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Characterization in one-dimensional compression of a Danish Paleogene Clay

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Abstract. The North Sea Basin is characterized by the presence of highly plastic, stiff Paleogene clays sedimented between 65.5 and 43 millions of years ago. During the Quaternary Period, this area underwent a series of cyclic glaciations that overconsolidated the underneath clay deposits and sheared the shallower layers. Different studies focusing on these superficial, folded strata are present in literature. On the other hand, less information are available regarding the mechanical behaviour of the deeper, intact layers. However, a good knowledge of these layers mechanical properties is necessary to guarantee an efficient design of the infrastructures built on these formations. This work focusses on the characterization of the Paleogene Røsnæs Clay Formation present in the Fehmarn Belt area, between southern Denmark and northern Germany, where a submerged tunnel will be constructed. The mechanical properties of the Intact Røsnæs Clay layer were determined and compared with those of the Folded Røsnæs Clay. Incremental Load Oedometer tests were performed by applying different load cycles in order to stress the sample below, in correspondence and above the estimated preconsolidation stress. The results were compared with those obtained from testing reconstituted samples in order to assess the influence of structure. This was done quantitatively by analysing the stiffness, the compressibility, and swelling indices. Environmental Scanning Electron Microscope micrographs were used to detect the presence of micro-folding. The mineralogical consistency among the different Oedometer tests was evaluated by means of X-Ray Diffraction. Despite the homogeneity in the mineralogy, differences in both the microstructure and the 1D behaviour of the Folded and Intact layers were observed. In particular, the Folded layers appear to have greater compressibility and swelling potential. These differences should be taken into consideration when building on partially pre-sheared Paleogene formations.

1. Introduction

The characterization of the mechanical behaviour of soil is fundamental when designing a geotechnical construction. The prediction of the soil response to the induced stresses is necessary in order to avoid undesired behaviour or damages and, eventually, failure or collapse of a structure. For this reason the definition of the geotechnical properties of soils has always had a central importance in geotechnical engineering. Fissured, stiff clays are widely spread across Europe, highlighting the need for good knowledge of their geotechnical properties. Several studies aiming to accurately describe the mechanical behaviour of different clay formations are available in the literature. The mechanical properties of stiff, fissured, Paleogene Italian Apennine clays, were intensively studied by Cotecchia et al. [1] and Vitone et al. [2]. It is reported that the presence of fissures strongly influence the mechanical behaviour of the clays, increasing their swelling potential and lowering their sensitivity below one. Gasparre et al. [3], and Hight et al. [4] observed a different behaviour by performing one-dimensional compression tests on the well-known stiff, fissured Paleogene clay formation London Clay. In their studies, the undisturbed samples consistently showed a positive sensitivity. Moreover, the reconstituted curves plotted on different positions, so that a unique Intrinsic Compression Line (ICL) and Intrinsic Swelling Line (ISL) could not be defined in a conventional $e:\log(\sigma'_v)$ plane, which was attributed to the difference in mineralogy. London Clay is located in the North Sea Basin, which is rich in Paleogene clay formations. Several studies ([5],[6],[7]) investigated the compressibility and swelling behaviour of the shallower Paleogene clay formations in Denmark, with particular attention to the Røsnæs Clay, the Lillebælt Clay and the Søvind Marl Formation. The studies show that these formations share common features. In particular, they all present a dependency of their swelling potential on the stress path and a consistent compression behaviour. These soil layers, together with the more superficial strata of Røsnæs Clay, underwent a series of glaciotectonic stresses that led to disturbances both in the soil micro-structure [8] and in its stratigraphic distribution [9].

This paper aims to contribute to the understanding of the behaviour of stiff, intact clays, with particular attention to the formations present along the Fehmarn Belt area, between Germany and Denmark, where a submerged tunnel will be constructed. To do so, a series of 1D compression tests were performed on Intact Røsnæs Clay samples retrieved from this area. In order to guarantee consistency in the mineralogical composition, X-Ray Diffraction (XRD) tests were performed on the powdered samples. The presence of micro-folding was investigated by the use of Environmental Scanning Electron Microscope (ESEM) micrographs obtained on natural samples. Incremental Load Oedometer (ILO) tests were performed on both undisturbed and reconstituted samples. These were performed by applying load cycles that described the sample mechanical characteristics before, in correspondence and above the estimated preconsolidation stress. The mechanical behaviour of the soil was characterized and compared with the data obtained from the literature. Moreover, a comparison between the mechanical characteristics of undisturbed and reconstituted soil was performed, in order to quantify the influence of structure.

