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Cyclic DSS response of Danish Neogene clays

Réaction des cisaillement simple direct (DSS) cyclique d'argiles danoises néogènes

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ABSTRACT: Data presented herein are mainly obtained from the Danish Nearshore Windfarm project owned by Vattenfall Vindkraft A/S to be built in the Danish sector of the North Sea, near the west coast of Denmark. A total of 7 DSS and 18 DSScy tests have been conducted on Neogene clay, complemented by classification testing including Atterberg limits carried out on trimmings from the tested specimens. The goal of the testing was establishing the appropriate cyclic contour diagrams. The set of the reference contours included Drammen clay, Lower till and Folded Røsnæs clay. Overconsolidation ratio of tested specimens is in the range of about 5 to 15. Cyclic testing was carried out at a frequency of 0.1 Hz for up to 5000 cycles, with variable combinations of average and cyclic shear stress ratios. The overall test results agree well with the proposed references and depict the stipulated influence of the plasticity on the cyclic strength of the clay, with higher plasticity resulting in higher strength.

RÉSUMÉ: Les données présentées ici proviennent principalement du projet danois d'éoliennes Nearshore, appartenant à Vattenfall Vindkraft A / S, qui doit être construit dans le secteur danois de la mer du Nord, près de la côte ouest du Danemark. Un total de 7 tests DSS et 18 tests DSScy ont été réalisés sur l'argile Neogene, complétés par des tests de classification incluant les limites d'Atterberg effectuées sur les retailles de spécimens testés. Le but de l’essai était d’établir les diagrammes de profil cycliques adéquates. L’ensemble des profils de référence comprenait l’argile de Drammen, l’argile du till inférieur et l’argile de Røsnæs pliée. Le rapport de surconsolidation des éprouvettes testées se trouve dans un intervalle compris entre 5 et 15. Des essais cycliques ont été effectués avec une fréquence de 0,1 Hz jusqu'à 5000 cycles, avec des combinaisons variables de rapports de contrainte de cisaillement moyen et cyclique. Les résultats généraux du test sont en accord avec les références proposées et illustrent l’influence spécifique de la plasticité sur la résistance cyclique de l’argile, une plasticité plus élevée entraînant une résistance plus élevée.

Keywords: Cyclic DSS testing; Cyclic contour diagrams; Neogene clays

1 INTRODUCTION

The Danish Nearshore Windfarm (DNW) owned by Vattenfall Vindkraft A/S is to be built in the Danish sector of the North Sea, near the west coast of Denmark. Classification and advanced laboratory testing campaign has been performed by Geo, Denmark, including a series of direct simple shear tests (DSS) and cyclic direct simple shear tests (DSScy) on Neogene clay.

The goal of the testing was a comparison with the proposed reference contour diagrams and eventual fitting of the diagrams to the measurements at hand. The set of the reference contours included Drammen clay (Post-glacial, Quaternary) cf. Andersen, 2015, Lower till (Glacial, Lower Quaternary) and Folded Røsnæs clay (Palaeogene), cf. Femern A/S, 2014.

In terms of plasticity, the tested Neogene clay is similar to Drammen clay and falls between the Lower till and the Folded Røsnæs clay, whereas in terms of age it is between the latter two.

A total of 7 DSS and 18 DSScy tests have been conducted on Neogene clays collected from Northern and Southern sites. The testing is complemented by classification testing including Atterberg limits carried out on trimmings from the specimens tested in DSS / DSScy.

Cyclic testing was carried out at a frequency of 0.1 Hz for up to 5000 cycles, with variable combinations of average and cyclic shear stress ratios. Most of the DSScy tests have been conducted with a post cyclic shear phase.

2 NEOGENE CLAYS

The Neogene deposits in Denmark are generally overlying older Palaeogene deposits. Depending on the location and erosion of the site, they may be overlain by various glacial (till) or more recent deposits.

