Thor OWF – Geotechnical Site Investigation 2020

Factual Geotechnical Report
Seabed CPT Campaign and Borehole Campaign

Survey Period: May-August 2020

Geo Project No. 204307

Report no. 3

Report Revision	Date	Prepared	Checked	Approved
Draft	2020-10-19	ABP/KHL/LTR	MHF	TCL
Rev. 01	2020-11-16	MHF	ABP	TCL

QUALITY CONTROL				
Section	**Description**	**Prepared**	**Checked**	**Approved**
	Executive Summary	ABP	MHF	TCL
1	Introduction	ABP	MHF	TCL
2	Field Operations	ABP	MHF	TCL
3	Vessels	ABP	MHF	TCL
4	Navigation and Positioning	ABP	MHF	TCL
5	Equipment and Procedures	ABP	MHF	TCL
6	Verification Checks and Equipment Calibration	ABP	MHF	TCL
7	Seabed Level Measurements	ABP	MHF	TCL
8	Jack-up Leg Penetration	ABP	MHF	TCL
9	Results from Seabed CPTUs	ABP	MHF	TCL
10	Results from Seismic CPTUs	KHL	MHF	TCL
11	Geotechnical Drilling and Sampling Results	ABP	MHF	TCL
12	DTH-CPTU Results	ABP	MHF	TCL
13	Laboratory Test Results	MHE	MHF	TCL
14	Soil Conditions	MHE	MHF	TCL
15	Typical Geotechnical Characteristics	MHE	MHF	TCL
16	References	ABP	MHF	TCL

EXECUTIVE SUMMARY

Energinet Eltransmission A/S has contracted Geo to conduct a geotechnical investigation at the planned off-shore wind farm area named Thor. The Thor site is located in the Danish part of the North Sea.

The purpose of the preliminary geotechnical investigations is to gather geotechnical data and information as basis for evaluation of methods for wind turbine foundation and installation as well as preliminary design of wind turbine and offshore platform foundations.

The results of the preliminary geotechnical investigations shall be used as basis for the tender for Thor offshore wind farm, and provide information for:

- An overview of the geology in the area (3D Geological model), based on a correlation of the results of the geotechnical investigations and the geophysical survey
- Characterising the geological units in geological and geotechnical terms, and obtain geotechnical data and parameters for the observed soils and layers
- Evaluation of possibilities to jack up on the seabed when installing the foundations
- Evaluation of transport of sediments around the foundations after installation
- A preliminary engineering site assessment
- A general risk assessment for foundation conditions of the wind farm.

Under the present campaign the following work components/tests have been performed:

- CPTUs (enhanced CPTUs)
- SPTUs (seismic CPTUs)
- Sample Boreholes with DTH-CPTU testing and P-S Logging
- DTH-CPTU Boreholes
- Laboratory Testing
- Data Reporting.

The overall geotechnical investigation was divided into two separate campaigns. The seabed campaign was performed from the DP II vessel Wilson Adriatic, and the borehole campaign was performed from the vessel L/B Jill.

The seabed campaign was performed by the use of Geo's in-house seabed rigs GeoScope and GeoThor. The borehole campaign was performed by the use of Geo's in-house geotechnical drilling spread. The P-S Logging was sub-contracted to Robertson Geologging.

The campaign comprised in total 81 CPTUs (at 61 locations), 14 seismic SPTUs (at 9 locations), 18 geotechnical sample boreholes (with P-S logging in 4 of these boreholes) and 2 down-the-hole (DTH) CPTU boreholes.

In order to maximize the penetration depth for the CPTUs, all the tests were performed as enhanced CPTUs, which includes seabed CPTUs performed with push capacity, increased to 250kN and the possibility to reduce skin friction on the CPT rods. When activated, the rod skin friction is reduced by continuous injection of lubricants behind the CPT cone during the tests.

SCPTU tests were performed at positions selected by the Client. The aim for these tests were to obtain high quality seismic data (shear velocity measurement Vs) to maximum depth.

The target depth for all CPTU tests were initially 70 m, however the Client instructed to change the target depth to 50 m for some locations in order to optimise the lubrication application of these tests.

The general strata encountered at the Thor OWF site consist of a series of different layers predominantly alternating between sand, gravel, silt, clay and till deposits. Based on contents of minor constituents and similar macroscopic petrographic characteristics, the sequence of layers has been subdivided into the following geological soil units:

- Holocene Marine Sand and Gravel
- Holocene Marine Clay and Silt
- Holocene Marine Gyttja and Peat
- Meltwater Sand, Gravel and Cobbles
- Meltwater Clay and Silt
- Till deposits
- Inter glacial deposits
- Neogene marine deposits
- Neogene freshwater deposits

This report includes the following factual data:

- Overview of the work carried out during the geotechnical campaign, including descriptions of methods used for the in situ testing and sampling
- Data from the seabed CPTU tests
- Data from the seismic seabed CPTU tests
- Data from the boreholes (including sampling, DTH-CPTUs and P-S Logging)
- Onshore laboratory tests.

The onshore laboratory programme included five main components:

- Classification Tests
- Advanced Tests
- Chemical Tests
- Microfaunal and Palynofloral Dating
- Cyclic Testing

Preliminary geological description was performed offshore, as well as index tests, moisture content and bulk densities.

