Permanent uplift Anchors in Copenhagen Limestone

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Abstract. On the former Postal Service Centre parcel in central Copenhagen a new urban area of 200,000 m² is under construction, which accommodates service and retail trade, as well as apartments for housing. Below ground a parking basement in two levels is established with excavation to 8 m below ground level, corresponding to approximately 8 m below the design ground water level. To resist the uplift forces on the basement approximately 950 vertical ground anchors were needed. Because of the large number of ground anchors an initial test programme has been performed with the goal of minimizing the overall costs and to ensure a robust anchor project. The test programme consisted of 23 investigation tests on vertical ground anchors with varying anchor bond length, where the aim was to obtain failure in the interface between the grout and the limestone. All test anchors were installed with the anchor bond length in the Copenhagen Limestone. This paper describes the geology of the area, the concept for the preliminary anchor design, the test programme, and the results and conclusions. Furthermore, a description of the design and installation of the production anchors. The test programme showed that the anchor bond length could be reduced to (at least) 4 m for resisting a design anchor load of 1250 kN, corresponding to a measured shear resistance more than 70% greater than initially presumed. Based on this the production anchors were installed and tested by suitability and acceptance tests according to DS 1537, and all anchors passed the test.

1. Introduction

Close to the Central Station in Copenhagen a new urban area of 200,000 m² is under construction on the former Postal Service Centre parcel. The development project is divided into 3 design and build contracts consisting of a new domicile for a large Danish bank (codenamed Sunflower), a building for small and medium-sized companies and five large towers for both business and apartments. Below ground a parking basement in two levels is established with excavation to level -5.5 m, corresponding to approximately 8 m below ground level.

The buildings will be founded on a cast-in-place base slab supported by piles. To resist the uplift forces on the basement the base slab will be anchored by vertical, pre-stressed ground anchors. Because of the large number of uplift anchors an initial test programme has been performed with the goal of minimizing the overall costs and to ensure a robust anchor project.

2. Soil and groundwater conditions

Prior to design of the foundation of the new buildings 36 geotechnical boreholes were carried out. 24 of the boreholes were core drillings brought 10.5 – 16.7 m into the limestone.

The upper layers from ground at level +1.7 to +3.3 m consisted of 3.2 to 8.3 m fill of sand or clay to level -0.1 to -6.3 m. Beneath the fill and underlying thinner layers of postglacial and late glacial deposits...
various, stiff glacial deposits were found, dominated by glacial clay till and meltwater sand. Below the glacial layers a 1.4 to 4.9 m thick layer of green sand deposits of clay, silt and sand from Selandian age was found.

The Copenhagen Limestone (upper part) was found from level -10.8 m to -13.4 m until the bottom of the boreholes in level -13.2 m to -28.3 m. The limestone is a marine deposit from Danian age, with a relative large vertical variation in terms of induration, fractures and flint content.

For all cores the fractures and the degree of induration were described according to Bulletin 1, "A guide to engineering geological soil description", published by the Danish Geotechnical Society ref. [1]. 80% of the extracted cores were in the fracture categories S2 – S4. The degree of induration was predominantly in the categories, H2 – H5 where 80% of the cores were in H2 – H4.

In relation to the project, 32 Unconfined Compression Strength tests (UCS) were carried out on selected core samples from the Copenhagen Limestone. The results of the UCS tests are shown in Figure 1, where the unconfined compression strength is plotted against the level of extraction of the cores.

As shown in figure 1 a lot of scatter is observed in the measured strength of the Copenhagen Limestone. There does not appear to be a relation between the depth of extraction and the measured strength in the limestone, and since the boreholes are evenly distributed there is neither a relation of compression strength across the construction field. But as expected a trend was registered that the strength was a function of the geologically described degree of induration.

The mean value of the measured, unconfined compression strength in the limestone, $\sigma_{UCS}$, is 34 MPa, and the lower limit of the 95% confidence interval around the mean is 26 MPa.

In 2016 the primary ground water level in the limestone was measured at level +0.1 to -0.2 m in the standpipes installed in the boreholes, and the secondary ground water level in the glacial sand- and gravel layers was measured at level +0.1 to -2.2 m.
3. Uplift anchoring of base slab
The buildings on the Postal Service Centre parcel were constructed on a cast-in-place slab with base at level -5.5 m. Since the uplift forces from the high water level were larger than the weight of the basement, the vertical stability had to be ensured by anchoring the base slab with vertical, pre-stressed ground anchors (uplift anchors). By installing the uplift anchors with a general centre to centre distance on 3.75 m it was initially expected there would be a need of approximately 950 ground anchors. With design ground water level at terrain the design anchor load (UPL) was determined to 1250 kN per anchor.

