Is it reasonable to reduce the shaft resistance for bored cast-in-situ piles?

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ABSTRACT
According to the Danish National Annex to Eurocode 7, the shaft resistance for a bored cast-in-situ pile should not be assumed to be greater than 30 per cent of the shaft resistance of the corresponding driven pile. This principle has been applied in Denmark for many years due to an unsuccessful project. Today, however, it is widely recognised that this reduction is not reasonable if the bored cast-in-situ pile is established correctly.

This reduction of the shaft resistance proved problematic during the expansion of the Køge Bay motorway, which involves construction of a new bridge. The bridge is an underpass of a new railway line below the existing motorway, and the bridge shape required the establishment of a middle support. Because of the heavy load and the reduced shaft resistance, documenting the bearing capacity of the foundation of the middle support proved problematic.

As no recognised documentation allowing a larger bearing resistance was available, it was decided to establish a Ø508 mm bored cast-in-situ test pile. In order to document the bearing capacity of the test pile, in particular the shaft resistance, the test pile was re-driven and PDA measurements (a CAP-WAP analysis) were performed.

The geological conditions at the location primarily consist of limestone (H1), clay till and sand till. The expected bearing capacity of the test pile based on an analytical method and the measured capacity of the test pile were compared, showing that no reduction was necessary.

Keywords: bored cast-in-situ pile, shaft resistance, test pile, PDA measurements.

1 INTRODUCTION

According to the Danish National Annex to Eurocode 7 – part 1 (2013), Annex L (6), the shaft resistance for a bored cast-in-situ pile should not be assumed to be greater than 30 per cent of the shaft resistance of a corresponding driven pile. This principle has been applied in Denmark for many years due to an unsuccessful project.

This reduction of the shaft resistance proved problematic during the expansion of the Køge Bay motorway, and as no recognized documentation was available for comparable ground conditions, allowing a larger bearing capacity, it was decided to establish a bored cast-in-situ test pile. In order to document the bearing capacity of the test pile, in particular the shaft resistance, the test pile was re-driven and PDA measurements (a CAP-WAP analysis) were performed.

This paper contains a description of the test pile from planning and establishment to test and interpretation of the results.

2 PROJECT

The expansion of the Køge Bay motorway involves construction of a new bridge (Bridge no. 79.80). The bridge is an underpass of a new railway line below the existing motorway, and the bridge shape required the establishment of a middle support.

The middle support is a contiguous pile wall designed with 15 pieces of Ø880 mm concrete piles cast with a pile spacing of 760 mm. Consequently, the pile wall measures 0.88 m in width and 11.52 m in length. The piles above ground level are finished with a concrete cover, giving the final wall a width of 1.2 m and a length of 12.1 m.

Because of the heavy load and the reduced shaft resistance, documenting the bearing capacity of the middle support proved problematic. Therefore, it was decided to establish a Ø508 mm bored cast-in-situ test pile.

The location of Køge Bay motorway is shown in the following Figure 1.

Figure 1 Location of Køge Bay motorway.

3 GROUND CONDITIONS

For bridge no. 79.80 at Køge Bay motorway, geotechnical investigations were carried out and reported in the geotechnical investigation report by Rambøll (2014). The test pile was established near geotechnical borehole no. J102, see Figure 2.

Uppermost in the geotechnical borehole is 0.8 m of clay fill, beneath which there are glacial deposits, primarily consisting of clay till down to the top of the limestone at level -0.7 m.

Locally within the clay till, there is observed a 1.2 m deposit of sand till from level +5.4 m to +4.2 m.

Flint layers have been encountered in the limestone.

The primary groundwater level is measured at level +2.9 m in a screen positioned in the limestone.

