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Deformation properties of highly plastic fissured Palaeogene clay – Lack of stress memory?

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ABSTRACT

The geological preconsolidation of the Palaeogene clays in Denmark is estimated to 5-8 MPa or more, whereas laboratory and field experiences indicate values between 100 and 3000 kPa. Presumably, the high plasticity clay loses its memory of earlier preloads due to swelling, or as an effect of fissuring or debonding. Based on a large amount of high quality tests on Palaeogene clay partly encountered at Fehmarn Belt the typical deformational behaviour during unloading and swelling is discussed and evaluated with focus on stress states. K_0-OCR relations are established and the relations are evaluated based on the degree of debonding caused by natural processes insitu as compared to processes induced during severe loading and unloading in laboratory. A long term oedometer test on Lillebælt Clay with a series of loading and unloading cycles was carried out. The test results are used to evaluate deformation properties, and to help explain the large primary and secondary swelling indices measured in Palaeogene clays and how they are related to preconsolidation stress. It is proven that the Palaeogene clay tends to "forget" the preconsolidation stress and the consequence is that OCR is not always a suitable parameter to estimate deformation and strength parameters from, unless additional information on structure of the clay is included. This is not solved yet.

Keywords: Clay, Consolidation, creep, laboratory tests.

1 INTRODUCTION

Strength and deformation properties of clay are by many authors and in many different conditions related to void ratio, e, plasticity index I_P (%), overconsolidation ratio, *OCR,* or preconsolidation stress, σ_{pc} (kPa). Some of them are Burland (1990), Mayne & Kulhawy, (1982), Jaky (1944) and Steenfelt & Foged (1992). Vitone and Cotecchia (2011) studied the influence of fissuring on the mechanical behaviour of clays. They compared natural and reconstituted samples of high plasticity clays, and studied differences between loading and unloading stress paths in oedometer tests. Burland (1990) stated that difference between swelling indices for natural and reconstituted unfissured clays may be indicative of the strength of bonding. Vitone and

Cotecchia (2011) agreed but found that for fissured clays also structure of the samples has an effect. Foged and Baumann (1999) studied Palaeogene high plasticity clay from the Holmehus formation with focus on microstructure and advection and diffusion properties.

In the present study only natural clays are included. All samples are obtained by high quality boring and sampling techniques with a minimum of sample disturbance. Due to high capillary forces the samples are considered intact with respect to the insitu stress conditions. Debonding (meant as significant change of properties) is studied through comparison of samples from tectonically folded and intact formations. Samples subject to several subsequent loading cycles in laboratory are considered to be purposely destructurized as a consequence. Results from the
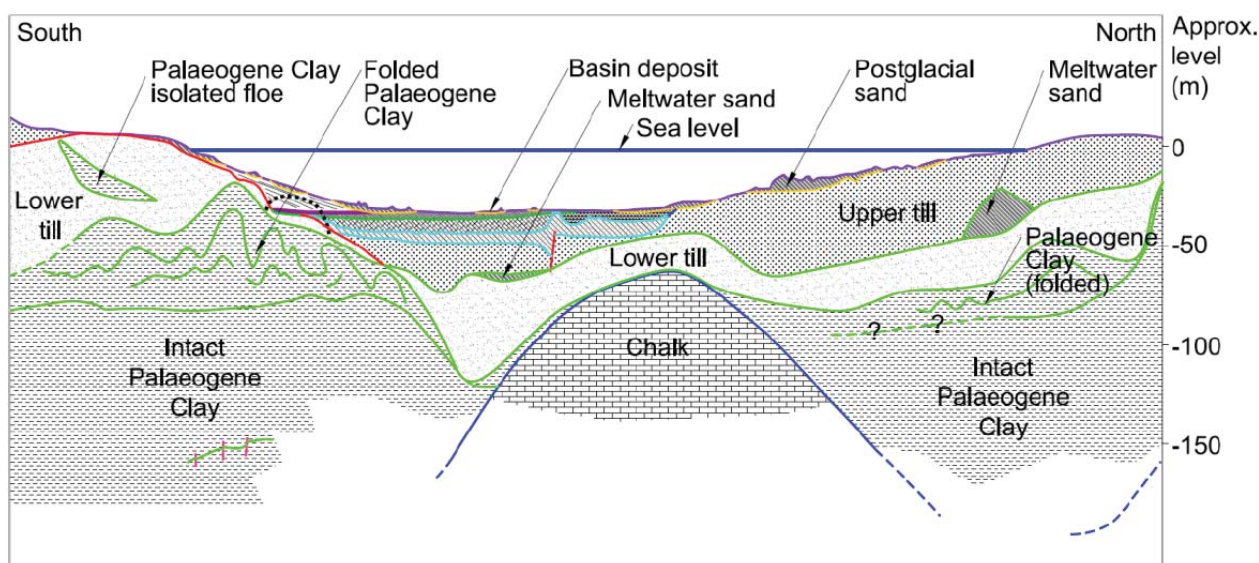
Figure 1 Simplified geological profile across Fehmarn Belt. From GDR 01.3-002.

