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Strength Properties of Aalborg Clay

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Division of Water and Soil

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by

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Strength Properties of Aalborg Clay

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Aalborg University, June 2010

Abstract

In the northern part of Vendsyssel, Denmark, the deposits made in the late glacial time are formed by the sea. The deposits are named after two mussels: Yoldia clay and Saxicava sand. However, in the southern part of Vendsyssel and in the area of Aalborg the clay and sand deposits from the late glacial time are characterised by the absence of this mussel. These deposits are named Aalborg Clay and Aalborg Sand. In the city of Aalborg, a fill layer superposes Aalborg Clay. This layer is at some places found to be $6m$ thick. This fill layer does not provide sufficient bearing capacity, which has resulted in many damaged buildings in Aalborg. To provide sufficient bearing capacity it is therefore necessary either to remove the fill or to construct the building on piles. Both methods imply that the strength of Aalborg Clay is important for the construction. This paper evaluates the strength of Aalborg Clay by use of triaxial tests from four different locations. Both the drained strength (c' and φ') and the undrained strength (c_u) are assessed through two different methods: one where the strength is assumed to vary with the effective stress and another where the strength is found to be constant.

1 Introduction

In the northern part of Vendsyssel, the soil layers are deposited by the sea in the late glacial time. Vendsyssel is marked with a circle in Fig. 1 and is a part on northern Jutland in Denmark. First, a sand-layer, Lower Saxicava Sand, is deposited, named after the Saxicava mussel. Hereafter, a clay layer named after the Yoldia mussel is deposited. On top of the clay a third layer, Upper Saxicava sand, is found. (Berthelsen, 1987)

In the southern Vendsyssel and in the area of Aalborg the conditions are different from the northern part of Vendsyssel in the way that neither the sand nor the clay layer contains mussels. Further, the sand layers are more sporadic, and the clay is deposited in a more layered structure. The clay deposited in the area of Aalborg is described in this paper. The clay is characterised by the absence of the Yoldia mussel, and the clay type has been given the name Aalborg Clay after the city of Aalborg, Denmark.

In the Middle Age, the first houses were built in Aalborg. At this time the ground surface was placed $1-3m$ above mean water level, and the inhabitants of Aalborg deposited their waste and surplus materials directly on the ground. This implies that the ground surface has been raised with $3-4m$, and in some places of Aalborg the fill layer is found to be $6m$ thick. (Berthelsen, 1987)

These soil conditions are not ideal for foundation of constructions, which has also led to a number of damaged buildings. Even in the Middle Age, wooden piles were used as a foundation. However, these piles were too

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short and too few to establish a proper foundation for the buildings. (Berthelsen, 1987)

Figure 1: Northern part of Jutland, Denmark. Vendsyssel is marked with a circle.

When designing constructions in Aalborg today, Aalborg Clay is often the layer that provides sufficient bearing capacity. Either the fill layer is removed or the building is constructed on piles, which transfer the loads to Aalborg Clay. The strength of Aalborg Clay is described in this paper. A geological description of Aalborg Clay is given together with a description of the environment that prevailed during its formation.

Based on results from triaxial tests both the drained and the undrained strength are defined by two different approaches. The drained strength is first evaluated as being dependent on the stress level to which the triaxial test is conducted. This approach shows that the strength parameters become constants when the stresses exceed a certain limit. The strength parameters are therefore found as constants by use of the MIT-plot (Lade, 2003).

The undrained strength is first found to vary with the insitu stress and the preconsolidation stress according to the SHANSEP formula (Ladd et al., 1977). This evaluation involves many variables, and the undrained strength is therefore found as a constant by averaging the undrained shear strength measured in the triaxial tests.

2 Geological Description

Aalborg Clay is deposited in the late glacial time in the area of Aalborg. The clay is found as deposits of $1-2cm$ clay layers separated by layers of $1-2mm$ fine sand and is a normal consolidated clay.

In the late glacial time, where Aalborg Clay is deposited, the glacier was located in Skagerrak just north of Denmark, cf. Fig. 2. The Aalborg Clay is deposited in the sea southwest of the glacier.

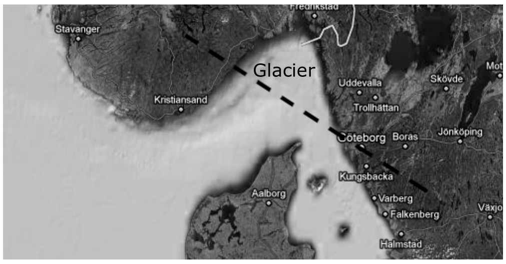

Figure 2: Placement of glacier in the late glacial time.