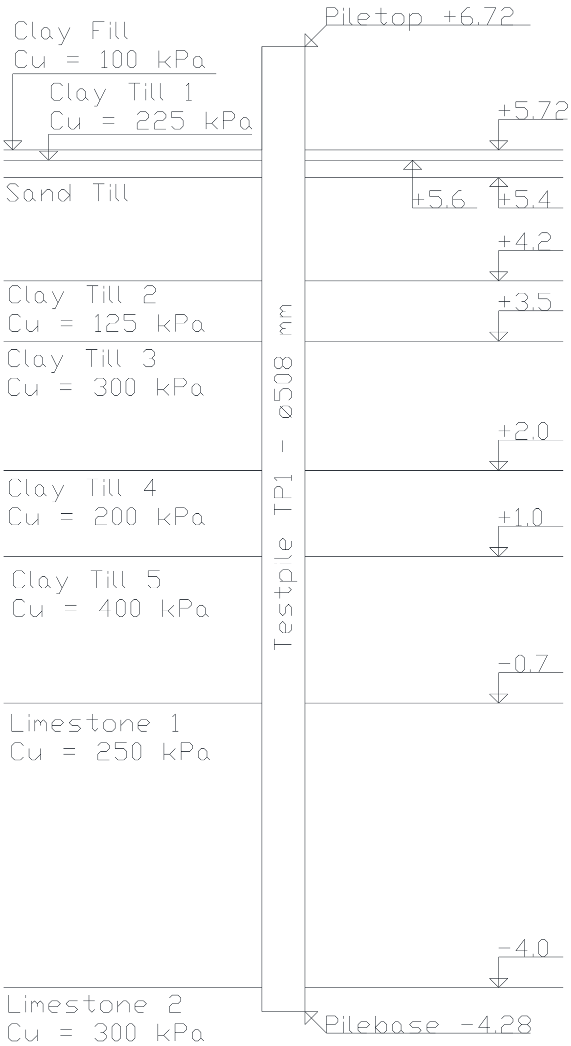

Figure 2 Geotechnical borehole no. J102.

4 ESTABLISMENT OF TEST PILE

The test pile was established as close as possible to the middle support and near a geotechnical borehole (Borehole no. J102). See Figure 3.

The test pile was established using a Ø508 mm casing, and a Ø350 mm auger for drilling inside the casing. The first 5 m of the test pile was drilled using a Ø500 mm auger to establish a stable hole for the casing, and the deepest 1 m of the test pile was drilled using a Ø400 mm hole saw in order to ensure the best clean-up possible for the bottom. Dimensions of the test pile are shown in Table 1:

Table 1 Dimensions of test pile.

Pile no.	Dim. (mm)	Top (m)	Ground (m)	Base (m)
TP1	Ø508	+6.92	+5.72	-4.28

A casing was left behind at the uppermost 3.2 m of the test pile in order to ensure casting of the test pile at a sufficient height above ground level to re-drive the test pile and perform PDA measurements (a CAP-WAP analysis).

5 TEST

The test pile was established on 14 October 2014, and it was re-driven on 10 November 2014 after 27 days of rest.

The test pile was re-driven with three blows and PDA measurements (a CAP-WAP analysis) were carried out in order to verify the shaft resistance, while this type of analysis determines the measured compressive resistance, divided into shaft resistance and base resistance.

The measured base resistance was used to check whether or not the bottom was cleaned sufficiently before casting, and whether or not the base resistance, as a minimum, corresponds to the value provided in the design.