The uplift anchors were planned to be installed as permanent Ø63.5 mm bar anchors in steel quality S670/800 with double corrosion protection, anchored in the Copenhagen Limestone. The ground anchors were drilled from the excavation level in the construction pit, while test and prestressing of the ground anchors was performed against the base slab after casting.

4. Preliminary design

4.1. Failure in the interface between grout and soil (fixed anchor length)
The design bearing capacity of the uplift anchors was in the project set at 1250 kN. Assuming anchoring in the Copenhagen Limestone the core drillings showed indurated to very strongly indurated limestone (H3 – H5) from the upper side of the Copenhagen Limestone. In the upper part of the limestone there were no indications of a glacially disturbed zone, probably because of the protective layer of green sand deposits found on top of the limestone.

With reference to the Christiansbro project and investigation tests performed on ground anchors installed in the upper part of the Copenhagen Limestone [2] a measured failure shear resistance in the interface between the grout and the limestone of minimum 720 kPa, or corresponding to approximately 900 kPa in at least 98% of the cases was expected. The experience from previous projects in the area of the design and build contractor Aarsleff was also a measured failure shear resistance of minimum 900 kPa.

Based on these experiences from anchoring in similar soil conditions (measured shear resistance on $\tau_{ult} = 900$ kPa), and the principles applicable to the calculation of tensile bearing capacity of piles, the necessary fixed length of the uplift anchors was initially calculated to 6 m, provided use of an OD152 anchor drilling system.

4.2. Loss of overall stability of construction (free anchor length)
The anchoring level of the uplift anchors and thereby the free anchor length was determined based on an analysis of equilibrium between the uplift on the whole structure and the anchoring force. The free length was determined such that the stabilizing force from the weight of the soil volume activated by the anchor was at least the same size as the uplift force, while at the same time neglecting the friction forces on the sides of the soil volume.

With a centreline distance of 3.75 m between the anchors preliminary calculations were used to determine the fixed anchor length in the Copenhagen Limestone between level -17 m and -23 m equivalent to a free anchor length of 11.5 m.

4.3. Test programme for uplift anchors
Due to a very tight time schedule for execution of the project and a need for a large number of uplift anchors it was early in the design process decided to perform a test programme covering among many other aspects the uplift anchors.

The test programme covering execution of preliminary investigation tests of uplift anchors had the following objectives:

- to ensure a robust anchor project with few or no risks related to the execution
• to reduce the overall costs
• to evaluate if the design tension bearing capacity of 1250 kN per anchor was achievable with a fixed anchor length of 6 m in limestone
• to evaluate if the fixed anchor length could be reduced.

With an expected number of 950 production anchors it was planned to install and test 21 test anchors at three test locations in the construction site divided into 3 x 7 anchors with a fixed length of respectively 4 m, 5 m and 6 m. The test programme formed the basis for evaluating if the initially determined fixed anchor length of 6 m was adequate or it could be reduced.

In order to have data basis being able to optimize the fixed anchor length it was the intention to load the test anchors until failure in the interface between the grout and the limestone was achieved. In order to test the anchors to sufficiently high tension loads the test anchors were installed with steel strands as opposed to steel GEWI bars in the production anchors.

Based on experience from the Christiansbro project, where permanent uplift anchors were likewise installed in the Copenhagen Limestone, the test loads were determined as given in Table 1.

| Anchor no. [-] | Top level anchor zone [m] | Fixed anchor length [m] | No. of strandsα [nos.] | Expected failure load, ground [kN] | Stop test load, steel [kN] |
|----------------|---------------------------|------------------------|------------------------|-----------------------------------|--------------------------|
| OA1 – OA7      | -17,0                     | 4                      | 15                     | 3200                              | 3300                     |
| OA8 – OA14     | -17,0                     | 5                      | 15                     | 3600                              | 3300                     |
| OA15 - OA21    | -17,0                     | 6                      | 15                     | 3800                              | 3300                     |

α Steel strand 0,62", steel strength S1670/1860 and maximum test load equal to 223 kN/strand.

The experience from Christiansbro is based on anchors with a fixed length of 3 m. Due to elasticity of the anchor, the bearing capacity will not increase linearly with the anchor length. For the test programme it was assumed that the increase in bearing capacity with a fixed length above 3 m diminishes, so a doubling of the anchor length from 3 to 6 would lead to a 50% increase in the expected failure load of the uplift anchors.

