	1 Comb. 2	1	1,3	1,25	1,25	-	-	-	-			
4/95	1 Comb. 1	1,3	1,5	1	1	1	1	1	-	1,7	1,7	-
4/95	1 Comb. 2	1	1,3	1	1	1	1,45	1,7	-	1,7	1,7	-
5/25	2	1,35	1,5	-	-	-	-	1,1	1,1	1,4	1,4	1
6/83	RBD	-	-	-	-	-	-	-	-	-	-	-
7/20	2	1,35	1,5	-	-	-	-	-	1,4	-	-	-
8/51	1 Comb. 1	1,35	1,5	-	-	-	1	1,25	-	1,4	-	1
8/51	1 Comb. 2	1	1,3	-	-	-	1,3	1,6	-			
9/116	2	1,35	1,5	-	1,5	-	1,4	1,4	1,4	-	-	-
10/33	3 Comb. 1	1,35	1,5	1,25	-	-	1,3	1,6	-	1,27	1,27	γR(γb,γs)
10/33	+Comb. 2	1	1,3	-	-	-	1,6	1,3	-			
11/109	1 Comb.2	1	1,3	1,25	-	1,4		1,7	1,6	-	-	-
12/91	2	1,3	1,5	1	1	1	1,15	1,35	1,3	1,7	1,7	1
13/54	2	1,35	1,5	-	-	-	1,1	1,1	1,1	-	-	-

Some of values given were not used in calculations

Results of Questionnaire Example 2.6

<u>Values of partial factors</u>

- **Actions**

most to EC7-1 Ann. A: γ_G =1.35 γ_Q =1.5 8 cases 62%

- **Ground resistances** γ_f = 1 (5) or 1.25 (3)

  γ_c = 1 (5), 1.25 (1), 1.5 (1) γ_{cu} = 1 (4), 1.4 (1)

- **Shaft resistance** γ_s = 1 to 1.6
- **Base resistance** γ_b = 1 to 1.7
- **Total resistance** γ_t = 1 to 1.6
- **Correl. Factors** ξ_3 = 1 to 1.7, ξ_4 = 1 to 2
- **Model Factor** (2 cases) γ_{Rd} = 1.4 (1), 1.5 (1)

Results of Questionnaire Example 2.6

<u>Design compresive forces F_{cd}</u>

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 case	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 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 2nd 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 mm = 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!