Prepared for:
Energinet Eltransmission A/S
Tonne Kjærsvej 65
7000 Fredericia
Denmark

Prepared by:
Allan Bach Pedersen, Project Engineer, +45 3174 0281; abp@geo.dk
Maja Heyden, Project Engineer, +45 3174 0277; mhe@geo.dk
Kasper Lundvig, Project Engineer, +45 3174 0203; khl@geo.dk

Controlled by:
Martin Hoffmann, Project Manager, +45 3174 0174; mhf@geo.dk

Approved by:
Thomas Carentius, Department Director, +45 3174 0189; tcl@geo.dk

CONTENTS

ENCLOSURES

TABLES IN THE MAIN TEXT

FIGURES IN THE MAIN TEXT

SYMBOLS AND TERMS

Symbol	Unit	Term of Definition
Density and Unit Weight		
γ	kN/m^3	Unit weight of soil (or bulk or total unit weight)
γ_d	kN/m^3	Unit weight of dry soil
γ'	kN/m^3	Unit weight of submerged soil
ρ	kg/m^3	Density of soil
ρ_d	kg/m^3	Density of dry soil
D_r	-, %	Relative density
w	%	Water content
n	-, %	Porosity

Cone Penetration Test		
B_q	-	Pore pressure ratio
c_u	kPa	Undrained shear strength
D_r	%	Relative density
F_r	MPa	Normalised sleeve friction
f_s	MPa	Measured sleeve friction
f_t	MPa	Corrected sleeve friction
N_{kt}	-	Cone factor between q_n and s_u or c_u
q_c	MPa	Measured cone resistance
q_n	MPa	Net cone resistance
q_t	MPa	Corrected cone resistance
Q_t	MPa	Normalised cone resistance
R_f	%	Friction ratio
R_{ft}	%	Corrected friction ratio
u	MPa	Pore water pressure
u_0	MPa	In situ hydrostatic pore water pressure
φ'	º	Angle of internal friction
N_q	-	Bearing capacity factor
K_0	-	The coefficient of earth pressure at rest
Soil Strength		
s_u or c_u	kPa	Undrained shear strength
σ_{v0}	kPa	Vertical stress
σ'_{v0}	kPa	Effective vertical stress
K_0	-	Coefficient of lateral earth pressure at rest
σ	kPa	Unconfined compressive strength

ABBREVIATIONS

ADV	Advanced Laboratory Tests
AL	Atterberg Limits
ALARP	As Low As Reasonably Practicable
ASTM	American Society for Testing and Materials
BD	Bulk Density
BS	British Standard
CACO3	Calcium Carbonate (“$CaCO_3$”)

CD	Consolidated drained
CEN	Comité Européen de Normalisation (*European Committee for Standardization*)
CID	Consolidated Isotropic Drained Triaxial Test
CPT	Cone penetration test
CPTU	Cone penetration test with pore pressure
DD	Dry Density
DGF	Dansk Geoteknisk Forening (*Danish Geotechnical Society* – “dgf”)
DIN	Deutsches Institut für Normung
DPR	Daily progress report
DS	Direct Shear
e_{min}	Minimum Void Ratio
e_{max}	Maximum Void Ratio
EN	English
ETRS89	European Terrestrial Reference System 1989
GI	Geotechnical investigation
GNSS	Global Navigation Satellite System
IL	Incremental Loading
IRTP	International Reference Test Procedure
ISO	International Organization for Standardization
LOI	Loss on Ignition
m	Metres (“m”)
mbsb	Metres below seabed
MBTS	Metres Below Test Start (“mbts”)
PP	Pocket Penetrometer
PSD	Particle Size Distribution
QA/QC	Quality Assurance / Quality Control
SCPTU	CPTU tests with seismic measurements
SI	Sieve (“Si”)
SIHY	Sieve / Hydrometer (“SiHy”)
TS	Technical Specification
TV	Tor Vane
UU	Unconsolidated Undrained
UTM	Universal Transverse Mercator
UXO	Unexploded Ordnance
VORA	Void Ratio
W	Water Content

1 INTRODUCTION

1.1 General Project Description

Energinet Eltransmission A/S has contracted Geo to conduct a geotechnical investigation at the planned offshore wind farm area at Thor. The site is located in the Danish part of the North Sea (see Figure 1.1).

The objective of the current report is to provide CPTU data, seismic CPTU data, geological data, borehole sampling data and geotechnical laboratory data for the preliminary design and installation of the wind turbines at the Thor OWF site.

Figure 1.1 – Overview of Thor OWF area

The overall geotechnical investigation was divided into two separate campaigns. The seabed campaign was performed from the DP II vessel Wilson Adriatic, and the borehole campaign was performed from the vessel L/B Jill.

The seabed campaign was performed by the use of Geo's in-house seabed rigs GeoScope and Geo-Thor. The borehole campaign was performed by the use of Geo's in-house geotechnical drilling spread. The P-S Logging was sub-contracted to Robertson Geologging.

1.2 Scope of Work

The overall geotechnical investigation was divided into two separate campaigns. The seabed campaign was performed from the DP II vessel Wilson Adriatic, and the borehole campaign was performed from the vessel L/B Jill.