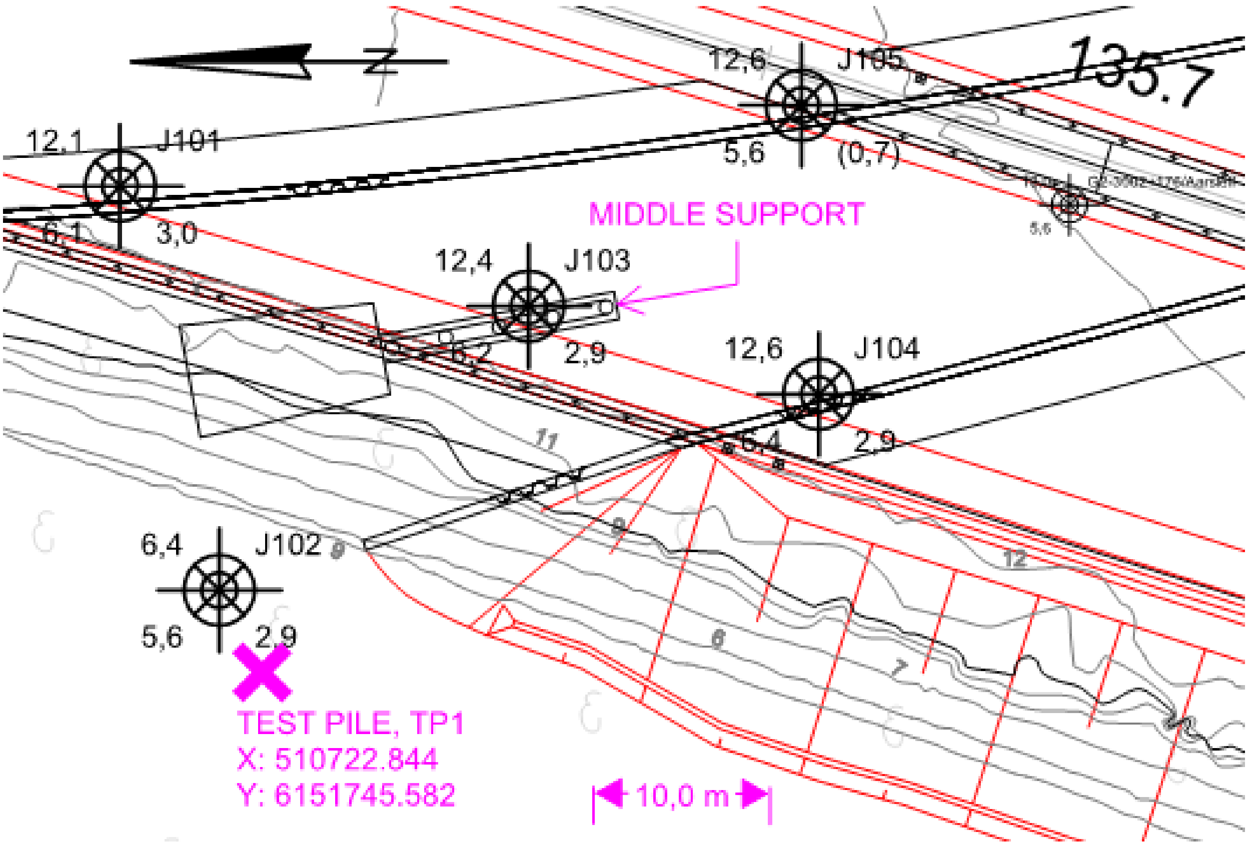

Figure 3 Illustration of middle support, test pile TP1 and geotechnical borehole no. J102.

6 RESULTS

6.1 General

An analytical method was used to determine the expected bearing capacity of the test pile to compare it with the results from the PDA measurements (a CAP-WAP analysis) in order to determine whether or not the 30-per cent reduction of the shaft resistance is reasonable.

6.2 Analytical method

An analytical method was used to determine the expected bearing capacity of the test pile based on the ground conditions described in section 3. The analytical method is based on equations according to the Danish National Annex to Eurocode 7 – part 1 (2013), Annex L (1):

$$R_{c,cal} = R_{s,cal} + R_{b,cal} \quad (1)$$

Where $R_{c,cal}$ (kN) is the expected bearing resistance for compression piles, $R_{s,cal}$ (kN) is the shaft resistance, and $R_{b,cal}$ (kN) is the base resistance.

Shaft resistance for cohesive soils:

$$R_{s,cal} = \sum m \cdot r \cdot c_u \cdot A_s \quad (2)$$

Shaft resistance for non-cohesive soils:

$$R_{s,cal} = \sum N_m \cdot q'_m \cdot A_s \quad (3)$$

Base resistance for cohesive soils:

$$R_{b,cal} = 9 \cdot c_u \cdot A_b \quad (4)$$

Where m (-) is a material factor, r (-) is a regeneration factor, c_u (kPa) is the undrained shear strength, N_m (-) is a bearing capacity factor, q'_m (kPa) is the effective overburden pressure, A_S (m²) is the shaft surface area, and A_b (m²) is the base area.

Realistic strength parameters (not design values) in the clay deposits and conservative strength parameters in the limestone due to lack of strength measurements were applied.

At the uppermost 3.2 m of the test pile, a casing was left behind, and the material factor was reduced to m = 0.5 · 0.7 = 0.35, because the supervision considered there to be limited contact between the test pile (casing) and the soil.

The following calculation results show an expected total bearing capacity of the test pile of 1893 kN, consisting of a shaft resistance equal to 1346 kN and a base resistance equal to 547 kN. Please note that all calculations are based on measured values, which means no use of partial factors γ_s and ξ values. See Table 2 and Table 3.

Table 2 Analytical method – shaft resistance.