Clay consists of very small particles with a diameter smaller than $0.002mm$ (Ovesen et al., 2007). Therefore, they only precipitate at very low velocities of the flow. However, if salt is added to the water, the particles of clay will be attracted to one another and the diameter increases. The particles will now be precipitated at higher velocities.

The glacier consists of fresh water while Skagerrak contains salt water. During the summer period, fresh water melts from the glacier and the content of salt in the seawater above Aalborg is lowered, cf. Fig. 3. At this dissolution, the clay particles are not attached to each other. Further, the currents in the sea in the summer time is higher due to the flow from the glacier and the subsequently summer deposits in the Aalborg area contain sand, which forms layers of $1-2mm$. (Stockmarr, 2010)

In the winter period the content of salt is not influenced that much by flow from the glacier, cf. Fig. 3. The salt content is higher and the clay particles are attached to each

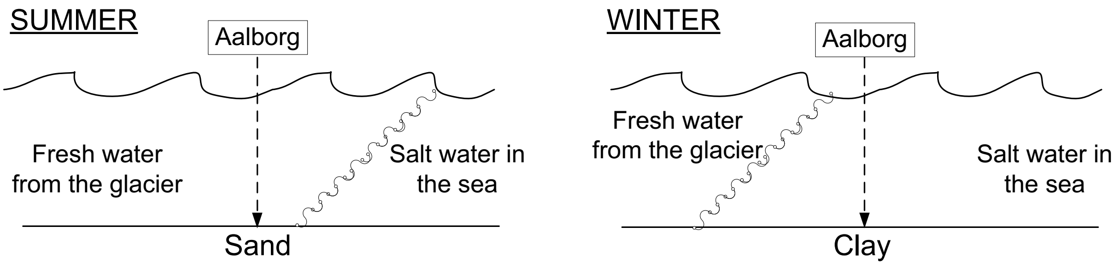

Figure 3: Theoretical placements of the separation of fresh and salt water in the summer and winter periods. (Stockmarr, 2010)

other. Moreover, the current in the sea in the winter time is lower and clay is deposited on the seabed in layers with a thickness of $1-2cm$. (Stockmarr, 2010)

3 Classification

The classification of Aalborg Clay can be seen in Tab. 1. The clay content of Aalborg Clay is found by Luke (1994) to approximately 60%. Further, the silt content is found to approximately 30% and the content of sand is found to 10%.

Table 1: Classification of Aalborg Clay based on the samples from triaxial tests.

	w [%]	γ [kN/m^3]	e [-]	I_p [%]
Minimum	22.4	19.0	0.604	13.3
Maximum	33.6	20.6	0.900	38.9
Average	28.2	19.8	0.758	22.5

The liquid limit is plotted against the plasticity index to classify the clay according to Casagrandes Chart, cf. Fig. 4.

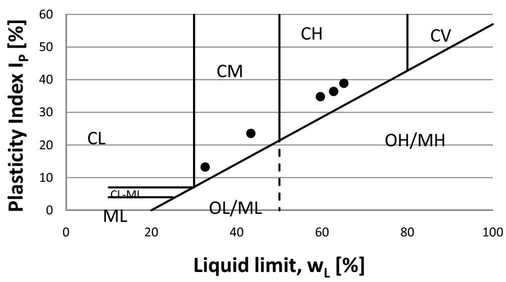

Figure 4: Classification of Aalborg Clay according to the Casagrande Chart. (Ovesen et al., 2007)

Five points are used: two from the Friis project (Ibsen, 2007), and three from Kirsten Lukes PhD (Luke, 1994). According to Ibsen (2007) the clay is classified as medium plastic clay (CM), while it is classified as high plastic clay (CH) according to Luke (1994).

The undrained insitu vane strength is tested in two projects: Ibsen (2007) describes that $c_v = 200\ kPa$, while Geoteknisk Insititut (1985) describes that $c_v = 75\ kPa$.

4 Triaxial Tests

Results from triaxial tests from four projects are collected, cf. Tab. 2. Unfortunately, the tests are not conducted with the same height-diameter ratio and pressure cells; the tests conducted in the 1990s and 2000s have $H = D$ and use smooth pressure cells, and the tests conducted in the 1960s to the 1980s are conducted with $H = 2D$ employing rough pressure cells.

5 Drained Strength

The drained strength of Aalborg Clay can be defined in two ways, i.e. it can be found as constants by use of the MIT-plot, and it can be found to be dependent of the stress level.

