Founding on (un)known chalk in Aalborg

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The North Denmark Region wishes to build a new hospital to accommodate all hospital functions in Aalborg. At a budget of DKK 4.1 billion, the complex of buildings will cover 155,000 m². The first turf was cut in 2013 and the construction works will run from 2015 to 2020. The foundation level will vary from approximately four metres to ten metres below ground surface.
The soil at the site consists of recent deposits, top soils and fillings, and below these are late glacial clay/silt/sand and clay till on top of chalk. A large proportion of the buildings are founded on chalk. The chalk in the Aalborg area is to some degree known from other projects, and is expected to be relative soft with 'chimneys' (decomposed chalk fissures filled with loose material).
The paper focuses on describing the general characteristics of the Aalborg chalk presenting results from old projects and comparing with results from new laboratory tests specified for the current project. Results from new oedometer and triaxial tests on the chalk are presented along with observations from the geotechnical supervision during construction.

Keywords: Direct foundation, chalk, testing, supervision.

1 PROJECT

1.1 Background

In 2007 the Danish Parliament passed a reform named the Quality Fond including a DKK 25 billion investment in new modern hospital facilities to improve the effectiveness of the Danish Health System. North Denmark Region (Health Authority) was interested in developing a Greenfield area of 92 hectares in the outskirts of Aalborg to a new Health Centre of North Jutland to join together different facilities spread across the city.

In 2012 North Denmark Region received final commitment from the Quality Fond to finance a new hospital building, named Nyt Aalborg Universitetshospital (NAU), of approx. 155,000 m² with a budget of DKK 4.1 billion. North Denmark Region contracted in 2012-13 joint venture company, INDIGO, for planning and design, NIRAS for construction management and COWI for geotechnical investigations to complete NAU before 2020.

Figure 1: Illustration of Nyt Aalborg Universitetshospital (NAU).

1.2 Building

NAU consists of 3-10 story buildings with up to 3 level basements (K0-K2) on slab and pad foundations of reinforced in-situ casted concrete, in total approx. 21,700 m². Foundation of the 10-story section is a 9,000 m² slab with a thickness of 500-1500 mm in basement level K2 (3 levels below ground surface). Design load on foundations is up to 450 kPa.

Construction started end of July 2015.

1.3 Excavation

The building is constructed in an open excavation of 250 x 300 m. Existing terrain level varies between level (DVR90) +10 m to +18 m and deepest foundation (basement level K2) is level +2.95 m.

Ground water level is measured as high as +5.5 m and a temporary groundwater lowering is installed consisting of 18 dewatering wells with a yield of approx. 80 m³/h.

Figure 2: Excavation for basement level K2.

1.4 Codes and categories

The buildings are designed according to Eurocode 7 and Danish national annex, with consequence class CC3 for the 10-story section and consequence class CC2 for the remaining part of the buildings.

2 GEOLOGY

The geology in the area of the city of Aalborg is dominated by three “islands” of Cretateous deposits, upon which Quartenary deposits are present. Layers from the geological periods in between these formations are not found in Aalborg.

On the “islands” the top of the chalk is found up to level +40 m to +60 m and at shallow depths, only covered by topsoil/mull, otherwise the chalk is often covered by glacial till and meltwater deposits. In the low-lying areas between the “islands” the top of the chalk is found at levels -30 m to deeper than -60 m, and the chalk and glacial deposits are additional overlain by various deposits of late glacial and postglacial origin.

The soil at the NAU site consists of recent deposits, top soils and fillings, and below these are late glacial clay/silt/sand and clay till on top of chalk.

This article focuses solely on the Cretateous layers, which consist of Maastrichtian chalk deposited in the period 65-144 million years ago.

The chalk may be found in its original deposition and state, but a number of processes have degenerated the chalk. Tectonic disturbance may be the dominating reason for the varying topside levels. Furthermore, the chalk is often glacially disturbed, e.g. by glacier erosion of weak chalk and dislocation of lumps of chalk (dislocated chalk of a thickness of more than 30 meters is registered on the northern “island”). Glacially created fractures caused by shear stresses during passage of glaciers and/or passive earth pressure during meltdown of glaciers have also affected the chalk. Erosion may also have taken place in the late glacial period. The surface of the chalk has subsequently been exposed to weathering and drying-out.