2. Geological description of the tested material

Paleogene Formations sedimented between 65.5 and 23 millions (Ma) years ago, during the Paleogene Period. This is subdivided in three Epochs named Paleocene (66-55 Ma), Eocene (56-33.9 Ma) and Oligocene (33.9-23 Ma). The North Sea Basin started developing during the Early Cretaceous ([10]) as a consequence of the thermally induced subsidence caused by the tectonic activity of the area. During the Paleogene Era, the North Sea Basin underwent a series of local, cyclic sea level variations [11]; leading to a change in the depositional environment and, thus, in the particle size distribution of the sedimented soils. The Late Paleocene and the Early Eocene were characterized by highly stable marine conditions and great abundance of sediments; primarily supplied by the intense volcanic activity of that period. During the Quaternary Era, the North-East area of Europe underwent a series of glaciations. The Elsterian (500-300 ka) and Saalian (300 ka-128 ka) thick ice layers covered entirely the eastern North Sea together with northern Germany and the Netherlands [12]. The following glaciation period (Weichselian, 150 ka-11.7 ka) did not reach the same extension. In particular, the glaciers did not cover continuously the southern part of the North Sea Basin. Here the ice sheets cyclically melted and froze, stressing the underneath Paleogene and Neogene Formations and causing a series of glaciotectonic deformations that can be observed from a microscopic [8] to a kilometric [9] scale, till 200 m depth.

Denmark is part of the outer geomorphic zone of the glaciotectonic phenomena that influenced the North Sea Basin area during the Weichselian glaciation [9]. Here, the glaciotectonic activity strongly sheared the shallower Paleogene Formations, known as Søvind Marl and Lillebælt Clay. The following Formation, called Røsnæs Clay, was only partially deformed by the glacier movements. Therefore, only its shallower strata underwent shearing resulting in a “Folded” structure, while the deeper strata remained unaltered, preserving their “Intact” structure.

The Røsnæs Clay Formation deposited in the North Sea Basin during the Early Eocene at the same time as the London Clay and the Ieper (or Ypres) Clay Formations, which can be found in England and Belgium, respectively. These formations sedimented materials having a common origin, and experienced a similar stress history, due to the glacial movements occurred during the Quaternary. Therefore, they share some physical and mechanical properties. According to Heilmann-Clausen et al. [13] the Røsnæs Clay Formation shows the presence of 7 depositional members having different geological history and mineralogical composition. Awadalkarim [14] characterized the soil composition of the same borehole used from the current study, from 19 to 113 meters depth, including both Folded and Intact layers. He found the Røsnæs Clay Formation to have a smectite content of 15-55%, an illite content of 30-55% and a kaolinite content of 10-35% of the total dry weight. The variation of the clay content with depth did not highlight the presence of any distributional pattern.

For this study, 100 mm rotary-cored Røsnæs Clay samples retrieved in the Fehmarn Belt area and obtained from two different boreholes were tested. The specimens obtained from Borehole_1 were retrieved from 59.5 m depth and present a Folded structure, while those from Borehole_2 are Intact and were sampled at 93.0 m depth.

3. Methodology

A series of ILO tests were performed on reconstituted and undisturbed Røsnæs Clay samples. The load steps had a minimum duration of 8 hours and terminated only after the sample reached full consolidation as per the Casagrande construction (ASTM D2435-04). For the current study, three different ILO setups were used. The first setup (S1) consists of a 60 mm diameter and 20 mm height floating ring, the second (S2) of a 50 mm diameter and 15 mm height fixed ring with incorporated cutting ring and the third (S3) of a 30 mm diameter and 10 mm height floating ring, also with incorporated cutting ring. Small diameter rings were needed in order to reach stresses higher than the preconsolidation stress of the Røsnæs Clay Formation. This was estimated, according to the geological history of the area, to be approximately 5-8 MPa [5]. The Reconstituted (R) samples were tested in the S1 ILO setup. The remoulding process was performed by wetting the trimmings obtained from the preparation of the undisturbed samples and by thoroughly mixing them with the use of a spatula, in order to dissolve any lump. The trimmings were first rehydrated to the in situ water content by adding deionized water, in order to keep the salt concentration in the soil unaltered. Afterwards, a synthetic saline water reproducing the one naturally contained in the Røsnæs Clay was added until a water content equal to 1.5 the liquid limit was reached, as per Burland [15]. The design of the saline water was performed by the Geological Survey of Denmark and Greenland (GEUS). The Undisturbed (U) samples were trimmed in cutting rings by means of a cutter knife. For samples tested in S1 ILO setup the soil was extruded from the cutting ring into the testing ring, while the cutting ring was installed directly in the oedometer cell for setup S2 and S3. After the specimen was installed into the oedometer cell, the bath was filled with synthetic saline water and left in contact with the sample for 24-48 hours, in order to allow its full saturation. During this phase, the ILO loading arm was kept fixed in order to avoid any volumetric deformation of the specimen. After the saturation was completed, the loading arm was released and the swelling pressure of the sample was determined by adding small load increments until compressive deformation was observed.

