Test of bored piles and the outcome of the Danish standard for designing bored piles

M.S. Rasmussen
Züblin A/S,Denmark,msrl@zueblin.dk

ABSTRACT
At a location in Copenhagen a 1.2 m circular bored pile was installed with a length of 24.6 m. The pile was installed with an Osterberg cell with a test capacity of 2x28460 kN corresponding to a design bearing capacity of at least 29000 kN. Calculated in accordance with the design methods in DE/EN1997-1 the geostatic calculated design bearing capacity for bored piles was 2930 kN. The pile was tested to its full capacity 56920 kN without reaching failure. The results of the test are evaluated in the different zones, limestone, clay till and fill for the surface bearing capacity as well as the toe resistance are evaluated and presented. An alternative method for calculating the bearing capacity are presented as well.

Keywords: Bored piles, Limestone, bearing capacity, static load test.

1 INTRODUCTION

This article is a case story with the results of a static load test of a ø1200 mm bored concrete pile. The static load test was carried out with an Osterberg cell (O-cell). The knowledge from the load test is used on a nearby site to show how the very conservative Danish design approach gives less safe structures. On the actual construction site ø900 mm bored piles were planned. Due to the very conservative calculation method for bored piles described in DS/EN 1997-1 the VC3 consultants required a full scale static load test. The costs are very high for testing a large diameter pile compared with smaller piles. As so the planned ø900 mm piles were shifted to 2xø180 mm concrete piles with 2.5 times less surface area and 12.5 times less toe area.

2 THE STATIC LOAD TEST

Thesoil conditions and the results of the static load test carried out are presented below.

2.1 Soil condition

The soil conditions on site are as listed in Table 1.

Table 1: The soil conditions

Soil type	Levels [m]
Fill – clay	+2,0 to -0,3
Fill – Sand	-0,3 to -4,3
Gravel	-4,3 to -5,1
Clay till	-5,1 to -8,9
Sand	-8,9 to -11,8
Limestone	-11,8 to

The strength parameters are show in Table 2

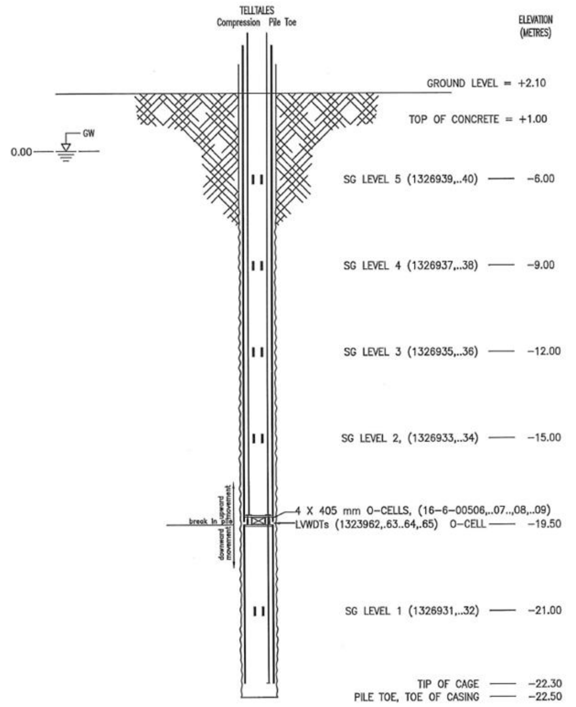
Table 2: The strength parameters

Soil type	γ/γ_m [kN/m³]	$\varphi'_{pl;k}$ [°]	$c_{u;k}$ [kN/m²]
Fill – clay	19/19	--	50
Fill – Sand	19/19	27	--
Gravel	19/19	27	--
Clay till	22/22	--	300
Sand	22/22	37	--
Limestone	22/22	--	1500/500

2.2 Test setup

The test pile is a ø1200 mm concrete pile. The pile is drilled with casing. Top- and toe level for the pile is +1,00 m og -22,50 m. Four 405 mm Osterberg cells (O-cells) are installed 3 m above the toe level, level -19.5. Strain gauges are installed in 5 different levels to make it possible to determine where the skin resistance is obtained. The strain gauges are installed in levels -6,0 m, -9,0 m, -12,0 m, -15,0 m and -21,0 m. The setup are shown in Figure 1.