All these processes affects potentially the geotechnical properties of the chalk, but the relevant states of the chalk are seldom fully recovered by traditionally geotechnical investigations.

In addition, dissolution pipes ('chimneys') of varying sizes are often seen in the surface of the chalk, in which case the produced cavities are filled with loose wash-down or drop-down materials from the deposits above. Hollow cavities in the chalk is seldom registered.

Aalborg has a glorious industry history for extracting chalk for production of cement, which is still produced in Aalborg as the only remaining production plant in Denmark.

3 INVESTIGATION OF CHALK

3.1 Investigation borings

Drilling in the chalk can be done by e.g. the traditionally auger method used for soils. Extracted of intact samples can normally be done by pressing traditionally Ø42 or Ø70 mm tubes into the chalk. Core drilling has occasional been used, but flushing out of soft material may lead to relatively poor core recovery.

Normally field vane tests and CPT's (Cone Penetration Test) can be performed in the chalk. In zones of hardened chalk these tests may though be rejected.

3.2 *Classification*

At normal investigation depths for structures, the chalk is usually seen as a purely white or light grey matrix of unhardened chalk (hardness H1) with parts of slightly hardened or hardened chalk (H2/H3). In some borings the chalk is registered as hardened and blocky. The structure of the chalk is muddy with particles predominantly corresponding to silt (0.002 – 0.06 mm) or may sometimes seem grainy/sandy in extracted samples. The chalk in Aalborg is poor of flint.

In Table 1 typical classification parameters are listed. The chalk may be categorised as low-density chalk according to CIRIA.

Table 1: Typical classification parameters

Parameter	Range
Moisture content, w (%)	24 – 39
Density, ρ (Mg/m^3)	1.71 – 2.04
Calcium carbonate content (%)	95 – 99
Specific density, $ρ_s$ (Mg/m^3)	2.69 – 2.71
Saturation, S_r (%)	95 – 100
Dry density, $ρ_d$ (Mg/m^3)	1.31 – 1.60
Void ratio, e (-)	0.85 – 1.01
Porosity, n (%)	46 – 50

3.3 *Performance of the chalk*

In geological terms the Maastrichtian chalk is often denoted lime<u>stone</u>. This term is not descriptive for the general performance of the chalk in Aalborg, as the chalk rather performs as silt with hardened gravels of chalk.

The chalk may consequently be handled as a soil and not as a rock.

The undrained shear strength may be measured by triaxial tests (c_u) in the laboratory or by field vane tests (c_{fv}), SPT's and CPT's.

SPT's (Standard Penetration Test) is traditionally not used in Denmark for cohesive soils (e.g. unhardened chalk). SPT's may though be used to document hardened chalk, but an evaluation of the corresponding strength is uncertain.

CPT's have been used for the last 20 years in Denmark, but no comprehensive study of the evaluation of CPT-data in chalk has yet been produced. It seems though reasonable to use $c_u \approx q_c/N_k$, where q_c is the cone resistance and N_k is the cone factor. Further analyses of N_k is though necessary for a specific site.

4 PREVIOUS INVESTIGATIONS

The a-priori knowledge of the geotechnical properties of Aalborg chalk is based on advanced geotechnical investigations for relatively large structures and building projects, as minor projects seldom is subject for investigations beyond simple tests. Most of these advanced investigations are performed by the Danish Geotechnical Institute in the period from the 1950's and the decades thereafter, see e.g. references below. The essence of a number of these investigations has been made available for the current paper and is described in the following.

4.1 *Undrained shear strength parameters*

A number of triaxial tests have been performed to determine the undrained shear strength of the chalk. The results of undrained shear strengths from a number of these tests (made as $CU_{u=0}$) are in Figure 3 compared with corresponding field vane tests made close to the tested sample.