Table 1 summarises the physical properties of the tested samples. The used code is Rø_σ_1_ σ_2_Set where Rø indicates whether the sample comes from a Folded (F) or Intact (I) Røsnæs Clay layer, σ_1 is the maximum stress applied during the ILO test (MPa), σ_2 is the stress applied just before ending the ILO test (MPa), Set is the ILO setup used for the test as described previously.

The presence of micro-foldings was investigated using an Environmental Scanning Electron Microscope (ESEM). Specimens of undisturbed sample were collected and split in order to generate a fresh fracture perpendicular to the sedimentation planes. The single specimen was installed on a Peltier stage, having a temperature of 4°C, and left there for 2 minutes. This time was estimated to be sufficient to let the sample reach thermal equilibrium with the stage and at the same time small enough to avoid any significant water evaporation. The micrographs were obtained with a spot opening of 3.0-3.9, at a working distance of 8-10 mm and with an electric potential difference of 12-20 kV. The pressure was kept constant at 812 Pa, in order to induce a humidity of 99.9% on surfaces having a temperature of 4°C.

The mineralogy of the clay samples was investigated by the use of X-Ray Diffraction (XRD). Trimmings from the preparation of the ILO undisturbed samples were collected, air dried, grinded and tested, in order to obtain a bulk sample spectrum. Afterwards, the <45 μm soil fraction was sieved and the passing fraction was prepared as per Moor and Raynolds [16], following a glass dropped (GD) and a vacuum (V) preparation method. The samples prepared with the former technique were analysed using a semi-quantitative analysis (error = ±25%) while the latter, thanks to the higher quality of the sample preparation, were interpreted with a quantitative method (error = ±3%).

Tab.1. Summary of the physical properties and test conditions of the tested samples.

	F_2_0.6_S1	F_2_2_S1	F_7_0.4_S2	I_2_0.6_S3	I_7_0.6_S3	I_20_0.6_S3
e_0	1.01	1.01	1.05	0.96	1.00	0.96
w_0	33.7	33.7	34.3	32	32.6	32.8
z [m]	59.42	59.46	59.50	92.97	92.97	93.00
$\sigma_v'_{max}$ [MPa]	2	2	7	2	7	20
$\sigma_v'_{final}$ [MPa]	0.6	2	0.4	0.6	0.6	0.6
w_L	106	104	104	123	123	123
w_P	43	37	37	40	40	40
G_s	2.85	2.91	2.85	2.8	2.8	2.8

e_o, initial void ratio
w_o, initial water content
z, depth at which the samples were retrieved.
$\sigma_v'_{max}$ maximum stress applied during the ILO tests
$\sigma_v'_{final}$ stress applied before the ending of the ILO tests
w_L liquid limit
w_P plastic limit
G_s specific gravity

4. Results and discussion

Tab.2. Summary of the samples mineralogy. * designates results obtained from glass drop sample preparation.

