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Geotechnical characterisation of faulted Paleogene clays

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ABSTRACT: Paleogene clays constitute the substrate for the foundation of several offshore wind farms which are built or planned in the North Sea. In some of these clay layers, intense faulting and other deformations (often referred to as Clay Tectonics) were reported in several studies since the 1980s. Several hypotheses were put forward to explain the occurrence of these deformations. However, high-resolution geophysical surveys in the Princess Elisabeth Zone (Belgian Part of the North Sea) shed a new light on the genesis of these large-scale faults in the Paleogene clays of the Kortrijk Formation. It is put forward that the presence of these faults may influence the installation and operational response of foundations. An investigation into the mechanical properties of these deformations in the Kortrijk Formation is reported in this contribution.

Undisturbed push samples were taken at an onshore site where the Kortrijk Formation occurs close to the surface and which is considered as a valid analogue for the offshore clay material. CT scanning of the samples reveals that in addition to the large-scale faulting observed in the geophysical surveys, intense fissuring on a smaller scale occurs throughout the sediment. Drained direct shear tests with a re-shear stage were undertaken to characterise the intact strength and the strength on a previously sheared sample. The index properties and drained shearing properties are compared to other studies from France and the United Kingdom and reveal consistent trends for the entire sedimentary basin.

Keywords: Laboratory testing; Fracturing; Clay

1 INTRODUCTION

To enable the further development of offshore wind energy in Belgium, the Princess Elisabeth Zone (PEZ) will be developed by 2030. This new zone for offshore wind development of 285km^2 will lead to a capacity increase between 3.15 and 3.5MW (FOD Economie, 2024).

The subsoil in the PEZ consists mainly of stiff Paleogene clays of the Kortrijk Formation overlain by a Quaternary sand cover of varying thickness (1 to 16 m). It should be noted that these sediments are older than those found in the first Belgian offshore wind farm zone and geophysical surveys in the PEZ-area revealed extensive faulting (Henriet et al., 1983; Henriet et al., 1987; Andikagumi et al., 2024).

Figure 1 shows an interpreted geophysical section through the PEZ. The figure features densely spaced faults, ranging in offset from 30 to 160 meters, showing fault displacements up to 3.3 meters.

These faults are expected in the depth range where monopile foundations will be installed. The presence of the fault can potentially impact the installation behaviour and operational response of the monopile. Moreover, the spudcans of jack-up vessels are also expected to interact with these faults if jacking operations are performed in their proximity.

The aim of this study is to quantify the properties of intact and fractured Paleogene clay of the Kortrijk Formation to inform the foundation design and installation planning. A literature survey on existing studies in this material was undertaken followed by a laboratory testing program from an onshore borehole in the vicinity of an observed shear zone.

In this contribution, the laboratory observations are compared to the previous studies on this material.