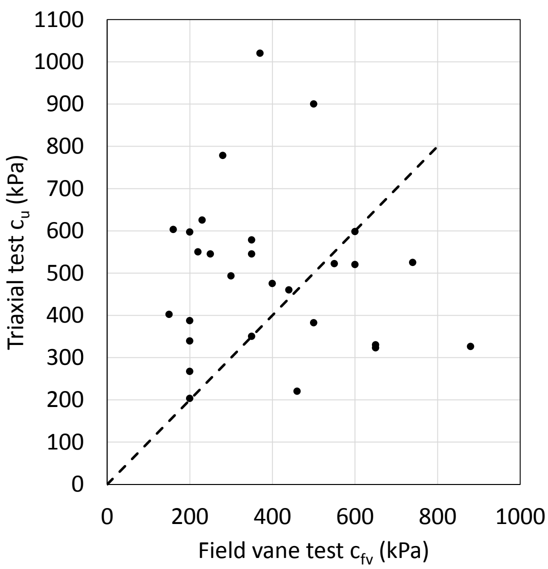

Figure 3: c_u versus c_{fv} from older tests

The comparison of triaxial tests and field vane tests shows some scatter for the factor $\mu = c_u/c_{fv} = 0.37 - 3.77$, but a linear regression through origo of the data gives $\mu = 1.0$ (equals dashed line in Figure 3). The scatter may be explained by the nature of the chalk with inhomogeneous hardening and fractures. It is noted, that $\mu \geq 1.0$ for $c_{fv} < 450$ kPa, which seems to indicate that use of $c_u = c_{fv}$ is conservative for $c_{fv} < 450$ kPa. A larger scatter of μ is observed for $c_{fv} > 450$ kPa. In 1972 (Geo, 1972), eight plate load tests were carried out on a surface of intact chalk. The plate used was Ø300 mm and the deflection during pressure was increased to respectively 4 % (slow loading) and 10 % (quick loading) of the plate diameter. A number of field vane tests was performed in the area around the plate load tests. In Table 2 the results of the tests are presented, using:

c_{fv} = field vane test
e = void ratio
$\sigma_{c,4\%}$ = stress at 4 % deflection
$\sigma_{c,10\%}$ = stress at 10 % deflection

Table 2: Results of plate load tests

No.	c_{fv} (kPa)	e (-)	$\sigma_{c,4\%}/c_{fv}$ (-)	$\sigma_{c,10\%}/c_{fv}$ (-)
101	325	0.95	6.3	-
102	325	0.94	5.6	-
103	300	0.96	5.6	-
104	300	0.95	-	8.3
201	92	0.95	6.5	11
202	>119	0.95	<7.6	<11.6
203	>117	1.00	<6.5	<9.7
204	>119	-	<8.8	<17

The ratio of $\sigma_{c,x\%}/c_{fv}$ (load/resistance) is, based on the general bearing capacity equation for undrained failure, expected to be $1.2 \cdot (\pi+2) \approx 6.2$, and it was concluded that the field vane tests may be used to estimate the undrained shear strength $c_u = \mu \cdot c_{fv}$, using $\mu = 1.0$, maybe even on the conservative side for large deflections ($\sigma_{c,10\%}$). This in compliance with the results in Figure 3 as $c_{fv} < 450$ kPa.

4.2 Drained strength parameters

The drained strength parameters have also been investigated by triaxial tests. It is often seen that the evaluation of the effective angle of friction and the effective cohesion is dependent of the stress level because of curved failure lines in a Mohr diagram. In Figure 4 and Figure 5 the results of these tests are presented, using:

σ_1' = Largest principal stress at φ'/c' read
φ' = Effective angle of friction
c' = Effective cohesion