	Borehole 1 – Folded samples	Borehole 2 – Intact sample
Clay minerals	62%	62 %
- Smectite	13%*	14%
- Illite	35%*	19%
- Kaolinite	14%*	29%
Quartz	13%	19%
Magnesium calcite	5%	4%
Potassium Feldspar	4%	3%
Plagioclase	0%	2%
Rhodocrocite	4%	4%
Hematite	7%	3%
Siderite	1%	2%
Anhydrite	2%	0%
Iron	2%	0%

XRD tests were performed on specimens obtained from the ILO Undisturbed samples, every 30 mm depth. The variation of the mineralogy with depth was negligible, with less than ±4% deviation for each detected mineral. Therefore, the mineralogical composition of the single boreholes instead of that of the single samples is presented in Table 2. The clay particle fraction of the Folded layer was investigated by testing glass dropped prepared samples, while the Intact layer was analysed using both the glass dropped and the vacuum preparation method. Quantitative analysis (error = ±3%) were performed on the Borehole_2 V samples, while semi-quantitative analysis (error = ±25%) were performed on the Borehole_1 and Borehole_2 GD samples. A high quality, direct comparison of the mineralogy of the Folded and Intact layer is not possible, as no V samples were available from Borehole_1. However, it was possible to compare the patterns obtained from GD samples obtained from Borehole_1 and Borehole_2 (figure 1). The XRD patterns of the two samples are almost identical. Therefore, it is possible to conclude that the two boreholes show a highly similar mineralogy. It must be stressed that, because of the poor repeatability of the glass drop method, this kind of comparison does not guarantee a perfect correspondence of the clay minerals abundance in the two samples. However, it is sufficient to assess that no significant variation can be observed among the clay fraction of the two boreholes. For these reasons, the clay minerals quantification of Borehole_1 is considered to be reasonably similar to that of Borehole_2. Therefore, the mass percentages obtained from the clay particle fraction of Borehole_1 are included, but not taken into consideration for the discussion of the results.

Figure 2 shows two micrographs obtained from undisturbed samples from both the boreholes, imaged at the ESEM. As the samples were fractured perpendicularly to the sedimentation planes, the image shows the sedimentation layers. Figure 2.a was taken from Borehole_1, while figure 2.b from Borehole_2. A series of micro-foldings can be observed in figure 2.a. In particular, the sedimentation planes were compressed along the horizontal direction, causing their folding. A series of parallel sedimentation planes can be observed in figure 2.b. Here, no shear action occurred, so that the clay micro structure shows a series of unaltered sedimentation planes, parallel to each other. These observations are consistent with the geological characterization of the two samples.

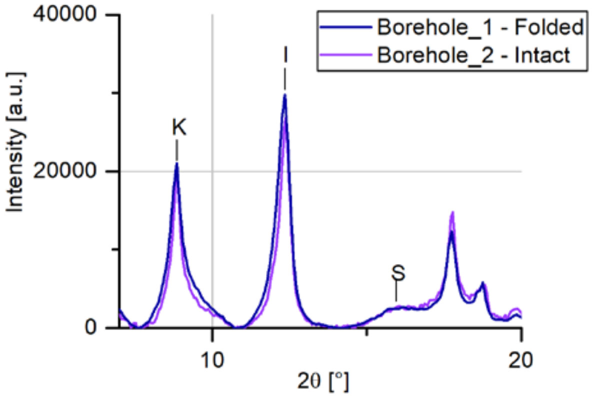

Fig.1. XRD patterns of Borehole_1 and Borehole_2 fine fraction GD samples

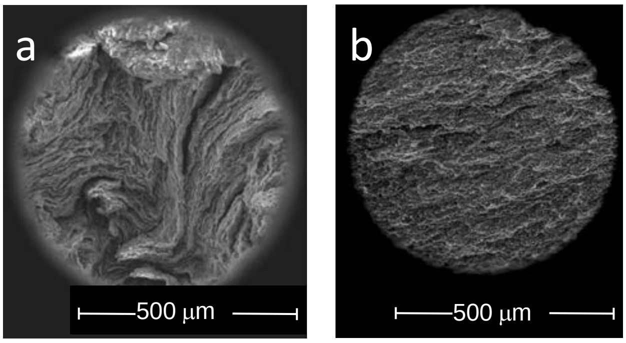

Fig. 2. SEM Micrographs obtained from undisturbed samples of a) Folded [17] and b) Intact samples at low magnification.

ILO tests were performed on both Folded and Intact samples. A precise assessment of the position of the compression curves is fundamental in order to determine the sample sensitivity and, thus, the structure effects on the undisturbed clay specimens [15]. Major effort was put in the reliable determination of the initial void ratio, in order to reduce the error in the position of the curves. This was calculated using 5 independent formulations [18] and the mean value was designated as e_0. Figure 3 shows a set of ILO tests, obtained by stressing up to 7 MPa samples retrieved at different depths of Borehole_2. The samples had similar mineralogy, in situ stress and they were tested to the same stress path in order to evaluate the repeatability. The average scatter in the position of the curves evaluated at all stress levels was equal to $\Delta e = \pm 0.03$. This was considered a reasonably small error, hence a good description of the sample sensitivity could be achieved.