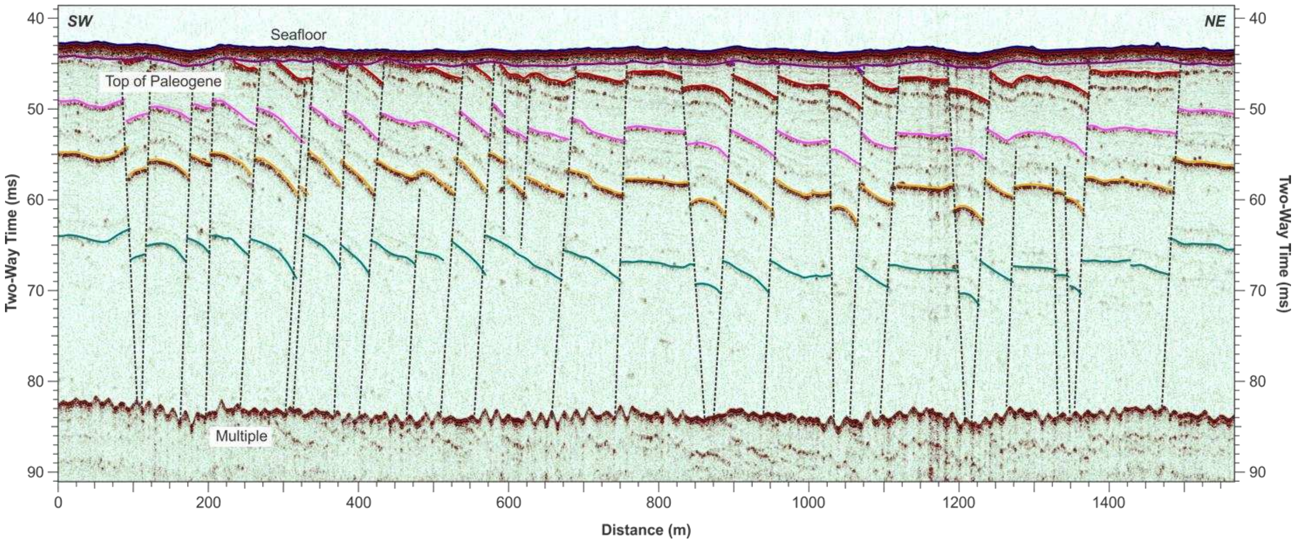

Figure 1. Interpreted geophysical section through the Princess Elisabeth Zone

2 GEOTECHNICAL CHARACTERISATION OF STIFF PALEOGENE CLAYS

Stiff Paleogene clays have been studied in the past, mainly in the context of large onshore infrastructure works. The occurrence of clay fissuring (discontinuities up to 10cm in length) and faulting (discontinuities of several meters in length) has been documented and has often been related to the occurrence of polygonal fault systems (Cartwright, 2011). The geotechnical properties of the fissured and faulted clays have been documented for a number of sites which are described in detailed below.

2.1 Investigations on Argile de Flandre

During the geotechnical surveys for quay wall construction in the ports of Dunkerque and Calais, geotechnical testing was performed to determine the drained shearing properties of the *Argile de Flandre*. This clay is the geological equivalent of the Kortrijk Formation and can be considered to be geologically comparable to the clays found at the onshore test site and in the PEZ offshore Belgium.

Josseaume (1998) reported the results from extensive consolidated drained and undrained (CD/CU) triaxial testing on samples from Calais and Dunkerque. The orientation of the failure planes was also observed from the tests. If a sample failed at an angle which was significantly different from 45°, failure on a pre-existing weakness plane was likely. Mohr's circle was then used to infer the normal stress and shear stress on a plane with this orientation. By combining all measurements where a pre-existing weakness plane was activated, a drained shear strength criterion for the weakness planes was identified. Figure 2 show the drained shearing criteria for intact material and on pre-existing weakness planes.

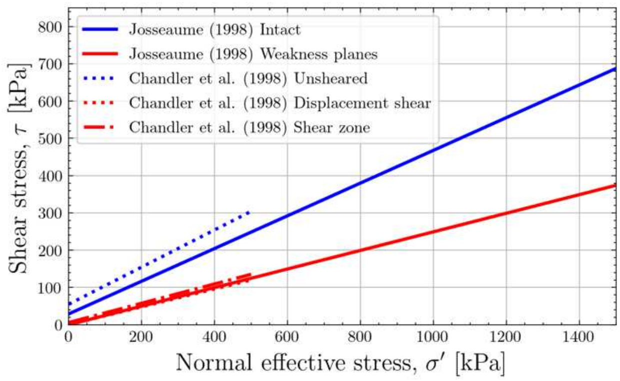

Figure 2. Drained shear resistance properties for Argile de Flandre and London Clay (adapted from Josseaume, 1998 and Chandler et al., 1998)

2.2 London Clay

Chandler et al. (1998) reported investigations into the geotechnical properties of subhorizontal shear zones in the London Clay at Prospect Park. The investigations were triggered by a slope failure at a shallow angle, indicating the existing of a pre-existing weakness plane. The shear zones had a finite thickness between 3 and 40mm bounded by two interfaces with the intact material called *displacement shears*.

The London Clay is the geological equivalent of the clays of the Kortrijk Formation and research into this material is therefore of great value for the characterisation of the PEZ.

The geotechnical testing reported by Chandler et al. consisted of index testing, one-dimensional compression tests and drained shear box tests. The index testing revealed a lower water content in the shear zone, which is aligned with the hypothesis of the shear zone being formed shortly after the deposition of the clay (prior to overconsolidation). The lower void ratio of the shear zone was also observed in the 1D compression tests.

The drained shear box tests performed on samples from the intact material and the shear zones respectively, were used to derive drained shear strength criteria. When plotted in the same chart as the drained strength criteria proposed by Josseaume (1998), very good agreement between the proposed strength criteria on the weakness planes is observed. Chandler et al. make a distinction between the strength of the displacement shears and the strength in the shear zone but the difference is limited. The intact criterion proposed by Josseaume (1998) is more conservative than that proposed by Chandler et al. This could be due to the larger sample size in the triaxial tests which could lead to a lower mass strength.