The dependency on the stress level is first found for the triaxial tests conducted in 1963, cf. Tab. 2. Here, the drained strength is found to depend on the maximum reached major and minor principal stress in the failure phase. The effective cohesion is found to increase

Table 2: Triaxial tests conducted on Aalborg Clay.

Case / Year	Conducted by / where	No. of tests and failure points	Pressure cells	H / D [mm]
Friis Aalborg Citycenter (Ibsen, 2007)	L.B. Ibsen, AAU	2/4	Smooth	70 / 70
Kirsten Lukes PhD (Luke, 1994)	K. Luke, AAU	1/1	Smooth	70 / 70
Aalborg Harbour (Geoteknisk Insititut, 1985)	PIT, DGI	2/6	Rough	68-82 / 42
Previous triaxial tests (Geoteknisk Institut, 1963)	N/A	NA/5	Rough	H=2D

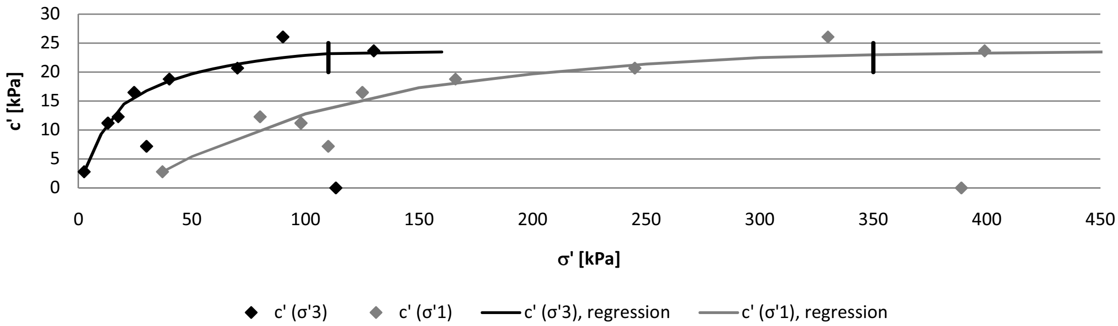

Figure 5: The cohesion as a function of the minor and major principal stress.

until it reaches $23.5kPa$, and the internal angle of friction is found to decrease until it reaches 25.2^{o}.

The results from the other triaxial tests are included in the evaluation of c' and φ', cf. Fig. 5 and 6. Only the first failure phase in multiple triaxial tests is included as these are assumed to match the stress history of the sample better. The results from the triaxial tests from the remaining three projects match what is found previously.

For the interpretation of the cohesion only one test lies far away, cf. Fig. 5, i.e. the one where $c' = 0$. This test is excluded from Fig. 6 as it is assumed that φ' is increased when the results are interpreted to have no effective cohesion.

The results show that for high stress levels, i.e. $\sigma_1' > 350kPa$ and $\sigma_3' > 110kPa$, the effective cohesion should be set to $23.5kPa$ and the internal angle of friction should be chosen as 25.2^{o}.

To find the drained strength as two constants, the failure points are plotted in a MIT-diagram (Lade, 2003).

The data consists of 16 failure points and one outlier will therefore have a great influence on a regression line. Possible outliers are therefore removed, based on the studentised residual. Here, an outlier is characterised as the studentised residual being higher than 3 or lower than -3, and one outlier is detected and removed. The remaining 15 failure points are plotted in the MIT-diagram, and a regression line is fitted to the points, cf. Fig. 7.

The internal angle of friction and the effective cohesion are found from the inclination of the regression line and the intersection of the line with the $(\sigma_1 - \sigma_3)/2$-axis, respectively. Despite of the triaxial tests being conducted under different conditions, the regression coefficient of the line is very high. The correlation between the points is therefore high and they are well described by a straight line. Hence, the results seem credible.

The regression line yields that the internal angle of friction is 28.1^{o} while the effective cohesion is $13kPa$.

6 Undrained Strength

The undrained shear strength generally varies with the insitu stress and the preconsolidation

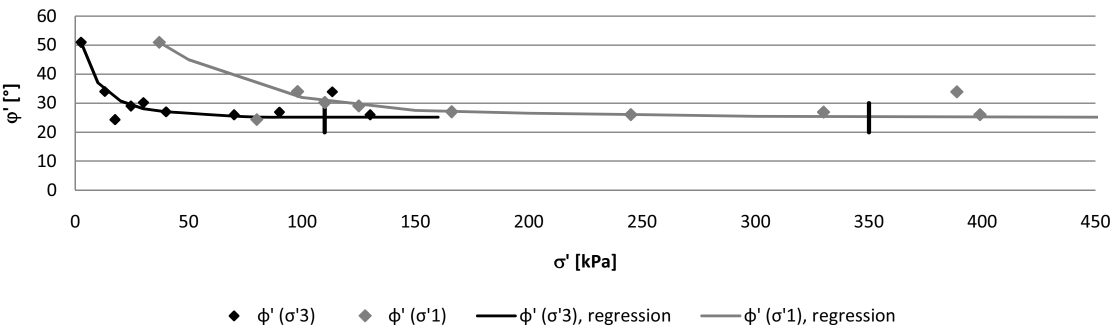

Figure 6: The internal angle of friction as a function of the minor and major principal stress.