Layer no. I	Top (m)	Base (m)	Soil (-)	c_u (kN/m²)	t (m)	D (m)	A_s (m²)	r (-)	m (-)	$R_{s,cal,I}$ (kN)
1	**5.72**	5.6	ClayFill	100	0.1	0.508	0.19	0.4	0.35	3
2	5.6	5.4	ClayTill 1	225	0.2	0.508	0.32	0.4	0.35	10
3	5.4	4.2	SandTill	-	1.2	0.508	1.92	-	0.35	6
4	4.2	3.92	ClayTill 2	125	0.3	0.508	0.45	0.4	0.35	8
5	3.92	3.5	ClayTill 2	125	0.4	0.508	0.67	0.4	0.35	12
6	3.5	2.52	ClayTill 3	300	1.0	0.508	1.56	0.4	0.35	66
7	2.52	2.0	ClayTill 3	300	0.5	0.508	0.83	0.4	1.0	100
8	2.0	1.82	ClayTill 4	200	0.2	0.508	0.29	0.4	1.0	23
9	1.82	1.0	ClayTill 4	200	0.8	0.508	1.31	0.4	1.0	105
10	1.0	-0.18	ClayTill 5	400	1.2	0.508	1.88	0.4	1.0	301
11	-0.18	-0.7	ClayTill 5	400	0.5	0.508	0.83	0.4	1.0	133
12	-0.7	-2.28	Limestone 1	250	1.6	0.508	2.52	0.4	1.0	252
13	-2.28	-4.0	Limestone 1	250	1.7	0.508	2.74	0.4	1.0	274
14	-4.0	**-4.28**	Limestone 2	300	0.3	0.508	0.45	0.4	1.0	54
Total										**1346**

Table 3 Analytical method – base resistance.

Layer no.	Top (m)	Base (m)	Soil (-)	c_u (kN/m²)	t (m)	D (m)	A_b (m²)	r (-)	factor (-)	$R_{b,cal}$ (kN)
15	-4.28	**-4.28**	Limestone 2	300	0.0	0.508	0.20	0.4	9	**547**

6.3 PDA measurements

PDA measurements (a CAP-WAP analysis) were performed by CP test A/S (2014) on the test pile, showing a measured shaft resistance equal to 1642 kN and a measured base resistance equal to 4933 kN. See Figure 4.

The PDA measurements were performed with a permanent settlement of 1.3 mm/blow, which means that the measured resistances are mobilized bearing resistances, not ultimate bearing resistances. To achieve ultimate bearing resistance, a permanent settlement of at least 3 mm/blow is required.

CAPWAP SUMMARY RESULTS

Total CAPWAP Capacity: 6575.1; along Shaft 1642.0; at Toe 4933.1 kN

Soil Sgmnt No.	Dist. Below Gages m	Depth Below Grade m	Ru kN	Force in Pile kN	Sum of Ru kN	Unit Resist. (Depth) kN/m	Unit Resist. (Area) kPa	Smith Damping Factor s/m	Quake mm
				6575.1					
1	2.0	1.8	24.9	6550.2	24.9	13.53	8.48	0.669	0.100
2	4.1	3.9	211.9	6338.3	236.8	103.87	65.08	0.669	5.000
3	6.1	5.9	399.3	5939.0	636.1	195.74	122.64	0.669	6.000
4	8.2	8.0	452.6	5486.4	1088.7	221.86	139.01	0.669	4.500
5	10.2	10.0	553.3	4933.1	1642.0	271.23	169.94	0.669	4.000
Avg. Shaft			328.4			164.20	102.88	0.669	4.694
Toe			4933.1				24338.99	0.083	7.693

Figure 4 Results from PDA measurements.

6.4 Comparison

Table 4 illustrates a comparison between the expected bearing capacity of the test piles and the results from the PDA measurements (a CAP-WAP analysis). The table states the results as shaft resistance, base resistance and total bearing capacity, respectively.

Table 4 Comparison between the analytical method and the results from the PDA measurements.