Fehmarn Belt project are included as well as results from other tests of Palaeogene clay. The geological conditions at the construction area of the Fehmarn Belt Project are summarised in Geotechnical data Report GDR 01.3-002 "Summary of geological conditions" April 2011 prepared by Rambøll Arup (GDR, 2011). They have made up a simplified cross sectional figure (Figure 1) which is used as a frame for describing the geological processes and geological formations in the following. Starting with the youngest formations, the geological units are: Postglacial marine sand and basin deposits of marine gyttja underlain in the basin area by Postglacial / Lateglacial marine freshwater lake / sea deposits. The soft deposits rest on firm to hard Glacial deposits of till and meltwater sand. The hard Upper Till reflects very high preconsolidation as expected for bottom till deposited by Quaternary glaciers. The Lower Till unit may be characterised as highly preconsolidated medium plasticity clay including minor layers / floes of meltwater sand and occurrences of Palaeogene clay being glacially up-trusted floes.

The Palaeogene clay Unit includes high to very high plasticity clay of different geological formations: Lillebælt, Røsnæs, Ølst, Holmehus and Æbelø, (Sheldon, 2010). The upper part of the Palaeogene Unit in the area has generally been heavily folded by ice pressure during the Quaternary. These folded parts are partially destructured due to folding

and weakened due to unloading after ice retreat and later erosion followed by swelling. This causes very variable geotechnical properties from apparently intact to fully weakened clay close to the sea bottom especially in the southern part of the area.

As the Palaeogene clays have a high content of smectite they are very prone to disturbances (Foged and Baumann, 1999). Debonding and weakening due to swelling is consequently of major concern in field tests as well as laboratory tests, carried out to provide design parameters for the construction works.

Future studies will relate to all the Palaeogene formations found at Fehmarn Belt, however here we only cover some studies of Røsnæs Clay (mainly folded) (GIR, 2011), Holmehus Clay and Lillebælt Clay. The test specimens from Lillebælt Clay have been collected from borings at the Old Lillebælt Bridge, but they are biostratifically comparable to the lower Lillebælt Clay found at Fehmarn Belt, (Sheldon, 2010).

2   TEST PROGRAMME

In the Fehmarn Belt project, a very large and high quality experimental programme has been carried out. The tests were carried out for Fehmarn A/S by GEO and Deltares and reported in the Geotechnical Investigation Report, (GIR, 2011), by Rambøll Arup Joint

Venture. Among the tests on Palaeogene clay of various formations are triaxial tests and oedometer tests with incremental loading and measurements of horizontal stress (K_0-IL). Results from these tests will be evaluated in another context and compared with additional test results in the following.

2.1 Experimental methods

The studied oedometer tests were carried out as incremental loading tests. Pore water chemistry was analyzed and artificially pore water with correct salinity and activity was applied in the cells.

Samples in the Fehmarn Belt project had diameters of 60mm and initial heights of 20 mm and were double-sided drained (GIR, 2011). Focus was on K_0 in preconsolidated state. K_0 was measured in a stress path starting typically with loading to the estimated preconsolidation pressure, and subsequent unloading in several steps, in which increasing values of K_0 were measured at increasing *OCR* (GIR, 2011).

The strength parameters obtained from advanced triaxial tests will be used here, but not further discussed.

An additional oedometer test was carried out at DTU, LC#1, being an oedometer test with incremental loading on a sample with diameter of 60 mm and initial height of 30 mm.