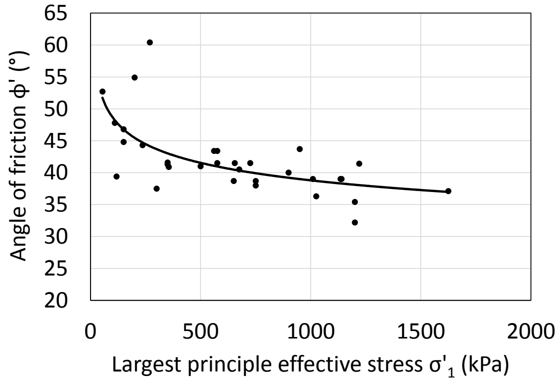

Figure 4: Angle of friction from previous triaxial tests

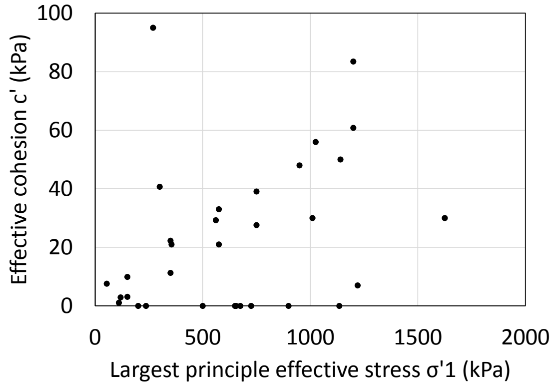

Figure 5: Effective cohesion from previous triaxial tests

The triaxial tests indicates a variability of φ' with the stress level, represented by σ_1'. For normal foundation stress levels less than 1,000 kPa it seems that an effective angle of friction φ' ≥ 38 – 40° may be applied. In some projects lower values of φ' have been used in the topside zone of chalk, where φ' for remoulded/weathered chalk may be indicated as low as 30 - 33°.

The effective cohesion varies and seems to be nearly independent of the stress level and the evaluated angle of friction, which presumably is caused by more or less random fracturing of the chalk and evaluation of parameters from individual tests. Consequently, it has often been necessary to choose a conservative value c' = 0 kPa in the design of structures.

4.3 Deformation parameters

The oedometer modulus of chalk is evaluated on the basis of 16 oedometer tests in Geo (1964 and 1965) for the Limfjordstunnel. The natural moisture content in the test samples was w = 29 – 34 % and field vane tests showed c_{fv} = 220 – 540 kPa. The following relation was determined:

$$E_{oed} = 5{,}000 \text{ kPa} + 1{,}200 \cdot \sigma'_a + 400 \cdot \Delta\sigma'$$

where:
σ'_a = effective stress before loading
$\Delta\sigma'$ = additional effective stress

5 PRESENT INVESTIGATIONS

5.1 Scope

A geotechnical investigation campaign was planned and executed based on the general knowledge of the geology in the area of the NAU. The objective of the investigation was to determine the soil conditions at the site and derive deformation and strength parameters for the slap and pad foundations utilized for the structure. The majority of the building is, as described in Section 1, build on chalk and the primary focus of the investigation campaign has been put on analysing the encountered chalk.

The geotechnical investigations consisted of:

- 49 initial borings with sampling and field vane tests carried out to a depth between 7 and 20 m below existing terrain.
- 33 supplementary borings with sampling and field vane tests carried out to a depth between 7 and 20 m below existing terrain.
- 3 oedometer and 6 triaxial tests on intact chalk samples.

The following sections summarizes the findings from the investigations with respect to the strength properties of the chalk. The investigations are further elaborated in COWI (2015).

5.2 Field vane tests

All borings include vane tests along the full depth of the borings. Ten of the supplementary borings have been carried out from an excavated level and next to initial borings, where up to 7 m has been excavated. These ten supplementary boreholes from the excavated level are used to investigate the change in undrained shear strength from unloading of the chalk during construction.

The measured strength in the chalk from the field vane tests between level +8 m and +2 m are plotted in Figure 6, where the field vane tests carried out from existing terrain has been plotted in blue where-as the latest field vane tests carried out from excavated level is plotted in red.

It is observed from Figure 6 that there is a significant variation in both horizontal and vertical direction of the measured field vane strengths prior to excavation across the site with majority of the measured values between 200 kPa and 400 kPa, though with some outliers between 80 kPa and 660 kPa.