Based on the geological descriptions of the tested samples, the tested material is found to include stiff to very stiff clays of variable plasticity. The samples were found silty, occasionally with silt streaks or laminae, some slightly sandy and/or gravely, or with burrows. The samples occasionally contained mica, they were sometimes slightly calcareous, organic or with some content of iron sulphide. Adding to it the dark to very dark brownish grey / greyish brown to black appearance, a resemblance is found with Neogene Marginal marine deposits occurring in Vejle fjord (Rasmusen, 2006). Furthermore, some similarities are found with Warsaw area Neogene clays (Kaczyński, 2003).

2.1 Classification of Neogene clays

In connection to the DSS and DSScy testing and in order to enable classification of the DSS and DSScy samples, 20 Atterberg limits tests were carried out. This plasticity classification testing was carried out on the trimmings from DSS and DSScy samples where available, or on the nearest available sample otherwise.

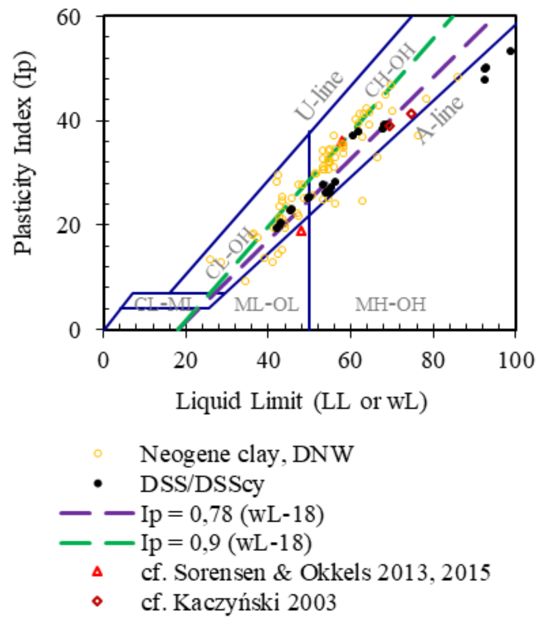

Figure 1. Neogene clays on Casagrande chart; Ip: plasticity index

The plasticity data for Danish Neogene clays encountered on the project is presented on Casagrande chart (Neogene clays DNW, Figure 1), together with points listed by Sørensen and Okkels (2013, 2015) and Kaczyński (2003). The plasticity of DSS/DSScy samples is outlined on Figure 1 and listed in Table 1.

The shown Casagrande chart demonstrates the scatter of the Danish Neogene clays plasticity between medium and high plastic clays and silts.

The data generally lays near the trends suggested for older Palaeogene clays, Ip = 0,9 (wL-18), and for Glacial and newer clays, Ip = 0,78 (wL-18), see Sørensen & Okkels (2015). The data below the A-line is found in agreement with the Neogene clays of Vejle Fjord (Geo, 2016).

Table 1. Classification of tested specimens

ID	**$\sigma'_{v0,\ est.}$** [kPa]	**γ_{bulk}** [g/cm^3]	**$w_{initial}$** [%]	**Ip** [%]
1_ref	185	2,04	24,4	38,3
1_2	185	2,04	24,8	39,0
1_3	185	2,05	25,3	39,1
12_ref	110	1,68	52,1	47,7
12_4	110	1,64	53,8	50,0
12_5	110	1,61	58,7	53,3
14_ref	130	2,01	25,6	26,3
14_2	130	2,01	26,4	27,2
14_3	130	1,97	29,4	28,1
15_ref	200	2,05	24,4	26,0
15_ref1	200	2,03	25,9	26,0
15_1	200	2,02	27,5	26,0
15_2	200	2,02	25,7	25,4
15_3	200	2,02	26,0	25,0
15_4	200	2,06	24,8	26,0
15_8	200	2,02	24,3	26,0
15_9	200	2,00	25,9	26,0
4_ref	40	2,06	23,1	34,1
4_3	40	2,09	20,6	34,1
4_4	40	2,04	25,8	34,1
4_5	40	2,07	23,5	36,9
6_ref	80	2,06	23,4	19,4
6_3	80	2,07	23,1	22,8
6_4	80	2,08	22,2	19,8

$\sigma'_{v0,\ est.}$: estimated vertical in situ stress; γ_{bulk}: bulk density; $w_{initial}$: initial moisture content

In terms of plasticity, possible references for comparison of cyclic response are thus selected as Folded Røsnæs (Palaeogene) clay with Ip~82%; Lower (Danish clay) till with Ip = 15-16% and Drammen clay with Ip ~ 27%.