5. Test programme

5.1. Installation

The test anchors were installed at the site spanning an installation period from October 2018 until March 2019 following the requirements of DS/EN 1537 [3]. The test anchors were installed using an anchor drilling machine of the type Klemm 806-5.

The anchors were drilled with a fully cased drilling system and excess material was transported out of the borehole using water as flushing medium. After the borehole reached the final depth, the drill head was retracted and the strands for the anchor were inserted. The anchor was injected using a grout (water/cement suspension) with a water/cement ratio of approximately 0.5. The cement type was Aalborg Portland Rapid cement. The injection was done using 20 bars of pressure in one operation and no post-injection was applied.

Anchor fixed lengths of 4 – 6 meters was used for the test anchors, with an equal number of each length. The free length of the anchors varied due to the excavation sequence of the excavation pit, however the fixed anchor zone had top level in -17.0 m for all anchors.
The anchors were planned to be drilled with the drilling system OD152 (drill head diameter 152 mm). However, an error occurred in the installation of the first seven test anchors (OA1-OA7), as these were installed using OD178 (drill head diameter 178 mm) drilling system. A larger outer diameter directly implies a larger bearing capacity of the anchor, and it was therefore decided to replace the first seven anchors and number them OA22-OA28. A total of 28 anchors were installed (OA1-OA28), but only two of the first seven anchors, OA1 and OA3, were tested.

An overview of all installed and tested anchors can be seen in Table 2.

### Table 2: Overview of all tested uplift anchors in test programme

| Anchor number [-] | Drilling system [mm] | Resting time [days] | Fixed length, \( L_{tb} \) [m] |
|-------------------|----------------------|---------------------|-----------------------------|
| OA1, OA3          | OD178                | 36, 46              | 4                           |
| OA8 – OA14        | OD152                | 23 – 144            | 5                           |
| OA15 – OA21       | OD152                | 27 – 38             | 6                           |
| OA22 – OA28       | OD152                | 14 – 36             | 4                           |

The anchors had to be tested simultaneously with the testing of the production anchors for the retaining walls in the excavation pit. Thus, the resting time differed quite significantly. A planned minimum rest time of 21 days was sought, primarily due to the curing of the grout body, i.e. necessary strength had to be reached, and this was kept for all anchors except OA26. It was assumed that the time-effects after installation of the anchors in the limestone was neglectable, as little to no regeneration will occur in this type of soft rock.

### 5.2. Testing

The anchors were tested using test Method 1 as given in DS 1537 [4]. The anchors were tested using a hydraulic jack system with a total capacity of 6000 kN. The force from the hydraulic jack was counterbalanced by a steel plate layout directly on the ground surface around the anchor. Each anchor was tested according to the specifications of DS 1537 with minor modifications as given below. The test sequence for each anchor can be seen in Table 3. The load steps 8 – 10 were added in order to try to achieve failure in the anchors (interface grout – limestone), and no unloading was undertaken between these load steps.

### Table 3: Test sequence of uplift anchors in test programme

| Load step [-] | Load [kN] | Observation timeᵃ [min] | Comment [-] |
|---------------|-----------|--------------------------|-------------|
| 1             | 250       | 1                        | Load cycle 1 |
| 2             | 800       | 15                       | Load cycle 2 |
| 3             | 1200      | 30                       | Load cycle 3 |
| 4             | 1700      | 30                       | Load cycle 4 |
| 5             | 1900      | 60 / 180ᵇ                | Load cycle 5 |
| 6             | 2200      | 30                       | Load cycle 6 |
| 7             | 2400      | 30                       | Load cycle 7 |
| 8             | 2700      | 30                       | No unloading from load step 7 |
| 9             | 3000      | 30                       | No unloading from load step 8 |
| 10            | 3300      | 30                       | No unloading from load step 9 |

ᵃ For some of the anchors the observation time for load steps 3-4 and 6-10 was lowered to 15 minutes due to time limits on the execution of the tests.

ᵇ For anchor OA1, OA8, OA15 and OA26 the observation time was prolonged to 180 minutes in order to evaluate long term effects.
The prolonged observation time in load step 5 was applied since the load of 1900 kN was equivalent of the test load for suitability testing of the production anchors.

The deformation at the anchor head during testing was measured by an analog dial gauge with a precision of 0.01 mm. The dial gauge was attached to a reference steel beam that was supported so it was not affected by the movements around the anchor at ground level. Measurements of coherent readings of force applied and deformation were taken at intervals given in DS 1537.