Shaft resistance								
Layer no. I		**Top**	**Base**	**Soil**	**c_u**	**$R_{cal,I}$**		**$R_{m,I}$**
Calc.	**PDA**	**(m)**	**(m)**	**(-)**	**(kN/m²)**	**(kN)**	**(kN)**	**(kN)**
1	1	**5.72**	5.6	ClayFill	100	3		
2		5.6	5.4	ClayTill 1	225	10		
3		5.4	4.2	SandTill	-	6		
4		4.2	3.92	ClayTill 2	125	8	27	25
5	2	3.92	3.5	ClayTill 2	125	12		
6		3.5	2.52	ClayTill 3	300	66		
7		2.52	2.0	ClayTill 3	300	100		
8		2.0	1.82	ClayTill 4	200	23	200	212
9	3	1.82	1.0	ClayTill 4	200	105		
10		1.0	-0.18	ClayTill 5	400	301	406	399
11	4	-0.18	-0.7	ClayTill 5	400	133		
12		-0.7	-2.28	Limestone 1	250	252	385	453
13	5	-2.28	-4.0	Limestone 1	250	274		
14		-4.0	**-4.28**	Limestone 2	300	54	328	553
						Total	**1346**	**1642**
Base resistance								
15	6	-4.28	-4.28	Limestone 2	300	**Total**	**547**	**4933**
Total capacity								
						Total	**1893**	**6575**

In Figure 5 and Figure 6 the shaft resistance and base resistance from calculations and PDA measurements are shown in bar charts.

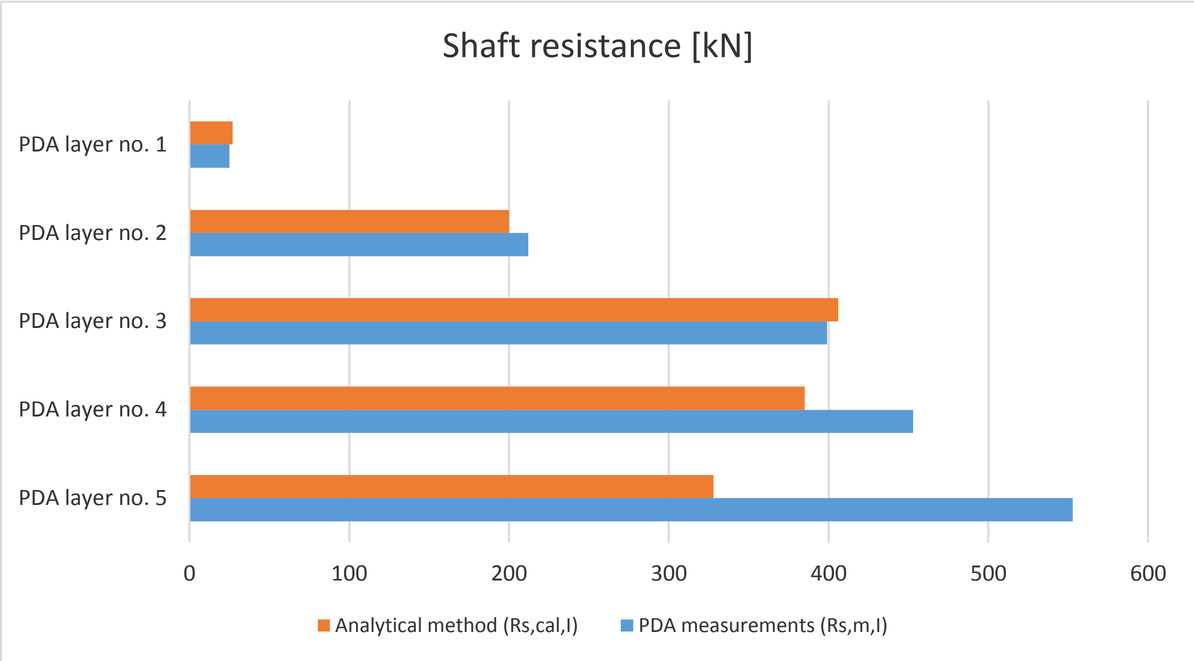

Figure 5 Bar chart showing shaft resistance from analytical method and PDA measurements, respectively.