3 CYCLIC TESTING PROGRAMME AND RESULTS

The testing programme mostly comprised tests on samples from the southern site, with only one set from the northern site (12_ref, 12_2 and 12_5). The cyclic DSS testing programme is overviewed in Table 2.

The clay specimens were preconsolidated to 80% of the estimated preconsolidation pressure before unloading to in-situ stress and shearing in constant volume condition.

Table 2. Overview of DSS tests

ID	**OCR**	**$s_{u,DSS}$** [kPa]	**ASR**	**CSR**	**Nf**
1_ref	5	130	-	-	-
1_2	5		0	0,67	n.f.
1_3	5		0	0,92	122
12_ref	8	130	-	-	-
12_4	8		0	1	20
12_5	8		0,23	0,69	312
14_ref	8	151	-	-	-
14_2	8		0	0,96	46
14_3	8		0	0,66	(40)
15_ref	8	202	-	-	-
15_ref1	8	190	-	-	-
15_1	8		0	0,97	5
15_2	8		0	0,51	n.f.
15_3	8		0,24	0,51	1127
15_4	8		0	0,71	1120
15_8	8		0,51	0,46	12
15_9	8		0,51	0,32	23
4_ref	15	87	-	-	-
4_3	15		0	1	32
4_4	15		0	0,57	828
4_5	15		0,34	0,57	n.f.
6_ref	15	147	-	-	-
6_3	15		0	0,67	263
6_4	15		0	0,95	11

OCR: estimated overconsolidation ratio, 80% of which is used in the test (see the text); ASR: average stress ratio, τ_a/s_u; CSR: cyclic stress ratio, τ_{cy}/s_u; Nf: number of cycles at failure
n.f.: not failed within 5000 cycles
() unexpected mode of failure

3.1 *Overconsolidation ratio and reference undrained shear strength*

The DSS tests were carried out in agreement with ASTM D6528–07 to the shear strain limit of 15%.

The estimated OCR (see Table 2) in DSS and DSScy tests is based on the results of the other tests during the campaign, interpreted by Vattenfall/Geo.

The samples are sorted in groups with similar OCR, with estimated OCRs of 8 and 15, and a single sample with an estimated OCR of 5. This is lower than expected, based on the geological history, but was also found for Neogene clays of Warsaw (Kaczyński, 2003).

Reference undrained shear strength (s_u, $s_{u,DSS}$) is based on DSS tests carried out on the closest possible sample. Overall, the OCR used for the reference tests and the obtained strengths fit well within the critical state soil mechanics framework defined by equation (1), see e.g. Mayne, 1985:

$$\frac{s_{u,DSS}}{\sigma'_{v0,DSS}} = ½ \sin \phi' OCR^{\Lambda} \qquad (1)$$

where $\sigma'_{v0,DSS}$ is the effective vertical in situ stress, ϕ' is the effective angle of friction and Λ is the critical state parameter.

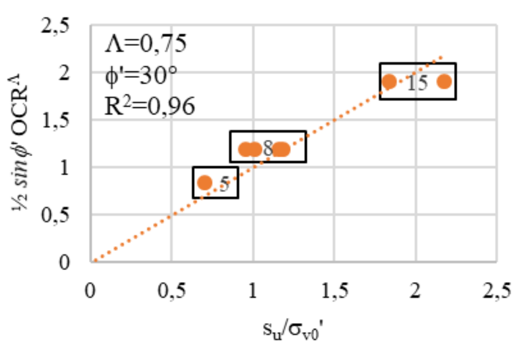

Figure 2 Critical state soil mechanics fit of undrained shear strength in DSS reference tests (s_u) cf. equation (1). Labels: estimated OCR

Using Λ=0.75 and ϕ'~30° results with a reasonably high value of the coefficient of determination, R^2, between the measured values and the values obtained using equation (1). This is illustrated in Figure 2.