Figure 1: The test setup

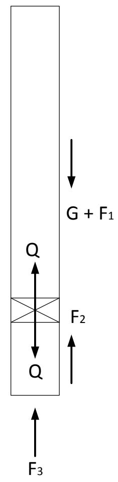


2.3 Test procedure

After breaking the weldings that keept the O-cells in the correct position during installation the test is started. The pile is loaded in 15 load steps with a maximum of 28460 kN,(Max capacity). After max load the pile is destressed in 4 steps.

Each load step is kept constant until the deformation rate is less than 0,1mm/20min. The deformations are measured after 0,1, 2, 5, 10, 30 minutes and therafter every 30 mi-nuts.
The load cell gives loads in both directions and as so both the surface capacity above the O-cells and the surface capacity and toe bearing capacity below the O-cell are investigated at the same time. Figure 2 shows in principle the loading principle.

Figure 2: Principle of loading



2.4 Expected bearing capacity

For an ø1200 mm circular pile with a length of 23.5 m, with toe level = -22.5 the theoretical bearing capacity of a bored pile is calculated according to DS/EN 1997-1:2007 NA:2013. It is calculated as a skin bearing capacity, $R_{s,k,dril}$ and a tip bearing resistance $R_{b,k,dril}$.

The geostatic calculation method is in principle the same for both bored piles and driven piles. For bored piles a few limitations are given in DS/EN 1997-1. These are:

$$R_{s,k,dril} = 0.3 \times R_{s,k,driv} \qquad (1)$$

$$R_{b,k,dril} = \min\begin{cases} R_{b,k,driv} \\ 1950 \times A_b \end{cases} \qquad (2)$$

With the soil conditions near the test pile the calculated characteristic skin bearing capacity for a bored pile becomes:

$$R_{s,k,dril} = 3505\,\text{kN} \qquad (3)$$

And the calculated characteristic tip bearing capacity becomes:

$$R_{b,k,dril} = 0.6^2 \cdot \pi \cdot 1950 = 2205\,\text{kN} \qquad (4)$$

This gives an total bearing capacity $R_k = 3505 + 2205 = 5710$ kN for the 23,5 m long ø1200 mm drilled pile.

Based upon (1) and (2) the characteristic geostatic calculated bearing capacity for a driven pile can be determined. For the skin friction the bearing capacity is calculated to:

$$R_{s,k,driv} = \frac{3505}{0.3} = 11675\,\text{kN} \qquad (5)$$

The tip bearing capacity is calculated by:

$$R_{b,k,driv} = 9 \cdot c_u \cdot A_b \qquad (6)$$

c_u is according to DS/EN 1997-1 limited to a maximum of c_u = 500 kN/m² even though the Limestone has a $c_u \approx$ 1500 kN/m². Using c_u = 500 kN/m² in (6) the tip resistance of a driven pile would be:

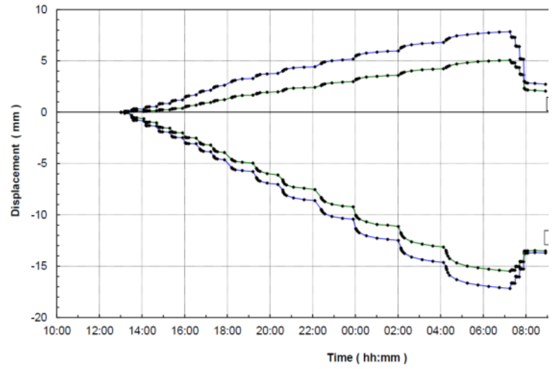
$$R_{b,k,driv} = 9 \cdot 500 \cdot 0.6^2 \cdot \pi = 5089\,\text{kN} \quad (7)$$

This gives in total an expected total bearing capacity of $R_k = 11675 + 5089 = 16764\,\text{kN}$ for a driven pile or approximately 3 times the bearing capacity of a similar bored pile. As so the expected measured bearing capacity of the fictive driven ø1200 mm 23.5 m long pile is 16764 kN.