The seabed campaign include the following work:

- Mobilisation of the vessel Wilson Adriatic and Geo's geotechnical equipment
- Seabed Cone Penetration Tests with pore pressure (CPTU) to a target depth of 50-70 mbsb
- Seismic CPTUs to a target depth of 50-70 mbsb
- Demobilisation of Wilson Adriatic
- Reporting of field work.

The borehole campaign include the following work:

- Mobilisation of the vessel L/B Jill and Geo's geotechnical equipment
- Sample Boreholes with DTH-CPTU testing to a target depth of 70 m below seabed
- DTH-CPTU Boreholes to a target depth of 40 m below seabed
- In selected boreholes there was performed P-S Logging
- Offshore Laboratory Testing
- Demobilisation of L/B Jill
- Reporting of field work.

Onshore laboratory testing performed by Geo:

- Onshore laboratory work – Classification testing
- Onshore laboratory work – Advanced testing

Data Reporting:

- Data reporting of all fieldwork, including Quality Assurance (QA)/Quality Control (QC).

1.3 Geotechnical Reporting under the Contract

The reports planned under the contract:

Table 1.1 – Reporting Overview

Report no.	Report Title
-	Acceptance Test Report (Seabed CPT Campaign)
-	Acceptance Test Report (Borehole Campaign)
1	Operational Report (Seabed CPT Campaign)
2	Operational Report (Borehole Campaign)
3	Factual Geotechnical Report (Seabed CPT Campaign & Borehole Campaign)

2 FIELD OPERATIONS

2.1 General

The objective of the investigation is to provide geotechnical data to be used as input for foundation design and installation at each wind turbine location within the wind farm area at Thor.

The investigation included a seabed CPTU campaign (incl. seismic CPTUs) and a borehole campaign. Additionally, onshore laboratory works including both classification and advanced tests were carried out on the collected samples.

The work included the following two main phases carried out in this sequence:

- Seabed CPTUs (including seismic CPTUs)
- Boreholes (including sampling, DTH-CPTUs and P-S Logging).

The seabed campaign was performed from 11th May 2020 to 30th May 2020. The operations were conducted on a continual 24-hour basis.

The borehole campaign was performed from 26th June 2020 to 19th August 2020. The operations were conducted on a continual 24-hour basis.

Table 2.1 shows an overview of the quantities of the performed work.

Table 2.1 - Overview of the performed work

Total boreholes, tests / (Locations)			
CPTUs	SCPTUs	Sample Boreholes	DTH-CPTU Boreholes
81 / (61)	14 / (9)	18	2

All tests are included on the General Location Plan in Enclosure A.01 and on the Detailed Location Plan in Enclosure A.02.

2.2 Seabed CPTUs

At locations selected by Energinet, seabed CPTUs were carried out to maximum 58.9 mbsb or refusal. A total of 81 CPTUs were carried out with penetration depths between 2.2 and 58.9 mbsb. The average penetration depth for the tests under this campaign was 27.9 m.

Target depth for CPTUs were initially 70 mbsb and adjusted to 50 mbsb. All CPTu's terminated at 50 mbsb did not meet max penetration nor refusal.

The re-runs were identified by the location ID followed by suffix "a", "b", or "c". The majority of the re-runs were performed at locations were the first test did not reach the expected minimum penetration. Additional re-runs were requested by the Client.

All tests are included on the General Location Plan in Enclosure A.01 and on the Detailed Location Plan in Enclosure A.02. The tests are also listed in the summary sheet, Enclosure B.01.

2.3 Seismic Seabed CPTUs

At locations selected by Energinet, seismic CPTUs were carried out to refusal or maximum 37.0 mbsb. A total of 14 SCPTUs were carried out with penetration depths between 1.1 and 37.0 mbsb. The average penetration depth for the SCPTUs under this campaign was 16.9 m.

At positions selected by the Client re-runs were performed. The re-runs were marked with the same location ID but with an “a”, “b” or “c” added to the ID. The majority of the re-runs were performed at positions were the first attempt did not penetrate the expected min. depth.

All tests are included on the General Location Plan in Enclosure A.01 and on the Detailed Location Plan in Enclosure A.02. The tests are listed in the summary sheets, Enclosure B.01 and B.02.

2.4 Sample Boreholes with P-S Logging

At locations selected by Energinet, sample boreholes were carried out. The target depth of the boreholes was 70 mbsb. A total of 18 sample boreholes were carried out to app. depths of 70 mbsb although borehole BH-18 was terminated at 67.8 m mbsb due to equipment failure.

P-S Logging was carried out in 4 of the sample boreholes.

Offshore and onshore classification-, chemical-, strength- and deformation tests have been executed on selected samples.

All tests are included on the General Location Plan in Enclosure A.01 and on the Detailed Location Plan in Enclosure A.02. The boreholes are also listed in the summary sheet, Enclosure B.04.

2.5 DTH-CPTU Boreholes

At two selected locations, BH-12a and BH-17a, Energinet chose to extend the level covered by CPTU testing by ordering additional DTH-CPTU boreholes targeting 40 mbsb. These boreholes was performed to allow for undisturbed sampling in the adjacent boreholes BH-12 and BH-17.

All tests are included on the General Location Plan in Enclosure A.01 and on the Detailed Location Plan in Enclosure A.02. The DTH-CPTU boreholes are listed in the summary sheet in Enclosure B.04 and B.05.