3.2 *Cyclic phase*

Cyclic testing was carried out at a frequency of 0.1 Hz for up to 5000 cycles. Most of the DSScy tests have been conducted with a post cyclic shear phase.

In the test on sample 14_3 at ASR=0 & CSR=0.66, the sample has developed a significant average shear deformation, in spite of the symetric loading. This indicated a possible existence of a non-uniformity within the intact sample, although this could not be confirmed by observation of the sample after failure. The results of this particular test have been excluded from the contour plot considerations.

Swelling has been observed in the DSScy tests on 4_3, 4_4 and 4_5.

CYCLIC CONTOUR PLOTS AND ANALYSIS

Cyclic contour plots have been made following the methodology presented within the 3rd McClelland lecture (Andersen, 2015).

3.3 *General methodology*

The essential subset of data is selected as the most elaborate subset comprising the samples with OCR=8 obtained on the southern site.

The procedure of building the contour plots included the analyses of strain development and the analyses of the numbers of cycles to failure under various stress conditions. The analyses included:

1. Analysis of the strain development under monotonic stress.
2. Analysis of the strain development under symmetric cyclic shear stress.

3. Fitting the cyclic contour curvature by way of analysing the results of asymmetric cyclic shear tests.

3.4 Strain development under monotonic shear stress

The reference DSS tests have shown that past the shear strain of 11%, the samples may fail or soften. The shear strain in all the reference tests is depicted on Figure 3, where the 11% shear strain is denoted as Limit strain. The shaded area depicts 95% confidence interval for the shear stress ratio inducing particular shear strain levels.

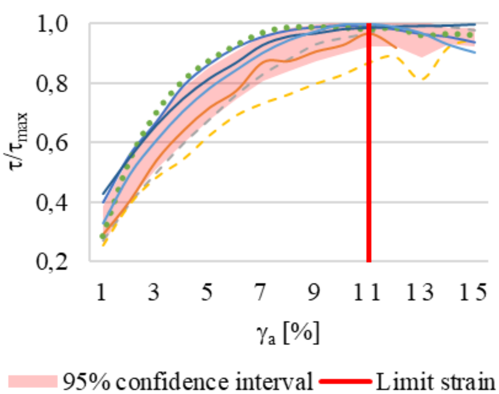

Figure 3 Shear strain development in monotonic tests. Dashed lines represent samples with OCR~15. t: shear stress during the test. Tmax: maximal shear stress during the test

This indicated that the cyclic contours for strains above 11% are likely to overlap at the lower part of the cyclic contour diagrams (for low cyclic stress ratios), whereas for the higher cyclic stress ratios, higher shear strains may be achieved.

3.5 Strain development under symetric cyclic shear stress

A series of symmetric cyclic shear tests is carried out in order to determine the strain contour diagrams plotting number of cycles for particular strain levels against the CSR, $\tau_{cy}/s_{u,DSS}$.

Generally, the shear strain contours in symmetric tests show declining CSR with increase of the number of cycles, which is modelled using Power decay curves, see Figures 4 and 5.

High coefficient of determination (R^2) values, typically above 0,8, are obtained on all the subsets modelled using Power decay curves. However, as the data set is limited, the coefficient of determination is cautiously taken as a measure of the quality of the model, and considered as a descriptive, rather than a determinative parameter (see also Vardanega & Bolton, 2011).