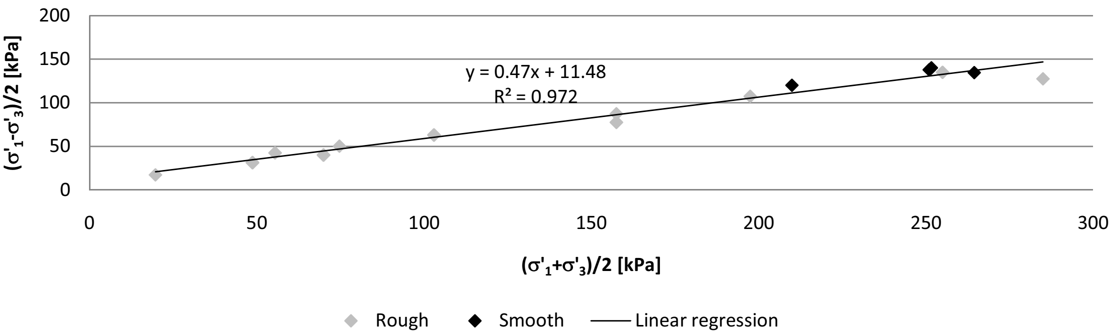

Figure 7: Failure condition in the MIT-plot. 15 failure points are shown in this plot as one point is detected as a statistical outlier.

pressure according to the SHANSEP formula, cf. Eq. 1 (Ladd et al., 1977). This is also found also to be the case for Aalborg Clay.

$$c_u = A \cdot \sigma'_{red} \cdot \left(\frac{\sigma'_{pc}}{\sigma'_{red}}\right)^{\Lambda} \qquad (1)$$

Here, c_u is the undrained shear strength, σ'_{pc} is the preconsolidation pressure σ'_{red} is the lowest effective stress of the soil, and A and Λ are regression constants. Generally, σ'_{red} is set equal to the effective vertical insitu stress.

The results from the triaxial tests are plotted in a diagram, where the right-hand side of Eq. 1 is plotted on the ordinate and c_u on the abscissa. The two coefficients are found by adding a linear regression line to the points and changing the coefficients until the highest regression constant is obtained for a regression line with the equation $y = x$, cf. Fig. 8.

The preconsolidation stress in the laboratory σ'_{pc} is increased by a factor $1/0.85$, as it is normal procedure to consolidate a triaxial test to 80-90 % of the estimated preconsolidation stress in the field. For Aalborg Clay the regression constants are found to $A = 0.446$ and $\Lambda = 0.72$. According to Mayne (1988) values of A should be in the interval $0.25 - 0.55$ when it is found from a CIUC [1] test. If it is found from a CAUC [2] test, the A value should be between $0.2 - 0.45$. Here, the triaxial tests used in the evaluation of Λ consist of both isotropic and anisotropic consolidation, and the found A applies in both intervals. The Λ value should be 0.70 and 0.78 for CIUC and CAUC tests, respectively. The found Λ is between these two values, indicating that both isotropic and anisotropic consolidated tests are used.

However, this definition of the undrained shear strength involves many variables, and another approach is therefore applied: c_u is calculated as the average of the results from the triaxial tests. The average is based on the results from all tests, even though some are

[1] Isotropic consolidation and undrained compression triaxial test

[2] Anisotropic consolidation and undrained compression triaxial test

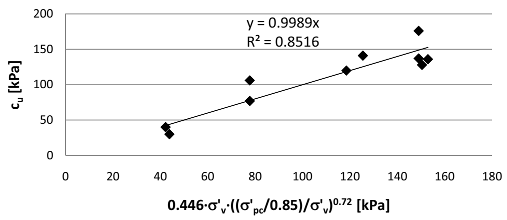

Figure 8: The undrained shear strength as a function of the vertical effective insitu stress and the preconsolidation stress. One outlier is removed according to the studentised resitual method.

conducted at very low stress levels. The average value of c_u is noted in Tab. 3 together with the minimum, maximum, and the characteristic value.