5.3. Post processing of results

The behaviour of the ground anchors was analysed by means of the creep rate during load application. The creep rate is defined as given in eq. (1).

\[ k_s = \frac{s_i - s_a}{\log\left(\frac{t_f}{t_0}\right)} \]  

where \( k_s \) is the creep rate and \( s_i \) is the deformation at time \( t_i \).

Failure in a ground anchor is per Danish tradition given as the ultimate load the anchor can sustain under unlimited deformation, which is equal to a horizontal asymptote in a diagram of creep rate plotted against the force applied. When such an asymptotic behaviour is not achieved failure is often practically defined as a creep rate above 5 mm. This definition is somewhat unique to Danish practice. For suitability test of a ground anchor the maximum allowable creep rate is 2.0 mm as given in DS 1537. Due to the definition of the creep rate it will vary with the observation time. It is normal practice to prolong the observation time if the creep rate criteria cannot be met.

All 23 tested uplift anchors were subjected to a total load of 3300 kN and failure was not achieved in any of the anchors as per the above definition, cf. figure 2 and figure 3. As for acceptance tests of ground anchors, the deformation was measured after 2 and 5 minutes and a maximum deformation of 0.2 mm can be accepted, which is equivalent of \( k_s \approx 0.5 \) mm. For all tested anchors the force plotted against the creep rate from 2 min to 5 min for all load steps is shown in Figure 2 and Figure 3.

**Figure 2:** Creep rates of test anchors with OD152 drilling system and \( L_{th} = 4 \) and 5 m for all load steps (from 2 to 5 minutes observation time).
Figure 3: Creep rates of test anchors with OD152 and OD178 drilling systems and respectively $L_{tb} = 6$ m and $L_{tb} = 4$ m for all load steps (from 2 to 5 minutes observation time).

From the results shown the following points can be made. None of the test anchors failed even with the maximum load of 3300 kN applied. There is quite a lot of scatter in the measured creep rates, which can probably be attributed to the many small irregularities and changes in strength and stiffness in the limestone, e.g. flint sections, the very small deformations measured and the inherent uncertainty involved with manual reading of a dial gauge. For none of the plots a clear trend of increasing creep rate with increasing force is seen, which otherwise could have been an indicator of imminent failure. Furthermore, almost all the calculated creep rates were in the range of 0.1 – 0.5, which is very far from the failure definition of a creep rate above 5 mm.

Compared to the requirements for acceptance test some of the anchors did exhibit creep rates above the maximum creep rate of 0.5 mm at a load of 1700 kN, which is approximately equivalent of the acceptance test load for a design load of 1250 kN. However, for larger loads the creep rates do tend to be lower.

The results with a load of 1900 kN can be compared with the requirements for suitability testing, the creep rate from 20 to 60 min can be calculated and compared to the acceptable creep rate of 1.0 mm. The results for all anchors with drilling system OD152 are shown in Figure 4. It can be seen that all anchors were within the requirements. Further no clear connection between the fixed anchor length and the creep rates can be seen.
Since failure was not achieved in any of the tested anchors, it was not possible from the results to estimate the ultimate capacity of the uplift anchors. As an alternative the mobilised shear resistance $\tau_{mob}$ of the anchors installed in Copenhagen Limestone can be calculated assuming a capacity equal to the maximum load of $R_{am} = 3300 \text{ kN}$ from,

$$\tau_{mob} = \frac{R_{am}}{\pi \cdot d_y \cdot l_{tb}} = \frac{3300 \text{ kN}}{\pi \cdot 0.17 \text{ m} \cdot 4 \text{ m}} = 1545 \text{ kPa} \tag{2}$$

where $d_y$ is the outer diameter of the grout body and $l_{tb}$ is the fixed anchor length.

Using the literature and experience related to bored piles in limestone, cf. ref. [5] and [6], the unconfined compression strength (UCS value) can be used to derive an expected shear resistance. With respectively a mean UCS value of 34 MPa and a lower 5% confidence value for the mean UCS value of 26 MPa, the failure shear resistance becomes approximately 2100 kPa. Comparing this value with mobilised shear resistance of the test anchors the value does not seem unrealistic, which supports an ultimate shear resistance of at least 1545 kPa.

This value is significantly higher than the initial design value of 900 kPa, and the actual ultimate shear resistance may be (significantly) higher. This result indicates that for future design of ground anchors in Copenhagen Limestone a higher ultimate shear resistance than previously assumed can be utilized. However, this hypothesis is to be verified on the future project sites.