2.5 Results

The displacement of the pile during the load test are shown on Figure 3.

Figure 3: The measured deformations during the test



The blue lines (The upper and lower line) are the movement of the O-cells and the green (the two middle lines) is the deformation of the top/bottom of the pile.
As shown there is a plastic deformation of approximately 2 mm for the upper part of the pile indicating that the pile has not reached failure. The deformation at the toe is approximately 13 mm, which as well indicates that the toe of the pile is not in a failure mode, while the skin friction might have reached its maximum as the deformations necessary for developing failure for the skin friction is much smaller than what is necessary for the tip failure to develop.
By looking into the stain gauge measurements it is possible to determine the skin friction measured in the different layers of the pile.

Table 3: The measured surface resistance

	Measured		Calculated	
Level	$R_{s;k;O\text{-}celle}$		$R_{s;k;dril}$	$R_{s;k;driv}$
[m]	[kPa]	[kN]	[kN]	[kN]
+1- -6	21,8	575	394	1.312
-6- -9	19,1	216	404	1.346
-9- -12	104	1.176	330	1.100
-12- -15	591	6.684	679	2.262
-15- -19.5	1.136	19.272	1.018	3.393
-19.5- -22,5	2.098	23.728	679	2.262
Total		51.651	3.505	11.675

Please note that this is for a pile not at failure. Based upon the measured results it is possible by the use of the program CEMSOLVE to estimate the failure capacity. This gives a surface capacity of approximately 53700 kN, an additional 2049 kN. As the deformation is smallest near the top of the wall it is here where the full "failure" has not yet occurred. If assumed equally divided between the 3 top layers the revised results are given in Table 4

Table 4: Revised result at expected failure

	"Failure"	Calculateded	
Level	$R_{s;k;O\text{-}cell}$	$R_{s;k;dril}$	$R_{s;k;driv}$
[m]	[kN]	[kN]	[kN]
+1- -6,0	1678	394	1.312
-6- -9,0	689	404	1.346
-9- -12	1.649	330	1.100
-12- -15,0	6.684	679	2.262
-15- -19,5	19.272	1.018	3.393
-19,5- -22,5	23.728	679	2.262
Total	53.700	3.505	11.675

The limestone is located from -12 and downwards. By comparing the measured and the calculated skin resistence in the limestone the measured is minimum 10 times larger than calculated for the drilled pile and at least 3 times the bearing capacity of the calculated capacity for a driven pile. As listed in Table 2 the undrained shear strength was acctually 1500 kN/m², and as so the results indicates a fine connection between the geostatic calculated bearing capacity if the requirement

from the Danish annex to the eurocode that a max value of 500 kN/m² is disregarded. For the layers above the limestone the measured bearing capacity at ”failure” is 4016 kN, where the calculated value for a bored pile is 1128 kN and 3758 kN for the driven pile. The results shows that the calculations carried out for a bored pile is highly conservative. It seems as if the results of a geostatic calculation as carried out for a driven pile gives reasonable results for a bored pile as well.
The test indicates that the 70% reduction of the skin bearing capacity that are used in Denmark according to the Danish annex should be neglected for this type of bored piles.