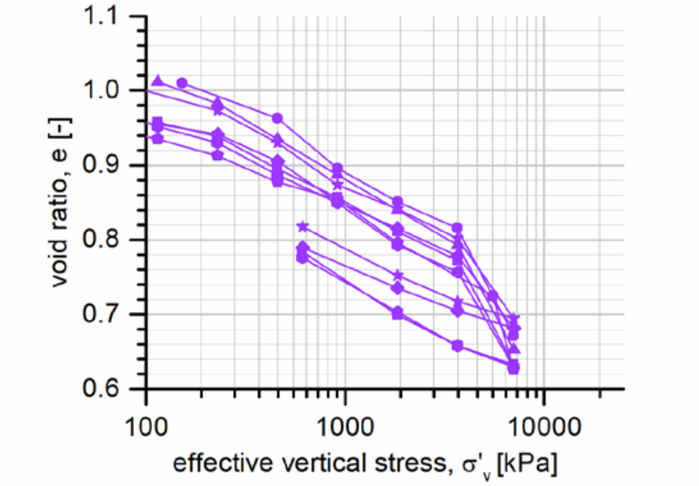

Fig.3. Repeatability of the test results based on ILO curves from Borehole_2, Intact samples.

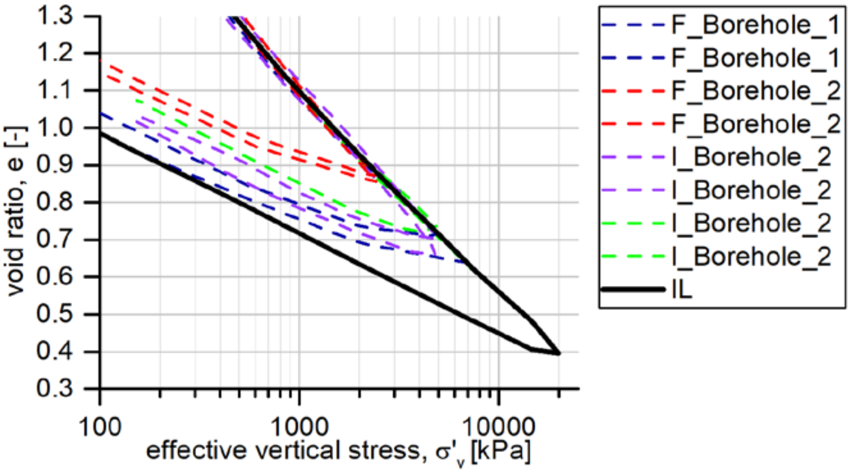

Fig.4. IL definition for the Røsnæs Clay Formation. The IL is defined on 8 reconstituted tests.

Different ILO Reconstituted tests were performed on samples retrieved from Borehole_1 and Borehole_2 at different depths (figure 4). The samples showed a common mineralogy and the ILO reconstituted curves a similar compressional and swelling behaviour. Therefore, it was possible to define a unique ICL for the two samples, but not a unique ISL in agreement with Hight et al. [4]. The swelling curves become parallel only after the friction effect due to the loading reversal is overcome, i.e. between half and a quarter of the maximum stress the sample underwent. Nevertheless, an ISL was defined, in order to have a reference IL for the discussion that follows. It may be noted that the mechanical behaviour of the Intact and Folded reconstituted samples does not show any significant difference. This is in accordance with the hypothesis that the remoulding process causes a complete destructuration of the clay, erasing the influence of the shear stress experienced by the Folded strata [15].