The test was carried out on Lillebælt Clay with water content of approximately 40%.

The in-situ stress was σ'_0=170 kPa. Classification parameters for the Lillebælt Clay sample are summarized in Table 1. It can be seen that the in-situ water content was close to the plasticity limit.

The sample LC#1 was loaded in 4 load cycles to 900 kPa and unloaded to various unloading levels. The fourth reloading continued to a maximum stress of 4800 kPa, and then unloaded in a series of steps down to 25 kPa. Every load step was continued for long enough to ensure that primary and secondary effects could be clearly distinguished from each other. In practice that meant load steps with durations of 3-14 days. The longest duration was in unloading steps. In all load steps, the dimensionless time factor T exceeded 2 indicating that primary consolidation was completed.

Table 1 Classification of Lillebælt Clay.

Liquid Limit	w_L	227 %
Plasticity Limit	w_P	44 %
Relative grain density	d_s	2.81

2.2 Interpretation of oedometer test

The main result from the oedometer is void ratio *e* versus vertical effective stress σ'_v. Primary consolidation and swelling is described by the compressibility and swelling indices ($\Delta e/\Delta \log \sigma'_v$), C_c and C_s, respectively. Secondary axial strain index, ε_s (%/log cycle of time), was determined in each load step – always on the part of the time curve for T > 2. The secondary strain index is determined for compression (or creep) with positive values as well as swelling with negative values.

2.3 Preconsolidation stress

For the Palaeogene clay it turns out that we need to distinguish between apparent and factual preconsolidation stress. Apparent preconsolidation stress is the vertical stress level, at which the sample becomes significantly more compressible – corresponding to a yield stress. This is the preconsolidation stress ($\sigma'_{v,pc}$) as interpreted from oedometer tests, irrespective of whether interpretation is based on the method of Casagrande (1936), Akai (1960) or Janbu (1969). The factual preconsolidation stress is the maximum vertical stress the clay has ever experienced ($\sigma'_{v,max}$). For most clay, the factual and the apparent preconsolidation stress are similar, and for these clays it is possible to relate soil properties to overconsolidation ratio, *OCR*, normally defined as (i.e. Mayne & Kulhawy, 1982):

$$OCR = \frac{\sigma'_{v,pc}}{\sigma'_v} \qquad (1)$$

This is not always the case for Palaeogene clays, and the consequences with respect to interpretation of tests are discussed.

3 K₀-STUDY OF FEHMARN BELT SAMPLES

Results from oedometer tests, triaxial tests and classification tests on Palaeogene clay from the Fehmarn Belt experimental programme have been evaluated in a new way with focus on the relations between stress states and deformation properties.

In this part of the study samples of Røsnæs Clay are distinguished from each other by degree of disturbance or debonding. All samples are obtained by high quality sampling techniques, so disturbance caused by sampling and trimming are not an issue. Samples denoted "RC Intact" are obtained from the part of the formation in-situ that is not disturbed by glacial activities or folding. See Figure 1. "RC Folded" denotes samples obtained from the part of the formation that is folded. "RC Folded Destructured" means that the samples are from a folded formation and subsequently exposed to high stresses in the laboratory test followed by unloading to a very low stress. This will on purpose cause a debonding or destructurization of the sample. "RC Swelling" refers to samples that have not been loaded to a high stress in the laboratory, but instead have been allowed to swell, and thus are destructured.

3.1 K₀ – stress paths

Stress paths calculated based on K_0 measurements on samples from Fehmarn Belt project are shown in Figure 2, in which *p'* and *q* are mean effective stress and deviator stress, respectively, based on the measured values of axial (σ_a) and radial stress (σ_r):

$$p' = \tfrac{1}{3}(\sigma_a' + 2\sigma_r')$$
$$q = \sigma_a' - \sigma_r' \tag{2}$$

Friction angle was measured to 19.6° in 58 triaxial tests (GIR, 2011) as an average for samples of Røsnæs Folded, Ølst and Holmehus formations (in an interval 18-22°). The effective cohesion was determined to 14 kPa (in an interval 5-23 kPa). In Figure 2, the Mohr Coulomb (MC) failure criterion based on these properties is plotted with the K_0-stress paths as measured in oedometer tests.