The average value must be converted into a characteristic value, which is done according to Eq. 2 (Banverket and Vägverket, 2009).

$$c_{u,k} = \eta \cdot c_{u,average} \cdot e^{\frac{V_{cu}}{\sqrt{n}}} \qquad (2)$$

Here, η is a reduction factor, which for calculation of stability of walls should be chosen between 0.9 and 1.1 (Banverket and Vägverket, 2009). In this calculation η is set equal to 0.95. The parameter V_{cu} describes the variation coefficient of c_u, which can be set to 15% if nothing else can be proved (Banverket and Vägverket, 2009). The n parameter describes the number of tests included, which here is equal to 16. Hereafter, the characteristic value of the undrained shear strength is calculated to $100.8kPa$.

Table 3: Results on the minimum, maximum and average undrained shear strength from the triaxial tests conducted on Aalborg Clay.

$c_{u,min}$	$19.8kPa$
$c_{u,max}$	$176.0kPa$
$c_{u,average}$	$102.2kPa$
$c_{u,k}$	$100.8kPa$

7 Recommendations on Choice of Strength

Generally, it is recommended to use the drained strength found by the MIT-plot. The plot has shown a credible regression coefficient. Compared to the plots showing c' and φ' as dependent on the stress, the MIT-plot shows a better correlation between the points.

However, if the strength is to be used at a small stress level, it is recommended to apply a strength corresponding to the stress level, cf. Fig. 5 and 6.

For the undrained strength it is recommended to use the expression for c_u found by the SHANSEP formula. This expression provides a more precise description of the strength related to the depth as c_u generally is found to increase with depth. If the undrained strength is used to a draft design, it is recommended to use c_u as a constant. Using the expression found by the SHANSEP formula involves too many unknowns and complicates the calculations unnecessary.

8 Conclusions

The strength of Aalborg Clay has been evaluated in this paper. A set of drained strength parameters is found by two methods: a set where they depend on the stress level and a set where both c' and φ' are constants.

The first method implies that the cohesion increases from $3kPa$ to $23.5kPa$ when the vertical effective stress is increased from $20kPa$ to $400kPa$. The internal angle of friction is found to decrease from just above 50° to 25.2° in the same interval of the vertical effective stress. When the vertical effective stress is increased further, both the cohesion and the internal angle of friction are found to be constants.

The second method evaluates the drained strength as two constants by use of the MIT-plot. The effective cohesion is found to $13kPa$ and the internal angle of friction is found to 28.1°.

The undrained strength is evaluated by means of c_u. First, the strength is found to vary with the vertical effective insitu stress and the preconsolidation stress according to the SHANSEP formula (Ladd et al., 1977). The regression constants are found to $A = 0.446$ and $\Lambda = 0.72$.

This method might involve many variables, and the shear strength is alternatively found by averaging the strength found in the triaxial tests. This implies that the measured undrained shear strength is $102.2kPa$. The characteristic value of the undrained shear strength is calculated to $100.8kPa$.

Bibliography

Banverket and Vägverket (2009). *Tekniska kravdokument Geo*. Vägverket.

Berthelsen, O. (1987). *Geologi i Aalborgområdet*. Danmarks Geologiske Undersøgelse.

Geoteknisk Insititut (1985). *Aalborg. Havnen. Kajudretning mv. Bundforhold. Styrkeparametre mv.* Geoteknisk Institut.

Geoteknisk Institut (1963). *Styrkeparametre for Yoldialer*. Geoteknisk Institut.

Ibsen, L. B. (2007). Triaxialforsøg på Aalborg ler. Internal report.

Ladd, C. C., R. Foott, K. Ishihara, F. Schlosser, and H. G. Poulos (1977). Stress-deformation and strength characteristics. *Proc. 9th Int. Conf. on Soil Mechanics and Foundation Engineering*, 421–494.

Lade, P. V. (2003). *Opførsel og konstitutiv modellering af jord*. Noter for K-8 kursus. Aalborg University.

Luke, K. (1994). *The use of CPT in Danish soils with special emphasis on measuring the undrained shear strength*. Ph. D. thesis, Aalborg University.

Mayne, P. W. (1988). Determining OCR in clays from laboratory strength. *Journal of Geotechnical Engineering 114(1)*.

Ovesen, N. K., L. Fuglsang, and G. Bagge (2007). *Lærebog i Geoteknik* (1 ed.). Polyteknisk Forlag.

Stockmarr, P. (2010, March). *Dannelse af Aalborg Ler*. Personal comminication.

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