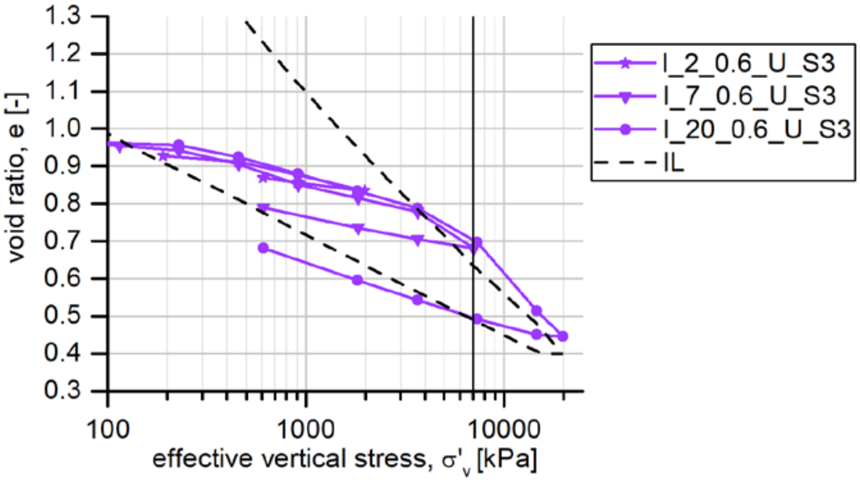

Fig.5. ILO curves from Borehole_2, Intact samples – stress path comparison

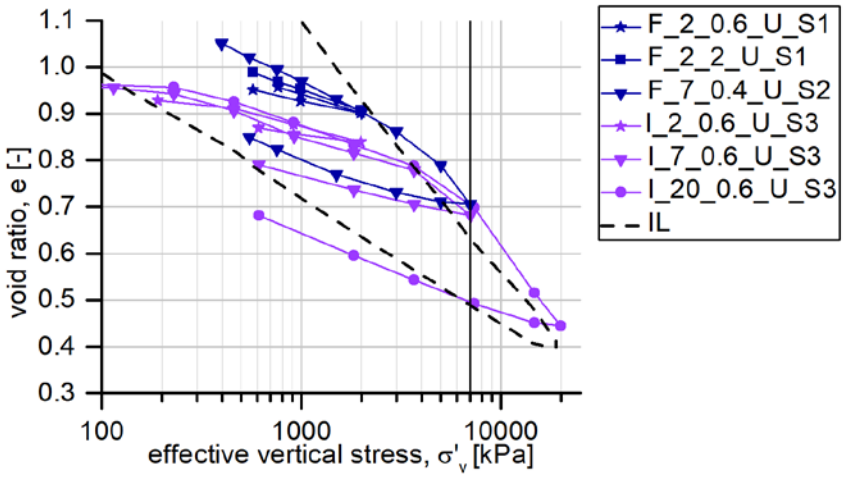

Fig.6. ILO curves from Borehole_1, Folded samples and Borehole_2, Intact samples – stress path comparison

Figure 5 shows a selection of ILO tests performed on Intact Røsnæs Clay. The samples were stressed to 2, 7 and 20 MPa in order to reach stresses lower, equal and greater than the preconsolidation stress. This was estimated to be equal to 7 MPa using the Casagrande construction. Samples having a small depth difference (92.97 and 93.00 m depth) were chosen in order to reduce the possibility of changes in mineralogy or particle size distribution. The curves show a good consistency, with small scatters and a common compression behaviour at the same stress level. The position of the reconstituted curve suggests a positive sensitivity of the sample. This hypothesis is reinforced by the fact that the undisturbed curve becomes parallel to the ICL only after 15 MPa, a stress that is double the preconsolidation one. However, the undisturbed samples never reach the ICL, as per Gasparre et al. [3]. Also in this case, the remoulding action concurred to destructurate the soil micro structure in a more effective way than the one-dimensional compression.

Figure 6 plots a comparison of ILO tests performed on samples obtained from the Intact and the Folded layer. The initial void ratio of the Folded samples is larger than that of the Intact samples, probably due to their lower in situ stress. The curves develop on different paths until the preconsolidation stress (7MPa) is reached. Here, the two sets of curves converge. It may be noted that the Compression

Index (C_c) of the 5-7 MPa part of F_7_0.4_S2 is similar to that of the 7-20 part of I_20_0.6_S3. This can be better appreciated by looking at figure 7.