2.3 Boom Clay

Although geologically more recent than the clays of the Kortrijk Formation, the Boom clay is a Paleogene clay which has been extensively studied in Flanders. It should however be noted that in contrast to the Kortrijk Formation, no large-scale faulting has been reported in the Boom Clay.

As reported by Verastegui-Flores et al. (2023) Boom clay shows brittle behaviour and a tendency to swell. To better quantify the mechanical properties of the clay properties immediately after deposition, the researchers prepared normally consolidated samples of Boom clay by mixing material from an outcrop with demineralised water into a slurry. The intrinsic properties of the slurry were then determined and compared to those of the intact Boom clay.

The drained shear box testing with multiple reversals according to EN ISO 17892-10 were of special of interest. These tests determined a residual drained friction angle by shearing the reconstituted sample in a shear box. After each shearing episode, the sample was brought back to its initial position and was allowed to reconsolidate. Except for the first stage, the sample shows a residual friction around 15° which aligns well with the values proposed for London Clay and Argile de Flandre. Reconstituted samples could therefore be used to characterise the strength of the fault infill material.

2.4 Offshore geotechnical surveys PEZ

The Belgian Federal Government executed the geotechnical and geophysical surveys for the PEZ. These surveys consisted of 17 boreholes with continuous sampling and 75 CPT tests (Figure 3). The surveys revealed the presence of the clays of the Kortrijk Formation throughout the site. The presence of large-scale faults could not be observed in the CPT testing but slickensides, which could be evidence of a shear zone, were reported in the geotechnical parameters report. Samples with such slickensides did not show significantly different undrained shear strength in CU triaxial tests (Fugro, 2024).

Drained friction angles for the clay material were not described in the geotechnical parameters report.

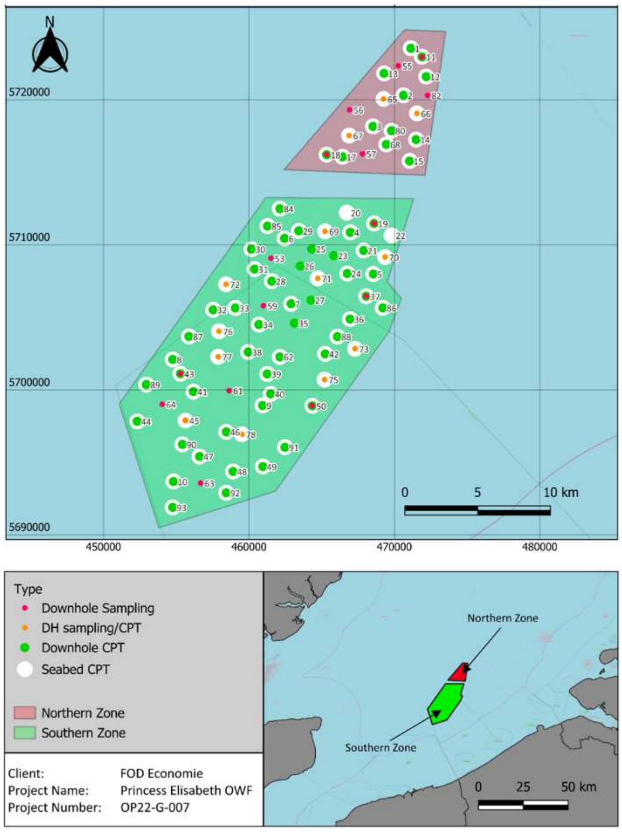

Figure 3. Geotechnical survey map for the Princess Elisabeth Zone surveys

3 ONSHORE LABORATORY PROGRAMME

While the sampling of a fault plane in the offshore zone was not possible, shearing on pre-existing weakness was observed in onshore clay quarries in West-Flanders. Figure 4 shows a picture of an observed slope failure in the clay quarry of Rumbeke. The failure plane looked very similar to the slickensides reported from the offshore surveys.

Figure 4. Observed shear failure on a pre-existing failure plane in the clay pit at Rumbeke (image credit: Jan Maertens)

3.1 Onshore test site

Unfortunately, the failed slope at Rumbeke was no longer accessible for sampling. However, a continuous sampling borehole with 100mm diameter thin-walled push samples was executed next to the clay pit. The borehole was positioned to intersect with the anticipated position of the pre-existing failure plane.