Comparing the measured field vane strength values from before and after excavation shows a general tendency of strength reduction after excavation, where the majority of the measured values after excavation are between 100 kPa and 300 kPa, with some outliers above 300 kPa.

The variation in horizontal and vertical direction may be explained by the nature of the upper part of the chalk with variation in hardening and fractures.

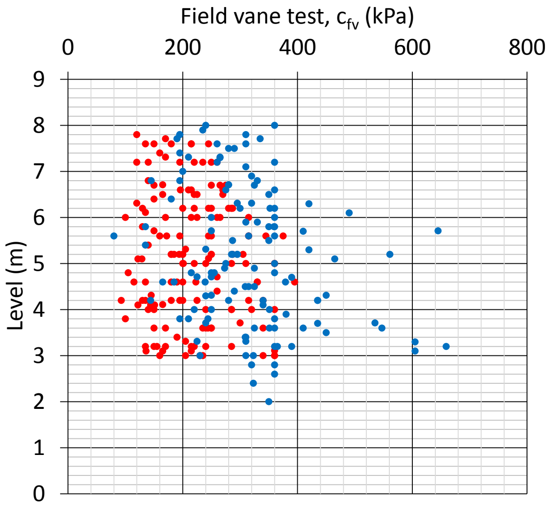

Figure 6: Field vane tests. Blue: before excavation and Red: after excavation to level +8 m.

5.3 Oedometer tests

A total of three oedometer tests were carried out on intact chalk samples:

- One constant rate of strain (CRS) test on a sample from level +6.3 m.
- Two incremental loading (IL) tests on samples from level -1.52 m and +3.69 m.

The maximum applied load in the CRS test was 8,800 kPa, whereas the final load step in the two IL tests was 4,800 kPa.

The yield stress of the chalk was estimated to be at least 1,500 kPa and the constrained modulus varied between 30 MPa and 500 MPa, depending on the effectives stress level in the soil.

It is assessed that the chalk behaves equivalent to an overconsolidated soil.

5.4 Triaxial tests

A total of six Anisotropic Consolidated Undrained triaxial tests (CAU), were for the NAU project carried out on samples taken at different levels, see Table 3.

Table 3: Samples for CAU tests

Boring and sample	Depth below existing terrain	Level for sample
B30B-3A	10.5 m	+4.4 m
B30B-11A	14.5 m	+0.4 m
B31B-15A	16.5 m	-1.6 m
B32B-3A	10.2 m	+3.5 m
B42B-P12	6.6 m	+6.4 m
B56-13	12.0 m	+1.5 m

The measured stress-strain curves from the six CAU tests are plotted in Figure 7 for comparison.

It is observed from Figure 7 that the strength generally increases with depth, and that the samples exhibit the same behaviour from 0 % to 1-1.5 % axial strain. The behaviour deviates after an axial strain of 1-1.5 %, with the three deepest samples bundled until an axial strain of 5-6 %.

The undrained shear strength is interpreted from the CAU tests, where failure is defined based on a deviator stress at 10 % axial strain.

The undrained shear strength determined from the CAU tests is plotted in Figure 8 with corresponding strength determined by field vane tests. Comparison of results from triaxial tests and field vanes gives a factor of $\mu = c_u/c_{fv} = 0.76 - 2.54$, and Figure 8 shows that a factor of $\mu = 1.0$ is applicable and reasonable conservative for the site. This complies with findings from other locations in the Aalborg area, cf. Figure 3, for $c_{fv} < 450$ kPa.