The MC-criterion can here be considered to limit feasible from unfeasible stress states in the sample. High axial stresses, above the apparent preconsolidation stress, may cause debonding in the clay, which could result in a drop in cohesion to almost 0, (Burland, 1990). Therefore the MC-failure criterion with values of c = 0 and c = 14 kPa is plotted for comparison.

From Figure 2 it is clear that many of the samples in the K_0-tests reached stress states very close to the limit of feasible stress states when unloaded to very low stresses in the final part of the tests. The clay was probably subject to debonding, because the radial stress had to decrease in order to keep the sample in a feasible stress state, when the axial stress decreased.
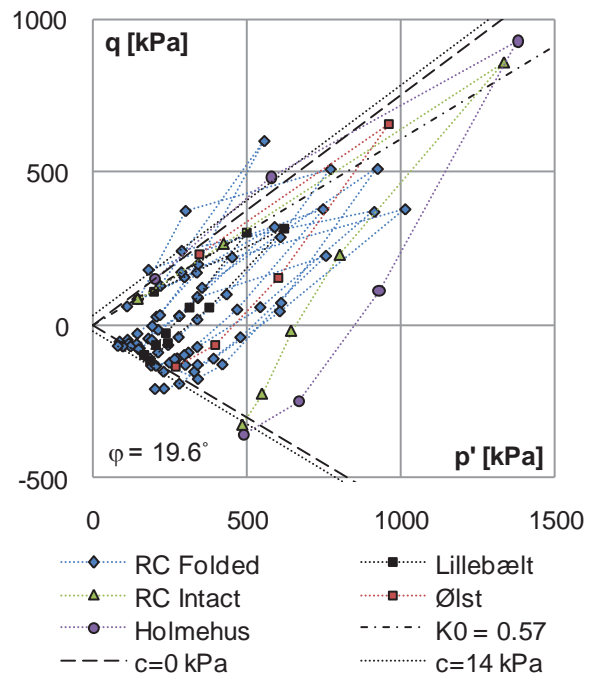

Figure 2 K₀ stress paths from oedometer tests plotted with typical K₀ stress path and MC failure criterion.

3.2 K₀-OCR Relations

Our best fit relation between K_0 and *OCR* for Røsnæs Folded samples are as indicated in Figure 3:

$$K_{0,oc} = K_{0,nc} \cdot OCR^{\alpha} = 0.57 \cdot OCR_{lab}^{0.58} \tag{3}$$

$K_{0,nc}$ is on average 0.57, but with a large variation, as shown in Figure 3. The values differ slightly from the values in GIR (2011), since the number of samples is different. Here, $OCR=OCR_{lab}$ refers to the maximum vertical stress as imposed in the laboratory. Consequently, the limit for how high OCR can be without reaching the limit for feasible stress states, corresponding to shear failure in extension is low. Shear failure corresponding to a friction angle of 19.6° and no cohesion gives a limiting value of $K_{0,max}=2.04$.
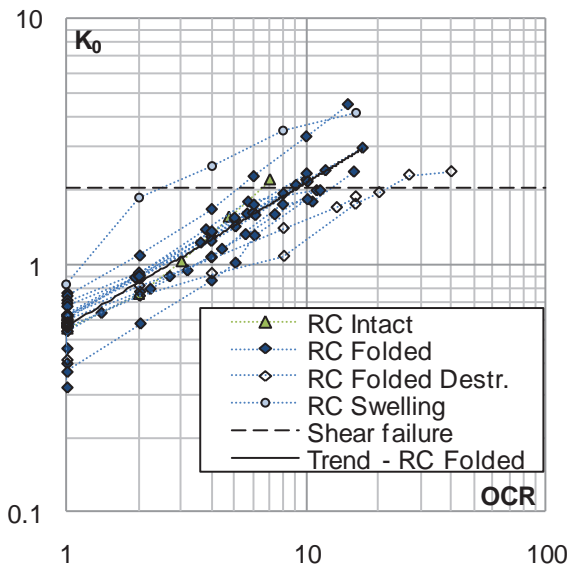