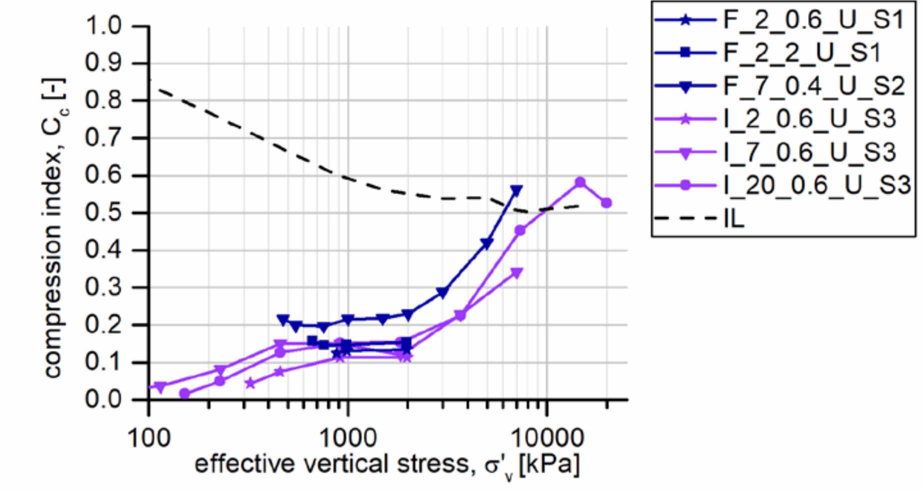

Fig.7. C_c variation with vertical effective stress from Borehole_1, Folded samples and Borehole_2, Intact samples

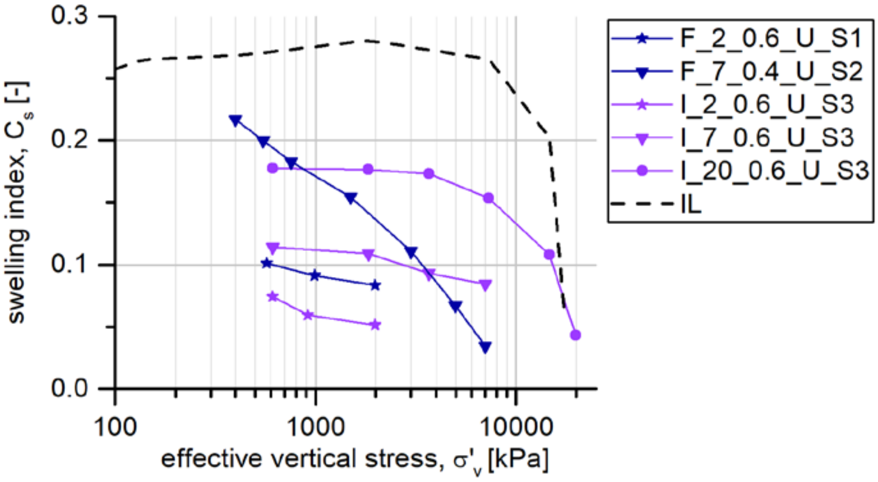

Fig.8. C_s variation with vertical effective stress from Borehole_1, Folded samples and Borehole_2, Intact samples

Figure 7 illustrates the variation of the soil Compression Index with the stress levels, using forward differentiation scheme. The Folded samples stressed up to 2 MPa present C_c values similar to those obtained from the tests on the Intact samples. On the other hand, F_7_0.4_S2 shows a higher compressibility than the Intact samples. This is in accordance with the hypothesis of shear destructuration experienced by the Folded Røsnæs Clay. Regardless their stress history, all the samples show an increase in C_c after 2 MPa. This behaviour was observed in another Danish Paleogene Clay called Lillebælt Clay [7]. Although the curves show a similar pattern, those from Krogsbøll et al. [7] on Lillebælt clay attain a higher slope and thus a higher compressibility variation than those plotted in figure 7.

Figure 8 presents the variation of the Swelling Indexes at different stress levels. It may be noted that all the tests except for F_7_0.4_S2 show a tendency to display small C_s variation for stresses lower than the preconsolidation stress (7 MPa). Moreover, both the tests performed on Folded samples show a higher swelling potential. This is in accordance with the hypothesis that they underwent a strong shear action that destructured the clay microstructure, allowing for a greater swelling surface and thus potential. Cotecchia et al. [1] observed a similar behaviour by comparing fissured and intact samples.

They found that the fissured samples, having a higher swelling area, showed a higher swelling potential than those intact. In accordance with the swelling behaviour of other Danish Paleogene clays, greater C_s values are recorded when the samples swelled from higher stresses [5,6,7]. The C_s variations in figure 8 depict a common pattern with those obtained by Krogsbøll et al. [7], in particular showing a constant, maximum value equal to 0.2 for the samples stressed at higher stresses and a lower maximum value for samples stressed at 2 MPa. The reconstituted sample increase its C_s to stabilize at a constant value of 0.26 after 2 MPa.