As the pile has not reached failure it is not possible to verify the tip resistance. In Table 5 the measured, the calculated for a bored pile, for a driven pile with a 500 kN/m² and with 1500 kN/m² as shear strength are shown

Table 5: The measured and calculated tip resistance

	Measured	Calculated		
Kote	$R_{b;kO\text{-}cell}$	$R_{b;k;dril}$	$R_{b;k;driv}$	$R_{s;k;1500}$
[m]	[kN]	[kN]	[kN]	[kN]
-22,5	4.740	2.205	5.089	15.260

Please note that even though the pile is not at failure the values calculated for a drilled pile in limestone is clearly underestimating the tip resistance and a value at least equal to what can be calculated for a driven pile should be used.

As for the skin resistance an estimate of the tip resistance has been made by use of CEMSOLVE. This shows a tip resistance of as high as 55000 kN, but as only 4740 kN are activated during the test the extrapolation is too large and as so are not reasonable to use in the evaluation of the results.

2.6 Conclusion of the load test

As the results shows the Danish method for calculating the skin friction capacity in both limestone and quaternary layers are very conservative. The skin friction capacity is at least as large as calculated for a driven pile. In limestone indications shown much higher capacities. At least in limestone the results shows that the limitation from the Danish annex where the shear strength is limited to 500 kN/m² should be disregarded.

For the tip resistance it is more difficult to conclude, as failure did not occur. At least the results shows that the limitation from the Danish annex of 1950 kN/m² (1000 kN/m²) for the tip resistance is very conservative and should be disregarded at least if the tip of the pile is in limestone.

3 A STORY FROM REAL LIFE

At a nearby construction site it was planned to use 16.5 m long ø900 mm bored concrete piles, with the toe of the pile in H4 Limestone (σ_c >25 MPa) as the foundation of a part of a new building. The soil conditions was similar to the site where the test pile described above was installed.

To carry out static load tests is expensive, but with the above results from the nearby construction site we expected to be able to verify that the pile had a bearing resistance at least equal to what could be determined with a geostatic calculation of a driven pile. It was not possible to get this approved by the owners consultants. The augmentation were:

- The test pile was carried out on a location approximately 800 m from the actual construction site.
- The toe of the test pile was deeper than the planned piles and could as so not be used as documentation
- As so the tip bearing capacity could neither be used as documentation

Due to that 2 pcs 20,5 m long bored GEWI pile with a diameter of 180 mm was installed to replace the planned ø900 mm piles.

3.1 Soil profile

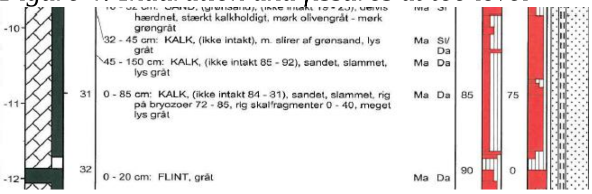
The soil profile at the construction site was

Table 6: The soil profile

Soil type	Level
Fill, clay	+5,8 - +2,1
Clay till	+2,1 - -0,5
Sand till	-0,5 - -1,0
Clay till, lower	-1,0 - -8,0
Greensand	-8,5 - -9,5
Limestone	-9,5 -

For evaluation of the strength of the soil/limestone at toe level the nearest borehole profile was evaluated. Figure 4 shows the induration and fissures at toe level. As shown the induration of the limestone is a H4 limestone (the right red column) with almost no fissures, S2 (the left red column).

Figure 4: Induration and fissures at toe level



This is even better than what was found at toe level of the test pile.

3.2 Theoretical bearing capacity

The required capacity of the ø900 mm piles was

$$F_d = 3347\,\text{kN} \tag{8}$$

The theoretical bearing capacity was

$$R_{d,dril} = 1568\,\text{kN} \tag{9}$$

if calculated as a bored pile.