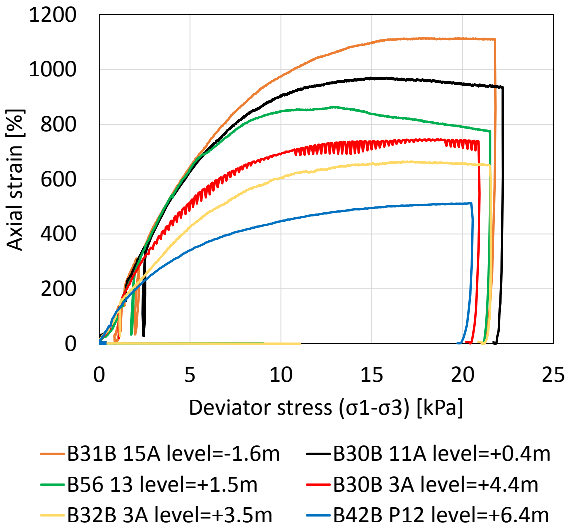

Figure 7: Stress strain curves from CAU tests

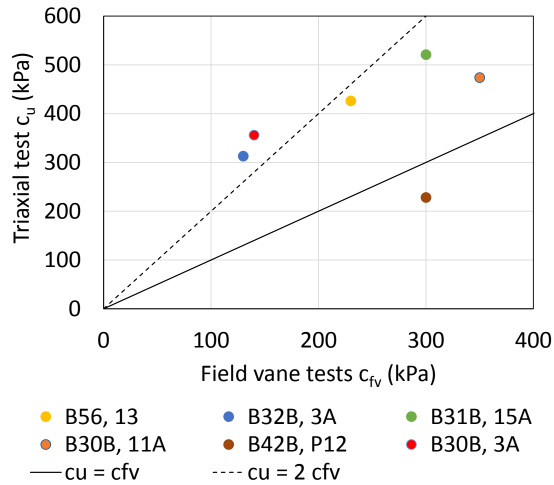

Figure 8: c_{fv} versus c_u from CAU tests

The effective stress path is for the six CAU tests plotted in Figure 9. There is a good agreement between the tests, having more or less the same inclination with a slight parallel displacement, corresponding to different effective cohesions. The two fitted dashed lines presented in Figure 9 corresponds to an effective friction angle of 40° and an effective cohesion of 20 kPa and 75 kPa. The range of effective cohesion represents an lower and upper bound value for the chalk at the NAU site, based on the actual tests (stress levels) and limited fractures in the tested chalk.

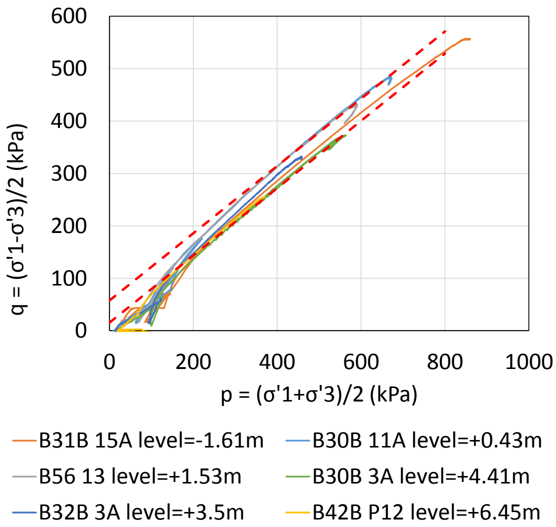

Figure 9: Effective stress path from CAU tests

6 CONSTRUCTION PHASE

Building on chalk includes a number of challenges to be handled during construction, due to the nature of the chalk and the geological processes that the chalk has been subject to:

- Variation in chalk surface
- Erosion, "chimneys"
- Variation in hardening and fractures
- Effects from the elements during construction.

6.1 *Surface of chalk*

The large open excavation for the NAU project made it possible to investigate the variation of the chalk surface. It was observed from the cuts, see. e.g. Figure 10, that the surface can vary significantly with slopes up to 1:1 and changes in level of 4-6 m.

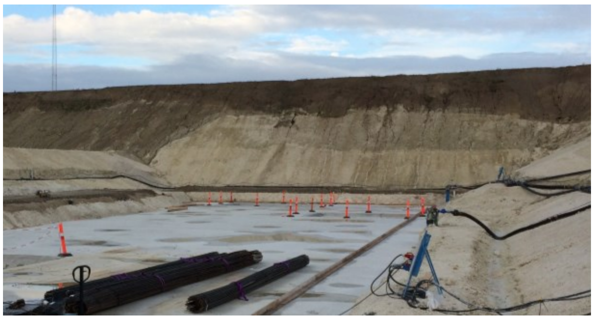

Figure 10: Variation in chalk surface.