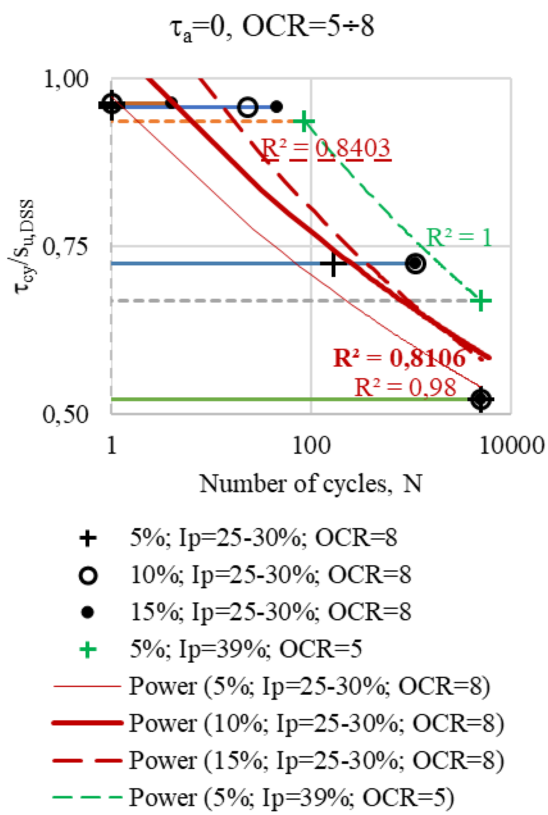

Figure 4 Shear strain contour plot for OCR=5-8

As an alternative model, Inverted logistic curve (ILC, inverse sigmoidal function) is considered, see Figure 6. Both the Power decay and the ILC are in agreement with the typical shapes of the shear strain contour decay shown by Andersen, 2015.

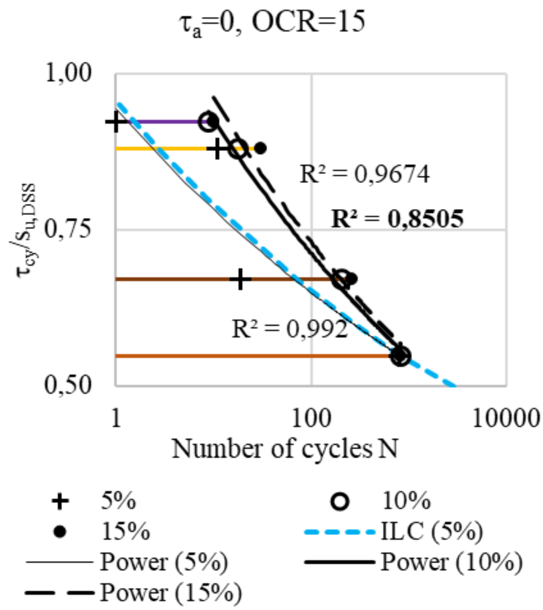

Figure 5 Shear strain contour plot for OCR=15

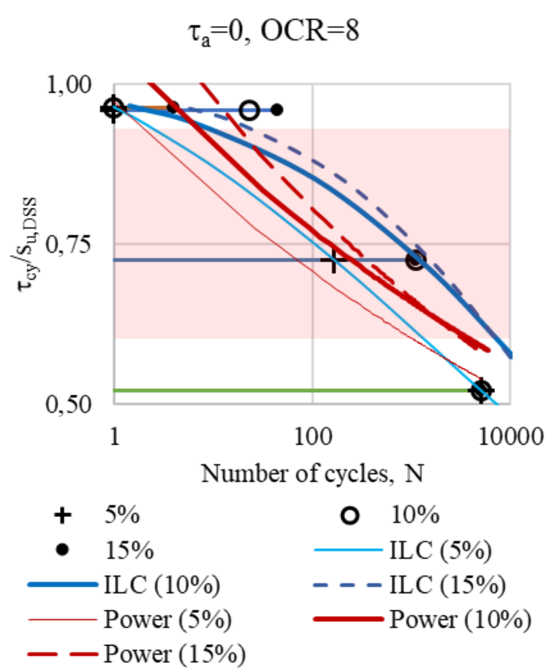

Figure 6 Comparison of shear strain contours with Inverse Logistic (ILC) and Power models

A particular advantage of ILC is the ability to capture the variation of the strain at high stress ratios (above 0,9) more acurately than the Power curves. For low stress ratios the ILC indicates a smaller number of cycles to failure. This is outlined in Figure 6, where the shaded area shows the stress ratio domain where the ILC model is more optimistic than the Power decay model.