3 VESSELS

3.1 Survey Vessel, Seabed Campaign

The seabed campaign was carried out from the vessel Wilson Adriatic, supplied by Wilson Offshore A/S.

The vessel Wilson Adriatic is a Dynamic Positioning (DP II) vessel with an overall length of 90.2 m and a maximum draft of 7.0 m.

The vessel is depicted in Figure 3.1 and further information can be found on the Operational Report.

3.2 Survey Vessel, Borehole Campaign

The borehole campaign was carried out from the vessel L/B Jill, operated by Fred. Olsen Windcarrier.

The vessel L/B Jill is a Dynamic Positioning (DP II) vessel with three jack up legs, with an overall length of 56 m, breadth of 41 m and a maximum draft of 4.5 m.

The vessel is depicted in Figure 3.2 and further information can be found on the Operational Report.

Figure 3.1 – DP II vessel, Wilson Adriatic with seabed CPT equipment installed

Figure 3.2 – L/B Jill with geotechnical equipment installed

4 NAVIGATION AND POSITIONING

4.1 Datum and Coordinate System

Coordinates for all CPT and borehole locations are provided in European Terrestrial Reference System (ETRS) UTM 32N.

The vertical reference on the different summaries, logs etc. are given according to Mean Sea Level (MSL) via the model DTU15 MSL.

4.2 Equipment and Procedures, Seabed Campaign

Two independent Global Navigation Satellite System (GNSS) receiver systems have provided surface positioning during the project.

The full survey system comprises the following main elements:

- POSMV INS navigation system, with gyro
- POSMV IMU
- HiPAP 5000 USBL.

The USBL system consisted of the vessels Kongsberg HiPAP 5000 USBL in conjunction with the Kongsberg cNODE Minis 34 Transponders. The USBL transponder was mounted on the geotechnical equipment and offsets to centre of the GeoScope and GeoThor were measured. Calibration of the USBL system was performed prior to arriving to site. The USBL pole was mounted at mid-ships.

A Kongsberg 1171 sonar head was mobilised to the vessel in order to determine the distance between the seabed rigs GeoScope and GeoThor. The sonar was mounted on the GeoThor rig.

A detailed description of the survey system can be found in the Operational Report.

4.3 Equipment and Procedures, Borehole Campaign

Two independent Global Navigation Satellite System (GNSS) receiver systems have provided surface positioning during the project.

The full survey system comprises the following main elements:

- Applanix POSMV IMU navigation system with RTG

- JAVAD (Sigma-3) with RTK.

A detailed description of the survey system can be found in the Operational Report.

4.4 Positioning at each Location, Seabed Campaign

A navigation display showing planned – and actual seabed rig position, enabled the vessel Captain/Officer to navigate the vessel to target position.

When the vessel was in position, the actual position was fixed with dynamic positioning using the NaviPac software.

The test positions (as built) are presented on all logs and in various summaries in Enclosure B.

4.5 Positioning at each Location, Borehole Campaign

A navigation display showing planned – and actual borehole position, enabled the vessel Captain/Officer to navigate the vessel to the target position.

When the vessel was in position, the actual position was fixed with dynamic positioning using the NaviPac software. The legs were then lowered until the pads of the legs reached the seabed surface. Hereafter the vessel was jacked up slowly while monitoring the penetration of the pads/legs into the seabed. The vessel was jacked up with a minimum air gap. The air gap was sometimes adjusted according to the wave height to avoid the waves from hitting the bottom of the vessel.

The recorded penetration of the legs/pads were generally less than 1 meter at most of the borehole locations. Larger penetrations of 2 to 4 m were recorded at borehole BH-09 and BH-04.

The borehole positions (as built) are presented on all logs and in the summary sheet in Enclosure B.04.

The positions of the legs (while the vessel was jacked up) along with the registered penetration into the seabed for each leg are presented in the summary sheet in Enclosure B.08.

5 EQUIPMENT AND PROCEDURES

5.1 Geotechnical Spread on Wilson Adriatic

5.1.1 General

The vessel was mobilised with Geo's Heavy Seabed CPT Rig, GeoScope, in order to perform all CPTUs. The rig was mobilised in the enhanced version that provides 250 kN thrust at seabed. A lubrication system that during the seabed testing is able to minimise the friction between the soil and the push rods was also mobilised to form the enhanced version of the setup.

Geo's seismic wave generator system, GeoThor, for the production of seismic CPTUs was also mobilised for this campaign. The GeoScope and GeoThor seabed units were operated over the side of the vessel by separate launching systems (can be seen on Figure 3.1).

The mobilisation of all equipment was carried out in Port of Esbjerg, Denmark and demobilisation was carried out in Port of Thyborøn, Denmark.

5.1.2 CPTUs

The overall dimensions for the GeoScope are a base plate diameter of 2.4 m and a height of 3.4 m. GeoScope has a total weight of approximately 33 tons and provides 250 kN thrust at seabed (enhanced version). The rig was handled by Geo's modular launch/recovery system mounted over the side on Wilson Adriatic.

The basic CPTU thrust system is a hydraulic dual clamp system, applying continuous penetration and full control of the total thrust applied to the CPTU rods. A hydraulic control system maintained the penetration rates in accordance with the requirements. Test data (q_c, f_s and u), tool inclination and penetration length were recorded with a frequency of minimum 1 reading pr. second.