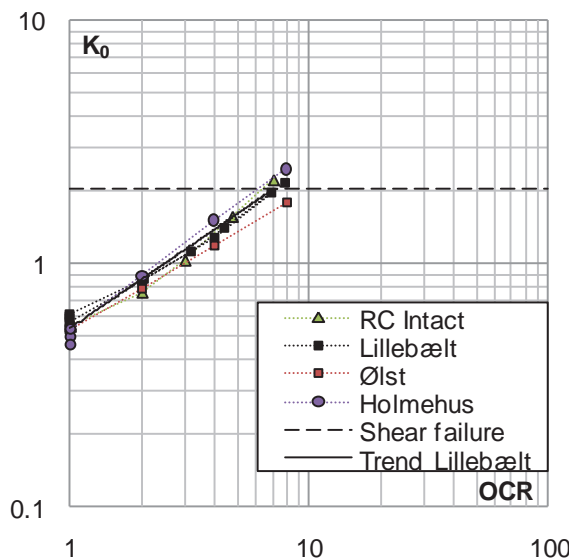*Figure 3 K_0-OCR_{lab} relations for Røsnæs Clay. Tests from GIR (2011).*

Figure 4 K_0-OCR_{lab} relations for other Palaeogene clays. Tests from GIR (2011).

As show in Figures 3 and 4, this implies that (3) is only valid for $OCR_{lab} < 9$, provided cohesion is disregarded, and it is assumed that there is no friction in the oedometer cells. Using the results shown in Figures 3 and 4, it is possible to determine the material constants in (3), for the other types of clay, see Table 2. Lillebælt Clay and Røsnæs Folded have similar properties, and generally intact clays have higher values of α than the folded or destructured samples. N is number of samples.

Table 2 K_0-OCR_{lab} relations for Palaeogene clays according to oedometer tests, (GIR, 2011).

Formation	$K_{0,nc}$	α	N
Røsnæs Folded	*0.57*	*0.58*	*10*
Røsnæs Folded, Destr.	0.56	0.41	2
Røsnæs Folded, Swell.	0.96	0.59	1
Røsnæs Intact	0.54	0.67	1
Lillebælt	*0.58*	*0.60*	*2*
Holmehus	0.51	0.77	1
Ølst	0.53	0.58	1

4 OEDOMETER TEST ON LILLEBÆLT CLAY

The results of the test are summarized in Figures 5-7. The numbers in the figures refer to load cycle. The first is considered to represent the intact Lillebælt Clay, 2nd and 3rd load cycle represent a partly destructurized or debonded sample, and 4th load cycle is considered to completely destructurize the sample due to a high degree of swelling. The load paths are summarized in Table 3.

Table 3 Overview of load cycles, LC#1.

Load cycle	Stress levels (kPa)
1 – Intact	170 – **900** – 340
2 – partly debonded	340 – **900** – 170
3 – debonded	170 – **900** – 85
4 – swelling	85 – **4800** – 25