3.6 Number of cycles and strain development for variable cyclic shear stress

The cyclic contour plots are prepared for the sets of data showing the strain development to N_f of 10, 100 and 1000.

Fitting of the N_f contours is performed by simultaneous consideration of the average and cyclic shear strains achieved at a particular number of cycles in various tests. This is illustrated on Figure 7.

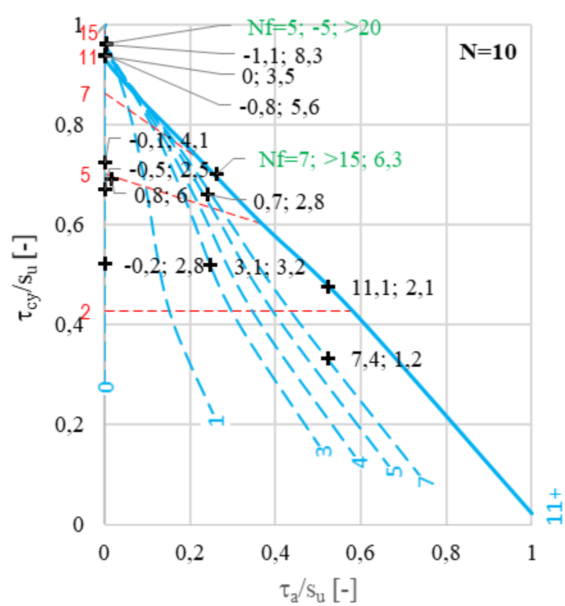

Figure 7 Cyclic contour development for N=10 at OCR~8. Data labels: Nf; average shear strain, γ_a; cyclic shear strain, γ_{cy}. Red lines: γ_{cy} contours, blue lines: γ_a contours. Green: samples failed in less than 10 cycles

The samples with higher plasticity achieved higher N_f then the samples with the lowest Ip (25-30%), as shown on Figure 8.

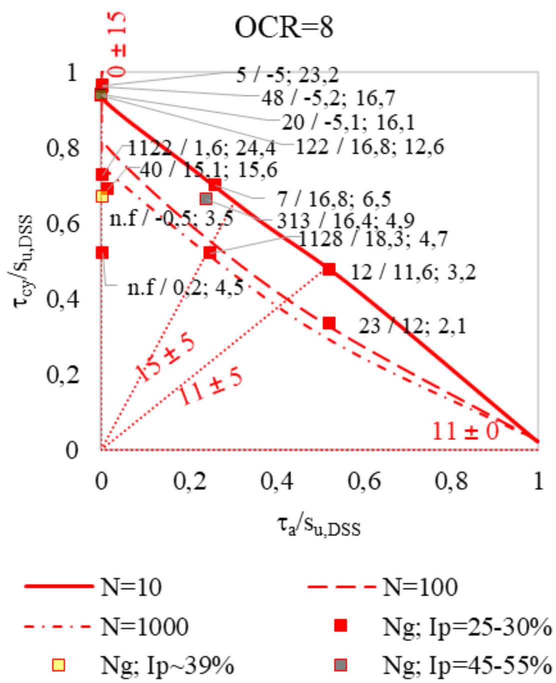

Figure 8 Cyclic contour plot for OCR=8. Ng: Neogene clay DNW

Comparison with the reference contours is presented on Figure 9. It should be noted that the reference contour for the Lower till is in an overall agreement with the reference contour for the normally consolidated clays from Storebælt (cf. Andersen, 2015).