Further technical specifications for the GeoScope set-up are presented in the Operational Report.

The CPTUs were conducted in accordance with ISO 19901-8 (ref. 01). Tip resistance, sleeve friction, pore water pressure and inclination of the cone were recorded during each test. The cones used were of the standard Van den Berg 60-degree type with cross sectional area of 10 cm². The cone geometry, filter and sleeve diameter, joint-widths and rods were in agreement with the ISO recommendations. The CPTU tests were performed with a friction reducer mounted on the CPTU rods. The pore pressure filter stones were all saturated in silicon oil prior to deployment.

Tests were terminated in accordance with one of the following criteria:

- Target penetration depth of 50-70 m (Max. Penetration Depth)
- Maximum thrust of 250 kN (Max. Thrust)
- Friction sleeve of 2.0 MPa = 30 kN for 10 cm^2 cones (Max. Sleeve)
- Tip resistance of 100 MPa = 100 kN for 10 cm^2 cones (Max. Tip)
- Gradual increase of cone inclination to max. 15 degrees (Max. Incl.)
- Sudden increase of inclination more than 3 degrees (Max. Incl. Dev.)
- Operators stop due to risk of damaging the equipment (Operator Stop).

The cone calibration data, for the cones used during the campaign, are presented in the Operational Report (ref. 02).

5.1.3 Lubrication System

In order to reduce the friction arising between the soil and the push rods, a lubrication system were installed as an integrated part of the GeoScope system.

The lubrication system was applied on all locations with conventional CPTUs (not on the SCPTU locations).

The lubrication was applied at a safe distance (larger than 400 mm from the tip) behind the CPT cone and was via the friction reducer performed from start of the test at seabed level and until end of the test at target or refusal depth.

The fluid was subject to the planned target depth and actual water depth applied as a combination of hydrostatic (top part), and constant pressure at the deeper part.

5.1.4 Seismic CPTUs

The production of seismic CPTU (SCPTU) were carried out using Geo's seabed CPTU rig, GeoScope, together with Geo's seismic shear wave hammer, GeoThor, that facilitates shear waves in two opposite directions. Both GeoScope and GeoThor were operated separately over the side of the vessel. A general description and technical specification for GeoScope and GeoThor are presented in the Operational Report.

The performance of the SCPTU testing is conducted through a launching operation that makes it possible to place GeoThor and GeoScope next to each other on the seabed. The distance from the hammer to the CPT was measured by a sonar installed on the GeoThor rig. Further, both rigs were equipped with USBL beacons for position determination.

When both rigs were positioned, CPTU testing was commenced and performed down to level for the first seismic test. In general, three strokes per test depth were made in each direction of “left” and “right”. The recording of compression waves was performed based on a generated shear wave.

The seismic signals were recorded with Geo’s in-house dual-head setup, working as an add-on module to our CPTU system. The dual-head consists of two accelerometers, with a fixed distance of 0.5 meter, each logging movements in XYZ directions. Penetration was stopped for every 1 meter, and seismic hammer stokes were performed. The seismic signals were recorded for every 0.5 meter, from seabed to refusal of the SCPTU. Each stroke was evaluated immediately after recording, and saved if passing the QC. The seismic CPTUs were conducted in accordance with ISO 19907-8.

5.1.5 Zero-values and Settlement of Seabed Rigs

Before and after each CPTU and SCPTU (at deck), zero values from the cone are logged for verification of the test data.

Zero values for each CPTU test are presented in Enclosure B.03. The zero values are one of the control measures to check if the CPT data recorded are of good quality. Before each test, the cone is visually checked and cleaned. The pore pressure filter is de-aired in silicon oil to ensure it is saturated at start of test.

Furthermore, the zero values are also used to evaluate the apparent “application class” for each CPTU according to Table 2 in ISO 19901-8 (ref. 01) and the “class” is presented in Enclosure B.03. The calculation uses the observed deviation (between before and after test zero readings) as input. In the evaluation, the measured value is defined as the highest measured parameter in the actual test. The comparable results for each test are shown in Enclosure B.03. The resulting “class” for each from this evaluation is based solely on the zero values and should only be used as a control measurement. The final acceptance of a test is based on a combined evaluation based on recorded zero values and other test observation that could have an impact on the test results (e.g. sudden change in inclination, intermediate stop caused by reached max. value etc.).

Settlement of the GeoScope rig was calculated based on the depth transducer measurements combined with load cell measurements on the lifting wire, handling the CPTU rig.

The estimated settlement is for each position presented and summaries in Enclosure B.01. The settlements are estimated with an uncertainty of approx. +/- 0.1 m. For many of the performed tests the observed settlements were “insignificant” (less than 0.1 m). Rig settlements for each test position are listed in Enclosure B.01. The CPT data levels are corrected at the positions with observed settlement.

At one location (SCPT-31), testing was not performed due to soft seabed, and it was not possible to place GeoScope without too much inclination.

5.2 Geotechnical Spread on L/B Jill

5.2.1 Geotechnical Drilling & Sampling

Geotechnical drilling was performed from Geo's specially designed drilling platform. The drilling platform was equipped with a Nordmeyer GmbH DSB 1/5 drilling rig facilitating both conventional drilling and drilling with the genuine Geobor-S system. The Geobor-S system secures the possibility to perform a wide range of sampling methods and Down-The-Hole tests, including core drilling, push sampling (Shelby Tubes), piston sampling, hammer sampling, DTH-CPTU testing and borehole logging.