The stress-void ratio and stress-strain relations in primary and secondary consolidation and swell are plotted in Figure 5. Compression index reach a value of $C_c = 0.349$ on the virgin compression line (Figure 5). Swelling index is $C_s = 0.081$ when determined in the first unloading step from 4800-2400 kPa (Figure 6). It then increases to a level about
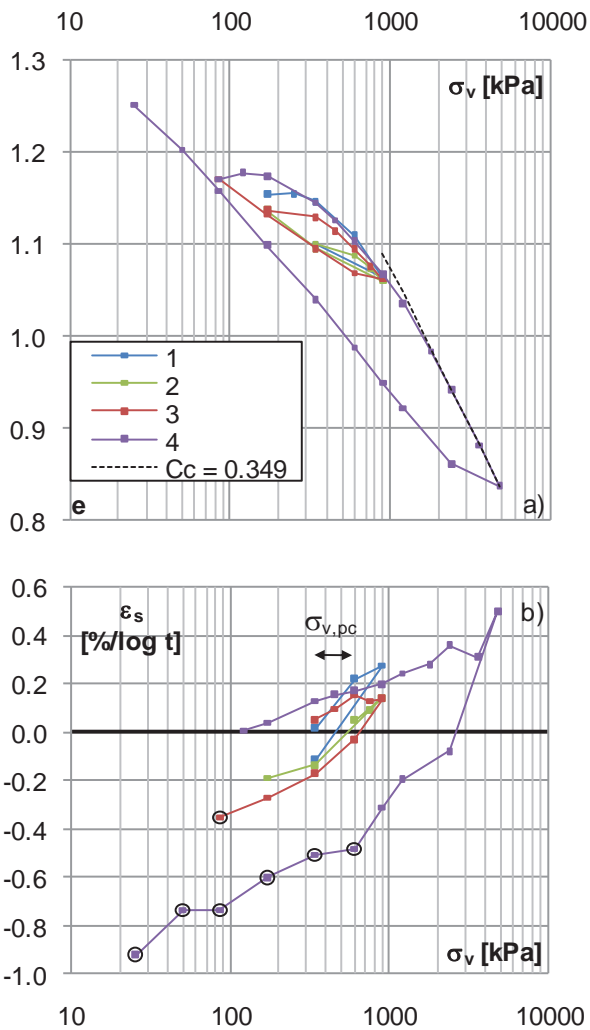
Figure 5 Oedometer test on Lillebælt Clay LC#1. a) Void ratio and b) secondary strain index for the same stress levels. Open circles indicate probable shear failure in extension.
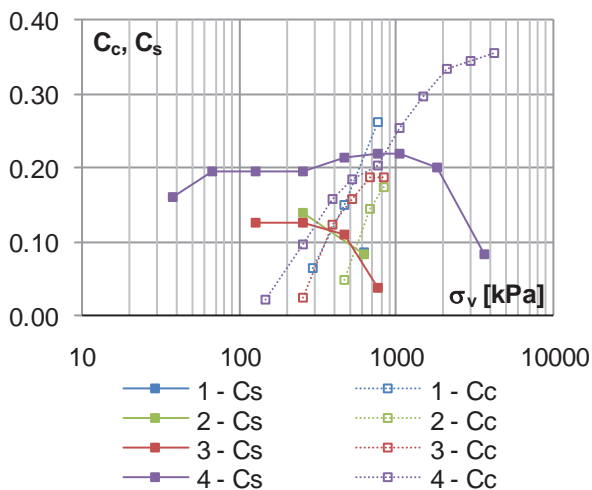

Figure 6 Compression and swelling indices for the 4 load cycles with average stress. Lillebælt Clay LC#1.

0.2, which is significantly higher (factor of 1.5-2) than for the first 3 unloading cycles. The constrained modulus at high stress levels in the 4th load cycle falls on the line corresponding linear dependency between the modulus and the vertical effective stress:

$$E_{oed} = \frac{d\sigma'}{d\varepsilon} = \frac{(1+e_0)\ln 10}{C_c}\sigma' \qquad (4)$$
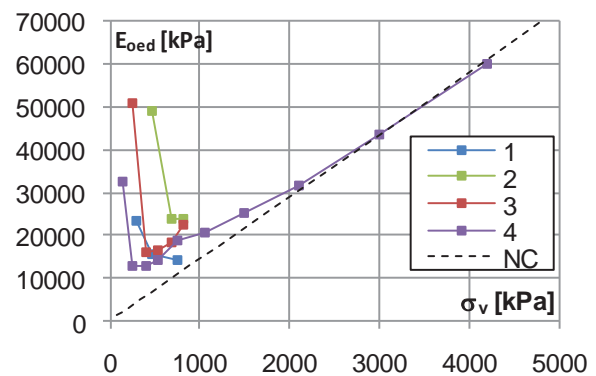
e_0 is the initial void ratio.

Figure 7 Constrained modulus with average stress in each load step. "NC" refers to $C_c=0.349$. Lillebælt Clay LC#1.

4.1 Preconsolidation stress

The in-situ vertical stress for sample LC#1 was 170 kPa. Swelling was prevented for a vertical stress of 250 kPa in the test. If the mean stress in-situ and at swelling pressure in the test are assumed the same, and if it is assumed that $K_{0,nc}$ was 0.58 in the oedometer test as indicated for Lillebælt Clay (Table 2), then it can be deduced that the $K_{0,oc}$ in the in-situ condition was 1.09. The *OCR* was then 2.9 if α is 0.60 (Table 2). This corresponds to an apparent vertical preconsolidation stress of 485 kPa. This value is in good accordance with the interpretation of the oedometer test, no matter which of the applied methods is considered. Figure 5a shows variation of void ratio with stress. Interpretations according to Casagrande (1936) and Akai (1960) imply a preconsolidation stress of 340-600 kPa. Figure 7 shows the constrained modulus, E_{oed} (kPa). Preconsolidation stress according to the method of Janbu (1969) is also 340-600