Push samples were taken from 4m to 10m depth. The clay of the Kortrijk formation was encountered from 5m below the ground surface. The samples were immediately transported to the laboratory for further testing.

3.2 CT-scanning

To identify the internal structure of the clay samples, CT-scanning was performed with a medical scanner. The images of the CT scans were used to guide the selection of samples for geotechnical testing.

The scanning revealed a zoner of higher density material in the sample between 6.5m and 7.0m below ground surface (Figure 5). This higher density zone was relatively thin and thus only index testing was performed on this material. After index testing, the material subject to further mineralogical testing using X-Ray Diffraction (XRD). This revealed similar mineralogy to that of nodules found in the Kortrijk Formation (Reyniers, 2020).

The clay surrounding the high density zone also showed extensive brecciation as revealed by the dark features in the sample. The exact location and thickness of the shear zone could not be reliably inferred from the CT scan images. Hence, it remains speculative whether the higher-density zone in the sediment can be linked with the observed failure plane in the quarry. This material was a mineralogy consisting of 23% Quartz, 2.9% K-spar, 1.3% Plagioclase, 63.5% 2:1 layer silicates, 1.6% Chlorite and 5.4% Kaolinite. Other minerals have an occurence of less than 1% by weight.

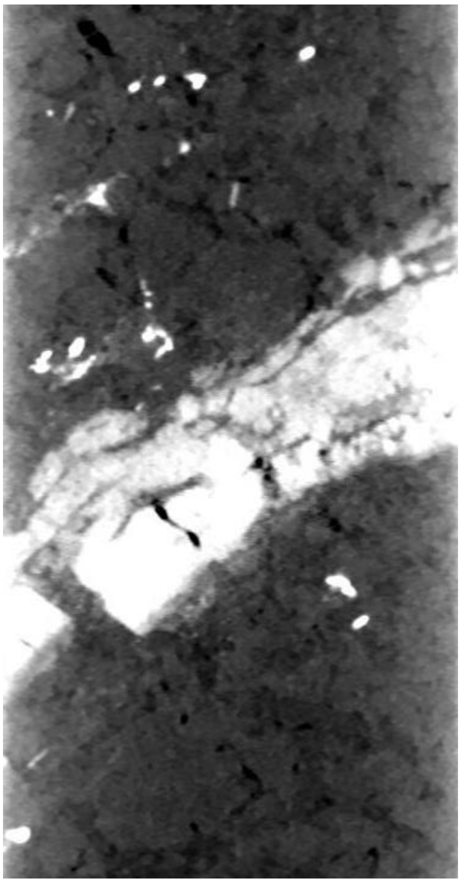

Figure 5. Higher density zone (lighter coloured) and brecciation observed in a sample taken in the vicinity of a shear zone

3.3 Index testing

Water content tests, Atterberg limit tests and sieving and hydrometer tests were performed on the clay material. The grain size distributions showed a very low sand content in the clay samples from the Kortrijk Formation. The natural water content and Atterberg limits are shown in Table 1 for selected samples. The samples showed increasing plasticity with depth and a water content close to or just below the plastic limit. The sample from the zone with high density in Figure 5 showed a lower water content. This is in line with the observations by Chandler et al. (1998) where a lower water content was also reported in the shear zone.

Table 1. Index properties for clays of the Kortrijk Formation sampled at Rumbeke.

Depth below ground surface [m]	Natural water content [%]	Plastic limit [%]	Liquid limit [%]
5.50	41.2	49.0	88.3
6.00	39.0	41.1	100.8
6.50	43.2	37.3	98.4
6.85(*)	22.8	32.9	56.0

(*) Sample from the high density zone in Figure 5

3.4 Oedometer tests

One-dimensional compression tests with incremental loading (ILT) were performed on two clay samples. These tests revealed a low permeability of the clay (2e-10m/s to 6e-10m/s) and an overconsolidation ratio between 2.1 and 3.0. The brecciation observed in the CT scans did not lead to improved drainage of the samples. Moreover, a check on the sample quality was possible based on the $\Delta e/e_0$ ratio (Lunne et al., 1998). These revealed that the samples were of poor quality. Detailed inspection of the sample tubes revealed corrosion on this inside of the tubes which could have caused the disturbance. For future surveys, the smoothness of the sample tube wall will be checked and block samples will also be considered.