The proposed contours for OCR=8 are slightly modified to reflect the case of OCR=15 illustrated on Figure 10. Based on the limited available data, the contour plots for N=10 cannot be distinguished for the two analysed OCRs. This is in agreement with Drammen clay model (Andersen, 2015), showing that N=10 curves for OCRs above 4 are very close. The curves N=100 and N=1000 for the higher OCR plot somewhat lower than the for the lower OCR, which is also in agreement with the Drammen clay model.

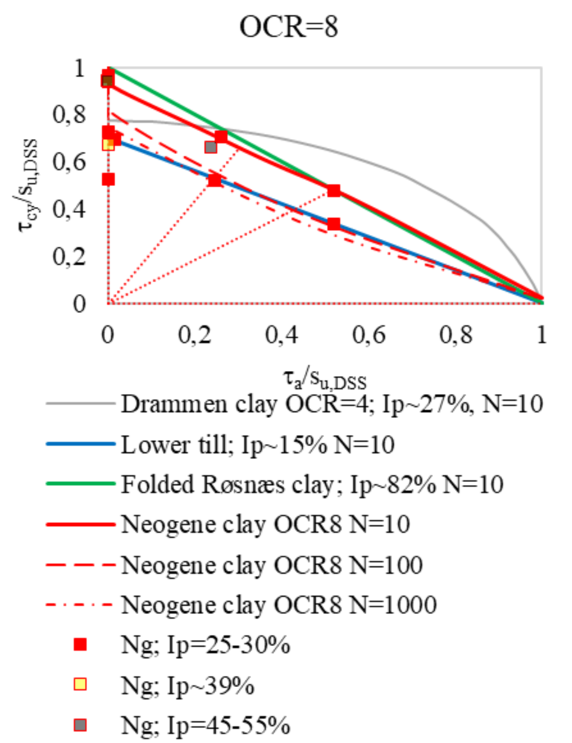

Figure 9 Cyclic contour plot for OCR=8. Ng: Neogene clay DNW

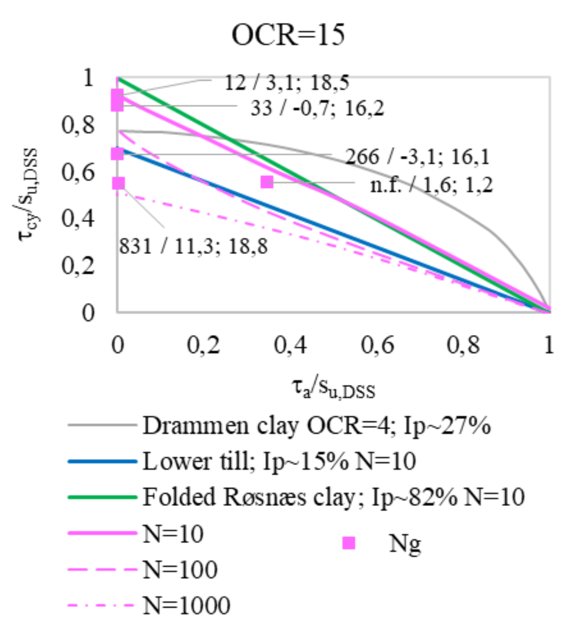

Figure 10 Cyclic contour plot for OCR=15. Ng: Neogene clay DNW

4 CONCLUSION

The analyses were challenged by the intrinsic properties of particular samples, such as variation in plasticity, possible inclusions or other variabilities of the material and/or material state. A non-uniformity may be embedded within the undisturbed sample in such a way that it cannot be detected prior to the testing. This was the case of the sample 14_3, which has developed a significant average shear deformation in spite of the symmetric loading.

Variation between samples resulted with the need to split the total set into subsets, each containing very few data points. Due to this, shown confidence intervals and coefficients of determination are considered as mere descriptive, rather than determinative indicators.

The overall test results depict the stipulated influence of the plasticity on the cyclic strength of the clay, with higher plasticity resulting in higher strength.

The proposed N_f cyclic contours are found in good agreement with contours for similar materials.

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Findings and conclusions expressed in this paper do not necessarily reflect the views of Vattenfall A/S.

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