The setup comprises a DTH-system operator office, workshop, laboratories (both geological and geotechnical), recycling drilling mud system, hydraulic power unit and sample storage.

Technical specifications for the drilling set-up including laboratory facilities are presented in Appendix III.

The boreholes were performed as sample boreholes or DTH-CPTU boreholes. Sample type and method were selected according to information from the performed seabed CPTU tests and the geology encountered during the drilling work. Various types of disturbed and undisturbed samples were collected by the use of various techniques and tools. A detailed description of the sampling is presented in Section 5.2.2. Further specifications for the sampling equipment are presented in the Operational Report (ref. 03).

5.2.2 Sampling

Undisturbed Sampling – Push Samples and Piston Samples:
Undisturbed Push Samples (Shelby Tubes) have been collected at 1 m intervals in cohesive soil. The sample tube could be equipped with a piston, generating a vacuum behind the sample, which in especially more silty and sandy soils often enabled a better recovery. The samples have been collected in thin-walled shelby tubes (TW), with an outer diameter of 75 mm, an inner diameter of 70 mm and a sampling length of 1000 mm (900 mm for the piston version). The push samples have been collected by the use of Geo's two DTH sample tools respectively for the 8" casing and the Geobor-S.

Hammer Sampling:
Hammer samples have mostly been collected where the expected sediment has little or no cohesive components or where a piston/push sample was not assessed to be suitable for successful sampling. All hammer samples were performed with basket and were subsequently extruded offshore.

Core sampling:

All cores have been collected in PVC lines, which form part of the Geobor-S core drilling system with an outer diameter of ø146 mm and inner diameter ø110 mm. The core runs have ranged between 0.5 - 1.5 m according to geological conditions.

5.2.3 Offshore Laboratory Work during Borehole Campaign

The following tasks have been carried out in the offshore laboratory:

- Extruding undisturbed samples and splitting PVC liners (cores and hammer samples)
- Core logging, geological description by a geologist of all samples
- Photography of all undisturbed samples, cores, and disturbed samples (hammer, bailer etc.)
- Pocket penetrometer and tor vane test on appropriate cohesive soil samples
- Determination of moisture content
- Determination of bulk and dry density
- Determination of Total Core Recovery (TCR) for all cores
- Selection and preservation of core sub-samples for onshore testing.

5.2.4 Preservation and Storage of Samples

The sub-samples have been preserved as follows:

- Shelby tubes – Preservation of the extruded sample is done in polythene film, aluminium foil, bubble plastic, wax and cardboard tubes
- Core samples – Preservation of sub-samples is done in polythene film, aluminium foil, bubble plastic wax and cardboard tubes. The remaining core are stored in the tube and the tube is wrapped in polythene film.
- Bulk sample – Each sample is stored in a plastic bag, which again is stored in one or more heavy duty plastic bags for each borehole.

5.2.5 DTH-CPTU

DTH-CPTUs were performed in all the boreholes. The tests were carried out with Geo's Down-The-Hole CPTU equipment 'Geo 2012 DTH'.

The CPTUs were conducted in accordance with ISO 19901-8 (ref. 01). Tip resistance, sleeve friction, pore water pressure and inclination of the cone were recorded during each test. The cones used were of the standard Van den Berg 60-degree type with cross sectional area of 10 cm². The cone geometry, filter and sleeve diameter, joint-widths and rods were in agreement with the ISO recommendations. The pore pressure filter stones were all saturated in silicon oil prior to deployment.

The cone calibration data is presented in the Operational Report (ref. 03).

With the listed equipment, it was possible to perform DTH-CPTU tests with a maximum penetration of either 2 m of 3 m.

The DTH-CPTU tests were terminated in accordance with one of the following criteria:

- Target penetration depth = 2.0 m or 3.0 m (Max Stroke depending on which tool is used)
- Maximum thrust of 100 kN (Max. Thrust)
- Friction sleeve of 2.0 MPa = 30 kN (Max. Sleeve)
- Tip resistance of 100 MPa = 100 kN (Max. Tip)
- Sudden increase of inclination more than 3 degrees (Max Incl. Dev.)
- Operators stop due to risk of damaging the equipment (Operator Stop).

5.2.6 Zero-values

Before and after each DTH-CPTU, zero values from the cone are logged for verification of the test data.

Zero values for each CPTU test are presented in Enclosure B.06. The zero values are one of the control measures to check if the CPT data recorded are of good quality. Before each test, the cone is visually checked and cleaned. The pore pressure filter is de-aired in silicon oil to ensure it is saturated at start of test.

Furthermore, the zero values are also used to evaluate the apparent “application class” for each CPTU according to Table 2 in ISO 19901-8 (ref. 01) and the “class” is presented in Enclosure B.06. The calculation uses the observed deviation (between before and after test zero readings) as input. In the evaluation, the measured value is defined as the highest measured parameter in the actual test. The comparable results for each test are shown in Enclosure B.06. The resulting “class” from this evaluation is based solely on the zero values and should only be used as a control measurement. The final acceptance of a test is based on a combined evaluation based on recorded zero values and other test observations that could have an impact on the test results (e.g. sudden change in inclination, intermediate stop caused by reached max. value etc.).