As part of the test programme of the whole development project on the Posten parcel, 7 ground anchors installed in the top of the limestone with a fixed length of $l_{tb} = 3$ m were tested to a load of 3200 kN with no indications of imminent failure. The results of these anchors indicate an ultimate shear resistance higher than 2000 kPa. It is emphasized that the bearing capacity of a ground anchor does not scale linearly with the fixed length due to elasticity of the anchor, meaning a 3 m fixed length of an anchor might show a higher shear resistance under identical soil conditions.

5.4. Long term effects

The long-term behaviour of the test anchors was estimated based on load step 5 in the test where an observation time of 60 or 180 minutes was used for anchors with a fixed length of 4 m. The long term behaviour is mainly influenced by the creep deformations in the limestone and relaxation of the steel. From the test it was questionable if the observation time was long enough to capture these effects in detail. Despite of the relatively short observation time, an extrapolation based on the measured displacements to the expected lifetime was made. It was assumed that the long-term deformation in a
logarithmic time scale can be fitted to either a linear or a quadratic function, and this function was then used to extrapolate the deformations to 50 years lifetime.

For anchors with a fixed length of 4 m the deformation plotted against the logarithm of the time as well as the fitted curves can be seen in Figure 5.

![Figure 5: Creep deformation for L_{ab} = 4 m at 1900 kN. Linear fitting in the figure to the left and quadratic fitting to the figure to the right. NB: Quadratic fitting leads to unrealistic results for OA25.](image)

The extrapolation from 60 min to 50 years will inevitably cause some quite uncertain results that should be interpreted with caution. The average creep deformation derived from the linear fit and the quadratic fit in the logarithmic time scale is 1.3 mm and 3.7 mm respectively extrapolated to 50 years (log(t) = 7.4). These results are both reasonable and an acceptable performance for permanent anchors.

6. Production anchors

Based on the results of the test programme it was not only possible to confirm the initial design assumptions, but it was further possible to lower the fixed anchor length of the production anchors to 4 m, which is a 50% reduction from the initial design of 6 m. Unfortunately, the time schedule for the test anchors meant that the majority of the production anchors on the design and build contract "Sunflower" were already installed with a fixed length of 6 m at the time of completion of the test programme.

At the time of publication of this article a total of 454 production uplift anchors were installed and tested during the project Sunflower. 444 anchors were tested using the approach for acceptance test and 10 anchors were tested using the approach for suitability test. All the tested anchors showed creep rates within the requirements in DS1537, which was a further validation of the very high bearing capacity of ground anchors in Copenhagen Limestone.

7. Conclusions

For the building project on the former Postal Service Centre parcel in central Copenhagen a test programme for uplift ground anchors in Copenhagen Limestone was carried out consisting of a total of 23 test anchors with fixed anchors lengths between 4 and 6 m. All anchors were tested as investigation
anchors with a procedure as given in DS 1537, ref. [4], to a maximum load of 3300 kN, and none of the tested anchor showed a behaviour indicating failure.

From the results a mobilized shear strength between the grout body of the anchor and the Copenhagen Limestone of approximately $\tau_{\text{mob}} = 1545$ kPa was derived, even though the actual failure value might be significantly higher as no clear failures were observed in the tests. The initial design value of the ultimate shear resistance was assumed to be approximately 900 kPa. This result indicates that for future design of ground anchors in Copenhagen Limestone a higher ultimate shear strength than previously assumed can be utilized.

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References

[1] Danish Geotechnical Society 1995 Bulletin 1E - A guide of engineering geological soil description (Copenhagen, Danish Geotechnical Society)
[2] Kristensen, P. S., Madsen, J. and Nymand, J. 2000 Christiansbro, kontor. Permanente jordankre i København Kalk (Copenhagen, NGM 2000)
[3] Dansk Standard 2013 DS/EN 1537: Geotechnical investigation and testing – Tesing of geotechnical structures – Part 1: Testing of piles: static compression load testing (Copenhagen, Dansk Standard)
[4] Dansk Standard 2014 DS 1537: Udførelse af særlige geotekniske arbejder - Jordankre - Prøvning (Copenhagen, Dansk Standard)
[5] Fleming et. al. 1992 Piling Engineering, 2nd edition (London, Blackie A&P)
[6] M. Tomlinson and J. Woodward 2008 Pile design and construction practice (London, Taylor & Francis)
[7] Dansk Standard 2015 DS/EN 1997-1 DK NA:2015: Nationalt anneks til Eurocode 7: Geoteknik – Del 1: Generelle regler (Copenhagen, Dansk Standard)