For a driven pile, which according to the static load test carried out is a conservative assumption for a bored pile as well, the bearing capacity of the planned ø900 mm pile becomes:

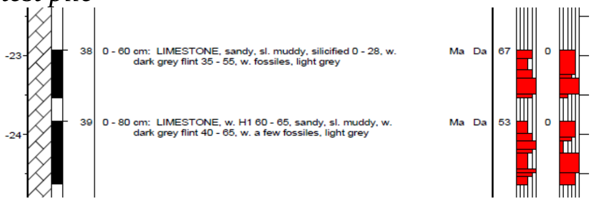
$$R_d = 7511\,\text{kN} \tag{10}$$

As so it was expected that the ø900 mm piles could be accepted.

The acceptance of the design was supported by the fact that eventhough the distance between the sites were 800 m the soil profile was similar as shown by comparing table 1 and table 6, till above limestone. The limestone level at the construction site was even higher than at the location of the test pile.

The bearing capacity of the tip of the pile is, as indicated in (6) not depending on the depth of the pile but on the strength of the pile. Figure 5 shown the induration and fissures at the toe level of the test pile

Figure 5: Induration and fissures at toe level of test pile



As shown by comparing figure 4 and 5 the induration at the toe of the test pile was H2-H4, where at the construction site the induration is more constant H4 and as so should be stronger. At the toe level of the testpiles a large number of fissures were found S3-S5, while almost no fissures were found at the construction site, S2. This indicates that the soil at the construction site should be stronger and more homogenious at the construction site.

This documentation could not be accepted by the VC3 consultants without a full scale load test on a pile with the same dimensions and installed with the same equipment.

3.3 Result

As the number of piles on the project was limited and as we could not get the calculation of the ø900 mm approved we had to find another solution.

It was chosen to install 2 pcs ø180 mm piles instead. These piles have approximately 2,5 times less surface area and approximately 12.5 times less toe level.

The only advantage is that a test of a ø180 mm bored pile is much less expensive.

The tensile test carried out showed the same results as the static load test. Using the geostatic calculated bearing capacity without the limitations given in (1) and (2) this design approach is still a very conservative design approach.

3.4 Conclusions

The two ø180 mm piles was as well installed as bored piles, where casing was used during the drilling work. As the much larger ø900 mm pile could not theoretically verify sufficient bearing capacity, the two much smaller piles with 2.5 times less skin area and 12.5 times less tip area have theoretic much to low bearing capacity, but in line with the static load test, the tensile test showed that the bearing capacity of the piles was much higher than what can be calculated according to Danish calculation method. The Danish calculation method is way too conservative and should be changed. In the actual case the calculation method was the main reason to switch pile type to piles with much less bearing capacity and much less stiffness and as so the Danish approach in principle have given a less safe construction.

4 REFERENCES

/1/ DS/EN 1997-1 + DK NA:2013. Eurocode 7 – Geotechnical design – Part 1: General

/2/ England, M.G. (2009) Review of methods of analysis of test results from bi-directional static load tests, Deep foundation on bored and augered piles, Ghent, sept. pp. 235-239 - CEMSOLVE

4.1 Symbols

γ :	Unit weight [kN/m³]
$\varphi_{pl,k}$:	characteristic plan friction angle
$c_{u,k}$:	characteristic undraind shear strength
$R_{s,k,dril}$:	Calculated skin bearing capacity for a bored pile
$R_{b,k,dril}$:	Calculated tip bearing capacity for a bored pile
$R_{s,k,driv}$:	Calculated skin bearing capacity for a driven pile
$R_{b,k,driv}$:	Calculated tip bearing capacity for a driven pile
$R_{s,k,O-cell}$:	Measured skin bearing capacity during O-cell test
$R_{b,k,O-cell}$:	Measured tip bearing capacity during O-cell test
$R_{s,k,1500}$:	Calculated skin bearing capacity for a driven pile if c_u =1500 kN/m²
$R_{b,k,1500}$:	Calculated tip bearing capacity for a driven pile if c_u =1500 kN/m²
σ_c :	Compressive strength
F_d :	Design load
R_k :	Bearing capacity
H :	Induration grade (H1 to H5)
S :	Fissure grade (S1 to S5)
A_b :	Base area of pile