5.2.7 P-S Logging

P-S Logging was carried out by Geo’s subcontractor Robertson Geologging Ltd. Equipment used for the P-S Logging is presented in the Operational Report.

During a single launch and recovery operation, the tests have been performed using a digital P-S suspension log probe. The P-S 'suspension' is a low frequency acoustic probe designed to measure compressional (Vp) and shear-wave (Vs) velocities in soils and soft rock formations. The instrument is capable of acquiring high-resolution P and S wave data in large borehole depths.

5.3 Laboratory Work – Test Program and Standards

The laboratories used for the testing of samples are summarised in Table 5.1. Reference to the applied test standards are listed in Table 5.2.

Table 5.1 – Summary of laboratories used for laboratory testing on borehole samples

Test/Laboratory Boreholes	**Geo off-shore**	**Geo on-shore**	**GSTL**	**NSC**
Geological description	X[1)]			
Moisture Content	X			
Bulk Density	X			
Pocket Pen	X			
Tor Vane	X			
Atterberg Limits		X		
Particle Size Distribution		X		
Particle Density		X		
Maximum and Minimum density		X		
Microfaunal and Palynofloral Dating				X
Organic content (LOI)		X		
Carbonate Content		X		
Acid soluble chloride			X	
Acid soluble sulphate			X	
Angularity		X		
Thermal Conductivity		X		
Oedometer (IL)		X		
UU		X		
DSS		X		
CAU_c and CAU_e – compression and extension		X		
CID		X		
CIU		X		

Test/Laboratory Boreholes	Geo off-shore	Geo on-shore	GSTL	NSC
CAUcy		X		

1) Subsequent adjusted according to laboratory test results.

Table 5.2 – Test standards used for the laboratory work

Test	Standard
Geological description	Dgf Bulletin 1E, rev. 1
Moisture Content	CEN ISO/TS 17892-1:2014
Bulk Density	CEN ISO/TS 17892-2:2014
Pocket Pen	Dgf Bulletin 15, Clause 6.3
Tor Vane	Dgf Bulletin 15, Clause 6.2
Atterberg Limits	CEN ISO/TS 17892-12:2018
Particle Size Distribution	CEN ISO/TS 17892-4:2016
Particle Density	CEN ISO/TS 17892-3:2015
Max and min density	DGF Bulletin 15
Microfaunal and Palynofloral Dating	In-house zonal nomenclature by NSC
Organic content (LOI)	ASTM D2974 – 07a
Carbonate Content	BS 1377-3:1990
Acid soluble chloride	BS 1377-3: 7 1990
Acid soluble sulphate	BS 1377-3: 5 1990
Angularity	Powers, 1953
Thermal Conductivity	ASTM D5334 – 14
Oedometer (IL)	CEN ISO 17892-5:2017
UU	CEN ISO/TS 17892-8:2018
DSS	ASTM D6528 – 07
CAU_c and CAU_e – compression and extension	CEN ISO/TS 17892-9:2018
CID	CEN ISO/TS 17892-9:2018
CIU	CEN ISO/TS 17892-9:2018
CAUcy	ASTM D5311 – 13

5.4 Soil Sections Available for further Advanced Testing

After completion of the laboratory works, there are still some sections of soil, which are available for further advanced testing. Further advanced testing could be performed on remaining core material and Shelby tubes restored by waxing.

By far, the most Shelby tubes has been extracted and only a few is restored by waxing. A substantial quantity of cores are restored although testing has already been performed on selected cores.

Enclosure F.03 presents the remaining restored material by waxing (both Shelby and core material) and all cores extracted. Each core including recovery length is detailed. Some material of the cores may have been used for already performed testing and an overview of performed tests is included in each borehole log in Enclosure D.08.

6 VERIFICATION CHECKS AND EQUIPMENT CALIBRATION

6.1 CPTU Cones

All cones used were calibrated in accordance with the given standards and Geo procedures. In total, 11 cones have been used (8 on the seabed campaign and 3 on the borehole campaign). The cone calibration and standard dimension data for the cones are enclosed in the Operational Report.

In addition to the above cone calibration, each cone was checked and approved to be fully functional in the field prior to deployment using a special field-press system, which checks the output signals from the cone tip, sleeve stress and pore pressure cell. All the pore pressure filters were saturated in silicone oil prior to deployment.

The CPTU operators observed the pore pressure readings during the whole campaign. If the pore pressure filters were blocked during a CPTU attempt, the filters were replaced for the next attempt. Filter changes were performed frequently during the campaign.

Prior to commencement of any seabed CPTU testing, “zero readings” of each cone sensor were logged on deck. The cone sensors were also logged just before commencement of each test, at which time the cone tip was positioned at the reference level. To check the full functionality of the cone upon testing, the zero values were recorded after the test at the reference level and deck, and compared with the initial zero values. A list of these values and deviations are shown in Enclosure B.03 and B.06.

6.2 Verification of Positioning Systems

A positioning check of the systems was performed during the mobilisation by external surveyors

Documentation of the positioning check for Wilson Adriatic and L/B Jill is included in the Operational Report.