The compression index C_c observed for the oedometer test was 0.35, which is in line with the values reported by Chandler et al. (1998). The swelling index C_s for unloading from 1000kPa to 500kPa was 0.07 which is identical to the value for intact clay reported by Chandler et al. However, for further unloading to 100kPa, the swelling increases to 0.13.

3.5 Drained shearing properties from direct shear tests

Drained shear box testing with reshear stages was performed on several clay specimens in a 60mmx60mm shear box. The specimens were consolidated to a vertical effective stress of 50, 100 and 200kPa and then subject to a first shearing stage which was considered representative for the drained shearing resistance in the intact condition. A horizontal displacement rate of 0.07mm/hr was selected. After this first shearing stage, the shear box was reset to its initial position and the specimen was allowed to reconsolidate. The subsequent re-shear was considered to be representative for the drained shearing resistance on a pre-existing weakness plane.

A comparison of the measured drained shearing resistance to the criterion proposed by (Josseaume, 1998) in Figure 6 shows that the shear box measurements plot below the intact shear criterion for the Argile de Flandre. This could be explained by the brecciation observed in the CT scans of the samples.

The drained shearing resistance measured in the reshear test did show reasonable agreement with the criterion by Josseaume for the weakness planes. This suggests that the reshear tests can provide representative properties for drained shearing on pre-existing weakness planes.

3.6 Drained shearing properties from CU triaxial tests

A CU triaxial test with pore pressure measurement was caried out on three subsamples of the clays from the geotechnical borehole drilled at Rumbeke. Drained shearing properties were derived from the CU triaxial test and the resulting drained shear strength envelope was plotted in Figure 6. The drained envelope shows correspondence with the intact shear box test results but shows lower strength than the Josseaume (1998) intact criterion. This could be due to the brecciation of the samples from the borehole at Rumbeke.

The angle of the failure plane was inspected in detail for each of the subsamples and the expected 45° angle of the failure plane in undrained conditions was observed for all specimens.

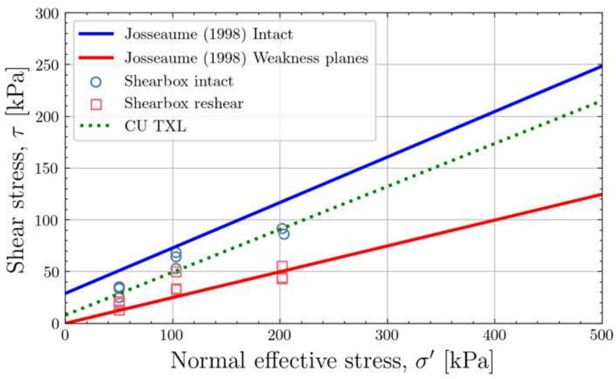

Figure 6. Comparison of drained shearing properties from direct shear and CU triaxial testing to criteria proposed by Josseaume (1998)

4 CONCLUSIONS AND FUTURE WORK

The Princess Elisabeth Zone (PEZ) offshore Belgium will require the design of foundations in stiff fissured clays, which also exhibit large-scale faulting. In this contribution, the geotechnical properties of unsheared and sheared clay of the Kortrijk Formation are characterised. Geotechnical index and strength testing on samples from a borehole in the vicinity of a reported shear zone shows good agreement with the properties previously identified for London Clay

(Chandler et al., 1998) and the Argile de Flandre (Josseaume, 1998).

While the drained shearing properties for a pre-existing weakness plane are nearly identical in all studies, the drained shearing resistance for the intact material shows a noticeably lower strength for the borehole in Rumbeke. This could be due to the brecciation of the sample and the effect of the smaller-scale fissured on the mass strength and stiffness will be investigated further in a follow-up project. The amount of small-scale fissures in the samples and their orientation relative to the failure plane will influence the results (Lo, 1970)

The drained and undrained strength properties derived from the laboratory testing will be used to create a numerical model of foundations in the vicinity of a pre-existing shear zone. While drained strength properties will be required for modelling the long-term resistance, undrained strength will need to be defined for loading of short duration as the faults are not expected to show good drainage. The effects of fissures on the undrained shear strength will also be studied further in the follow-up project.

AUTHOR CONTRIBUTION STATEMENT

Bruno Stuyts: Data curation, Formal Analysis, Writing- Original draft. **Hans Pirlet, Thomas Mestdagh, Harisma Andikagumi and Marc De Batist**.: Writing- Reviewing and Editing. **C. Devriendt**: Supervision, Funding acquisition.

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