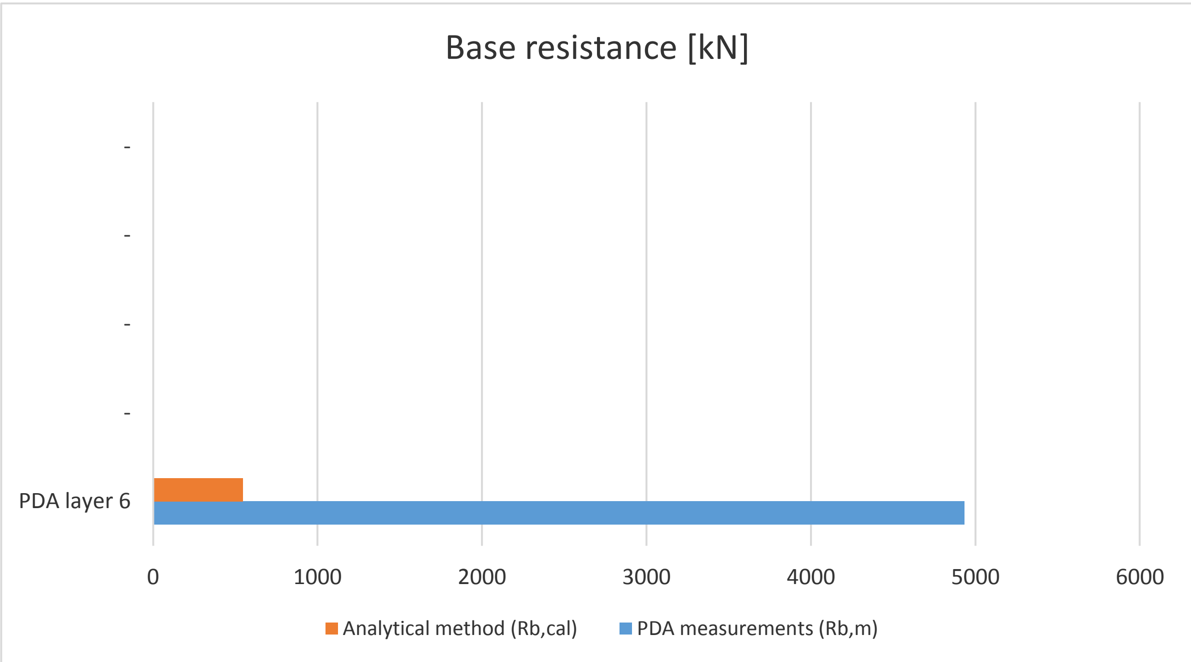

Figure 6 Bar chart showing base resistance results based on analytical method and PDA measurements, respectively.

7 CONCLUSION

The results listed in section 6 clearly shows that both the actual shaft resistance and the actual base resistance demonstrated by the PDA measurements are larger than those indicated by the representative calculation carried out for a similar driven pile based on the analytical method.

Regarding the shaft resistance, it is seen that the assumption regarding partial contact between pile and soil at the upper 3.2 m of the pile, due to the casing left behind, was correct.

The shaft resistance in the clay till from level +2.52 m to level -0.7 m shows good correlation between the analytical method and the results from the PDA measurements.

Finally, it is seen that the strength parameters in the limestone from level -0.7 m to pile base at level -4.28 m were significantly underestimated by the conservative estimate, because the actual shaft resistance demonstrated by the PDA measurements significantly exceeds the shaft resistance derived from the analytical method.

The actual base resistance in the limestone is especially higher in the results from the PDA measurements, which might be caused by locating the test pile on strong limestone/ flint layers, as the strength of the limestone may be expected to vary significantly. Nevertheless, it might be safe to conclude that there is no indication of insufficient cleaning of the bottom at the pile base.

Based on the results from the test pile, it is concluded to be safe to disregard the norm-based requirement in this particular case. Thus, the 30-per cent reduction of the shaft resistance for a bored cast-in-situ pile compared to a similar driven pile is disregarded.

Please note that conservative strength parameters (not realistic values) in the clay deposits naturally were applied in the final design.

8 PROJECT PARTNERS

Thanks to the Danish Road Directorate for permission to publish this article.

Other relevant partners for this project are listed below:

- Rambøll: Geotechnical investigation report.
- M. J. Eriksson A/S: Contractor, establishment of test pile.
- CP test A/S: Contractor, PDA measurements.
- COWI A/S: Consulting engineer, design of test pile.

9 REFERENCES

CP test A/S (2014). PDA measurements. M10, Køge Bugt, Bro 79.80. Case no. P15_001964.

DS/EN 1997-1 DK NA (2013). National Annex to Eurocode 7: Geotechnical design – Part 1: General rules.

Rambøll (2014). Geotechnical investigation report. Bro 1052-079.80, UF af bane, MV. ST. 135.7. Case no. 1100007980.