kPa, when the 1st load cycle is considered. So the apparent *OCR* in the actual depth (21.3 m below sea bed) is in the order of 2-3.5. The constrained modulus is expected to be high in the preconsolidated state and to decline clearly in the load step in which the vertical stress exceeds the preconsolidation stress, (Janbu 1969). The differences between the four load cycles are clearly seen in Figure 7.

The third and fourth load cycles both indicated that the sample did not behave overconsolidated except at low stresses. For each load cycle the preconsolidation stress seems to decline, indicating that the sample was debonded more and more.

4.2 Compression and swelling indices

The swelling indices measured in the fourth unloading indicate that the clay is debonded. A ratio of 1.5-2 between C_s for the 4th load cycle and C_s for the other load cycles is similar to values found by Vitone and Cotecchia (2011) for swelling indices of reconstituted and natural clays, respectively. Since Lillebælt Clay has a very high liquid limit and plasticity index, it is not likely though, that the destructurization reached the same level as for a reconstituted soil. The water content at the end of the test after load cycle no 4 was 47%, which is only slightly above the plastic limit. The destructurization observed in this test must therefore be related to the structure of the clay more than the water content, as it would be for a reconstituted soil.

4.3 Time curves

Secondary axial strain index is generally higher in unloading than in loading, as can be seen from Figure 5b. Especially for the unloading steps with high OCR_{lab} (marked with open circles in Figure 5b) the strain index was very high.

5   DISCUSSION

In the present study K_0 in the unloading stress paths increases to values higher than corresponding to shear failure in extension. The consequence is that if time is available the clay will "forget" about the preconsolidation stress.

In the Fehmarn Belt study (GIR, 2011) K_0 was measured with time. In unloading, K_0 did not always reach a completely steady value. So when values higher than corresponding to failure in extension were actually measured (Figure 3 and 4), it was probably because the swelling process with relaxation of the radial stresses and additional axial strain is slow, and much more time was required in order to reach a feasible stress state.

The secondary strain index for the present study of Lillebælt Clay is very high in unloading, which is probably caused by the fact that the vertical strain includes a part from simple unloading, but also a significant shear strain. If Figure 8 is considered it is clear that the clay has reached a failure state, yielding high secondary strain rates. The dotted blue line refers to the theoretical stress path if the relation (3) is applied, with the parameters $K_{0,nc} = 0.58$ and $\alpha = 0.6$. If the stress states are restricted by the MC failure criterion, the sample would follow a stress path along the failure line instead.
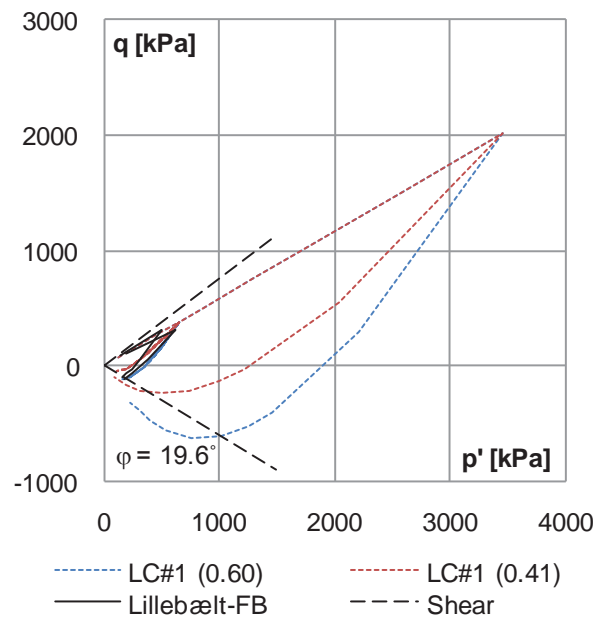

Figure 8 Estimated stress paths for the Lillebælt Clay when theoretical K_0-OCR relation is applied (LC#1). The number in parentheses is α from eq. (3). "Lillebælt-FB" are samples from the Fehmarn Belt project (GIR, 2011).