6.2 *'Chimneys'*

Over the years surface water has dissolved chalk creating holes filled with loose material with very limited load bearing capacity. This karst phenomenon, also known as 'chimneys', are very frequent at the current site.

The designer requested 'chimneys' excavated and filled with concrete before casting of blinding layer and reinforced concrete.

A situation with 'chimneys' at level +6.5 m can be seen at Figure 11. The foundation area consists of a section with many 'chimneys' (right side of photo) and a section without any chimneys (left side of photo).

Figure 11: Excavations of 'chimneys'

Existing terrain level was for the area shown in Figure 11 at +12.0 m with stratigraphic sequence of 1 m topsoil, 1 m glacial meltwater sand and chalk from +10.0 m. One of the 'chimneys' was measured to 400 mm in diameter and 3.1 m in depth, equivalent to bottom level at +3.4 m or approx. 8.5 m below terrain.

In general, field vane tests indicated lower strength characteristics in areas with chimneys.

6.3 *Variation in strength*

All foundations are inspected by a geotechnical engineer before casting of blinding layer. A part of this inspection is field vane tests. At the deepest basement level, K2 at level +2.95 m to +3.35 m, approx. 2200 test were performed across the area.

The variation in the undrained strengths measured by use of the field vanes are shown in Figure 12. It was possible to measure up to 330 kPa. Strength requirement was set by the designers to 150 kPa.

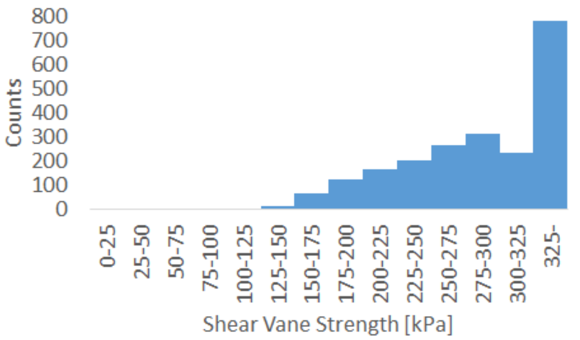

Figure 12: Variation in shear vane strength measured during inspection.

The slab at the deepest basement level has an area of 9000 m² where two small areas, in total 50 m², was replaced with concrete as geotechnical inspection showed unacceptable strength characteristics.

The entire foundation slab was excavated and closed with a blinding layer from 2015-08-10 to 2015-09-02, equal to 18 working days. The small areas with unacceptable strength was costly for the client as it interfered with this high speed and effective construction process.

6.4 *Effects from the elements*

The chalk is sensitive to the combination of water and mechanical processes, which combined easily results in a remoulding of the soil and a significant softening. In addition, the chalk is very sensitive to frost.

To protect the surface of the chalk a blinding layer was cast after excavation and geotechnical inspection.

Foundation work will continue through winter 2016 and therefore risk of frost induced heave will require monitoring and necessary protection of blinding layer. Methodology is measuring of soil temperature and levelling of casted blinding layer. No information is retrieved from this procedure yet.

7 SUMMARY AND LESSON LEARNED

The large excavation substantiated the existing knowledge regarding the possible variation in the surface of the chalk, and showed that slopes up to 1:1 and level variations of 4-6 m can be expected. In addition, significant variation in the distribution and density of chimneys was observed.

The present tests for the NAU project:

- showed that the stiffness of the chalk can be determined from oedometer tests, but it is necessary to be aware of the upper disturbed zone.
- substantiated that $c_u = c_{fv}$ is a reasonable conservative choice.
- showed that an unloading of the chalk results in a reduction of the undrained shear strength by approx. 15 - 35 %.
- documented that the effective friction angle of the chalk may be assessed to φ' = 40° for the NAU project.
- substantiated that the effective cohesion can vary significant and that a value of c' ≥ 20 kPa is representative for the NAU project. The large variation substantiated the necessity of project specific assessments of the effective cohesion.

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