The oedometric stiffness (M) variation with the vertical effective stress for both samples obtained from Borehole_1 and Borehole_2 is shown in figure 9. It may be noted that the Intact samples show a stiffness higher than the Folded samples. Moreover, all the tests stiffness convergence at around 6 MPa, in correspondence of the estimated preconsolidation stress and stays constant until 15 MPa stresses are reached. Above this value, the compressibility of the soil decreases as the soil void ratio gets close to the minimum geometrical void ratio admissible for the soil. It is possible to compare the values plotted in figure 9 with those obtained by Rocchi et al. [5], Grønbech et al. [6] and Krogsbøll et al. [7]. The results of Rocchi et al. [5] are well comparable with those in figure 9 as the curves show a similar position and pattern, with an increase of the M values towards higher stress levels and a maximum stiffness value of about 50 MPa at 2 MPa stress. A similar behaviour, but for higher stresses, is observed in Grønbech et al. [6]. The reported M values show a small variation, between 60 and 80 MPa, in the interval between 2 and 10 MPa. Afterwards, an increase of stiffness that reaches about 200 MPa at 20 MPa stress is observed. The results obtained from Krogsbøll et al. [7] show a linear increase of the M values with the stress increase. This is observed also in figure 9.

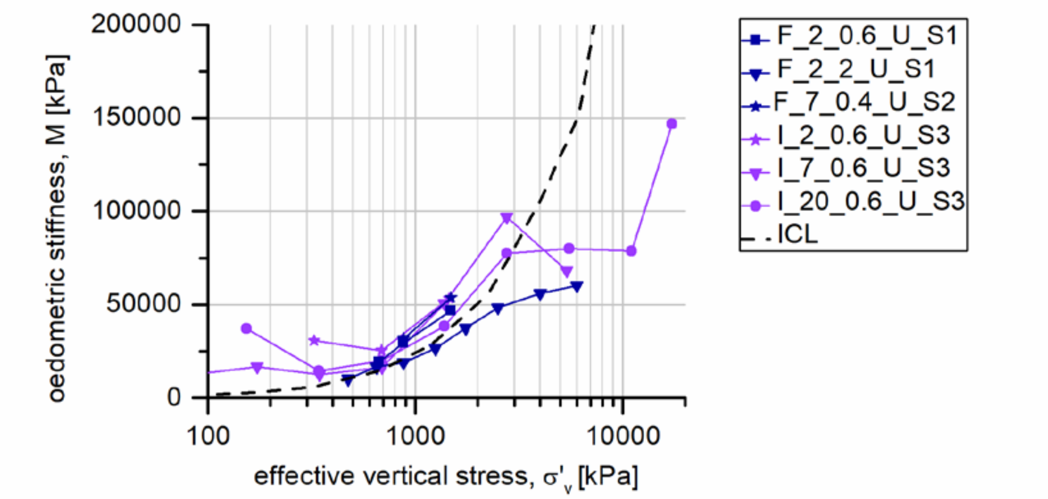

Fig.9. M variation with vertical effective stress from Borehole_1, Folded samples and Borehole_2, Intact samples

5. Conclusions

Samples retrieved from Intact and Folded layers of a Paleogene, highly plastic, fine grained, fissured clay named Røsnæs Clay were tested under 1D conditions, in order to assess the difference in their mechanical behaviour. This was done on samples retrieved from the Fehmarn Belt, the area where a submerged tunnel will be constructed. Moreover, by comparing the mechanical properties of the two layers, it is possible to quantify the influence of the pre-shearing glacial action on their mechanical behaviour. The ESEM micrographs confirmed the presence of a different microstructure for the two clay layers, showing sheared depositional beds for the Folded samples and even, parallel depositional beds for the Intact samples. Moreover, the 1D tests performed on Folded samples, showed a higher compressibility and a higher swelling potential than those performed on the Intact ones. Furthermore, the oedometric stiffness of the undisturbed samples tends to become uniform for the different boreholes when the preconsolidation stress (7 MPa) is reached. The swelling behaviour of the Intact samples is consistent, showing low C_s variation with vertical effective stress below 7 MPa. However, the Folded samples show a greater variation of the swelling potential. These differences in the 1D behaviour, should be taken into consideration for optimized design of the infrastructures built above partially pre-sheared, overconsolidated, stiff Paleogene clays.

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