Load steps in which the shear failure criterion is likely to be exceeded are indicated on Figure 5b with open circles: Vertical stress at

85 kPa in third load cycle, and for maximum of 600 kPa in unloading in the fourth load cycle.

In the Fehmarn Belt study, a significant difference was observed for RC Folded and RC Folded Destructured (Figure 3, and Table 2). The exponent α was significantly lower, indicating that when a sample is loaded to a high vertical stress in the oedometer, the sample becomes destructured or debonded, and a low value of α is found. If that is assumed to happen also for Lillebælt Clay, and a value of $\alpha = 0.41$ is assumed (as RC Folded Destructured) the stress path would instead follow the red line in Figure 8. In this case only the load steps at 170 kPa and lower in the fourth load cycle would exceed the shear failure criterion in extension.

6   CONCLUSIONS

It is concluded that for Palaeogene clays with very high plasticity, *OCR* is not perfect as a state parameter, since significant differences in K_0-*OCR*-relations between Intact, Folded and Destructured samples of Palaeogene clays were seen. Void ratio should be combined with classification of the samples into degree of natural disturbance from folding or uplift, and it should be distinguished from disturbance caused deliberately by experimental stress paths.

Destructurization or debonding during loading in the laboratory to vertical stresses highly above in-situ stress σ'_{0v} and subsequent unloading causes the specimen to lose its stress memory. This should be considered for future testing of highly plastic clays as they are very prone to such debonding. Structure in clay is more than bonding between minerals, but more studies are required in order to find the best way of classifying these clays.

7   ACKNOWLEDGMENTS

8   REFERENCES

Akai, K. (1960). Die Strukturellen Eigenschaften von Schluff, Mitteilungen Heft **22**, Die Technische Hochschule, Aachen.

Burland, J. B. (1990). On the compressibility and shear strength of natural clays. Géotechnique **40**, No. 3, p 329-378.

Casagrande, A. (1936). The determination of the preconsolidation load and its practical significance. Proc. of the 1st ICSMFE. Vol **3**, p60-64, Boston 1936.

Foged, N., Baumann, J., (1999). Clay membrane made of natural high plasticity clay: Leachate migration due to advection and diffusion. Engineering Geology **54**, 1999, p129-137.

Geotechnical Data Report. GDR-01.3-002. Summary of Geological Conditions. Fehmern Sund og Bælt. Prepared by Rambøll Arup Joint Venture. May 2011.

Ground Investigation Report. GDR-00.1-001. Fehmern Sund og Bælt. Prepared by Rambøll Arup Joint Venture. May 2011.

Hansen, J. B. (1961). A model law for simultaneous primary and secondary consolidation. Proc. of 5th ICSMFE, Vol 1, p133, 1961.

ISSMGE, (1999). Incremental loading oedometer test. In: Recommendations of the ISSMGE for geotechnical laboratory testing, ETC5-D1.97. DIN, Beuth 1999.

Jaký, J., (1944). The coefficient of earth pressure at rest. J. Soc. of Hungarian Architcs. and Engrs, Budapest, 355-358.

Janbu, N. (1969). The resistance concept applied to deformation of soils. Proc. of 7th ICSMFE, Vol **1**, p191, Mexico City 1969.

Mayne, P.W., (1988). Determining OCR in clays from Laboratory strength. Journ. Geotech. Engr. Vol **114**, no 1. p 76-92.

Mayne, P.W., Kulhawy, F.H., (1982). K$_0$-OCR relationships in soils. J. Geotech. Engr. Div. Am.Soc. Civ. Engrs. **108**, 851-872.

Sheldon, E. (2010). "Fehmarn Belt Fixed Link Pre-Quaternary Biostratigraphy", GEUS Report 15/12/2010.

Steenfelt, J.S., Foged, N., (1992). Clay till strength – SHANSEP and CSSM. Proceedings from NGM-92. Aalborg, Denmark. DGF Bulletin **9**, vol 1, pp 81-86.

Vitone, C., Cotecchia, F. (2011). The influence of intense fissuring on the mechanical behavior of clays. Géotechnique **61**, No. 12, p1003-1018.