7 SEABED LEVEL MEASUREMENTS

7.1 Seabed CPT Campaign

Water depths have been monitored with a pressure transducer mounted on GeoScope. The seabed level relative to MSL was calculated by combining the measured water depth with the absolute measured height recorded by the positioning system.

The calculated seabed levels for each of the CPTU locations are presented on the test logs and summaries.

7.2 Borehole Campaign

The level of the seabed has been measured through a combination of the GNNS receiver and a measuring wire. The measured seabed levels have been converted to MSL levels.

8 JACK-UP LEG PENETRATION

The recorded penetration of the legs/pads were generally less than 1 meter at most of the borehole locations. Larger penetrations of 2 to 4 m were recorded at borehole BH-09 and BH-04.

The borehole positions (as built) are presented on all logs and in the summary sheet in Enclosure B.04.

The positions of the legs (while the vessel was jacked up) along with the registered penetration into the seabed for each leg are presented in the summary sheet in Enclosure B.08.

9 RESULTS FROM SEABED CPTU'S

9.1 CPTU Summary

A total of 81 CPTUs were carried out with penetration depths between 2.2 and 58.9 mbsb. The average penetration depth for the tests during this campaign was 27.9 m.

The final penetration depths, coordinates, seabed levels, termination reason, identification and size of cone used are listed in the summary in Enclosure B.01.

The performed seabed CPTUs are plotted and presented on the General Location Plan in Enclosure A.01 and on the Detailed Location Plan in Enclosure A.02

During the CPTU testing, a total number of 9 dissipation tests were performed. The results are presented in Section 9.4.

The accumulated quantities are listed in Table 9.1.

Table 9.1 – Accumulated quantities for seabed CPTUs and Dissipation Tests

CPTUs (pcs.)	CPTUs (meters)	Dissipation Tests (pcs.)
81	2,257	9

In general, less than 0.4 m of rig settlement was observed during the performed tests, but at a single location (SCPT-31), testing was not performed due to excessive settlement and inclination of the seabed CPT rig.

9.2 Seabed CPTU Logs (measured values)

A combined log for all the performed CPTU strokes for each location is presented on Enclosure D.01. All CPTU tests are presented with the standard depth scale of 1 cm = 0.5 m (paper size A3) and are plotted against depths (with correction for inclination).

On all CPTU logs, the calculated seabed levels have been used.

The following data are presented on the logs for each test:

- q_c is the measured cone resistance. The values are shown in two scales, 0-10 MPa and 0-100 MPa.
- f_s is the measured sleeve friction resistance

- u is the pore water pressure
- R_f is the calculated friction ratio. Friction ratio is the ratio between the measured sleeve friction and the measured cone resistance i.e., $R_f = f_s/q_c$
- F_r = the normalised sleeve friction. F_r is defined by $F_r = \frac{f_s}{q_t - \sigma_{v0}}$
- B_q = the pore pressure ratio. B_q is defined by $B_q = \frac{u - u_0}{q_t - \sigma_{v0}}$

Legend and definitions for the CPTU logs are presented in Enclosure C.01.

9.3 Seabed CPTU Logs (interpreted values)

9.3.1 General

The seabed CPTU results are presented by a log for each test location in Enclosure D.02. All CPTU tests have been presented with the standard depth scale of 1 cm = 0.5 m (paper size A3). All the results have been plotted against depths with correction for inclination.

On all CPTU logs, the calculated seabed levels have been used.

The following data are presented for each test.

- q_t is the corrected cone resistance. The values are shown in two scales, 0-10 MPa and 0-100 MPa.
- f_t is the corrected sleeve friction resistance
- u is the pore water pressure
- Q_t is the normalised cone resistance
- F_r is the normalised sleeve friction
- φ' is the angle of internal friction
- c_u is the undrained shear strength
- D_r is the relative density
- B_q is the pore pressure ratio
- R_{ft} is the corrected friction ratio
- Auto interpretation of soil behaviour type.

An explanation of the abbreviations used in the processing is given below:

- q_t = the measured cone resistance corrected for the effects of cone shape and pore water pressure. q_t is defined by $q_t = q_c + (1 - a) \cdot u$

- a = the ratio of the area of the cone shaft to the area of the cone face. The ratio for the 10 cm^2 cone is 0.75.
- q_c = the measured cone resistance
- f_t = the measured cone sleeve friction corrected from the effects of pore water pressure. f_t is defined by $f_t = f_s - 0.005 \cdot (u - u_0)$
- f_s = the measured cone sleeve friction
- u = the pore water pressure measured behind cone
- u_0 = the in situ hydrostatic pore water pressure (relative to seabed level)
- Q_t = the normalised cone resistance. Q_t is defined by $Q_t = \frac{q_t - \sigma_{v0}}{\sigma'_{v0}}$
- σ_{vo} = the vertical stress. σ_{vo} is defined by $\sigma_{v0} = \gamma \cdot d$
- γ = the unit weight of the soil. γ is set to 19 kN/m^3
- d = depth in m below seabed
- σ'_{vo} = the effective vertical stress. σ'_{vo} is defined by $\sigma'_{v0} = \gamma' \cdot d$
- γ' = the submerged unit weight of the soil. γ' is set to 9 kN/m^3
- F_r = the normalised friction ratio. F_r is defined by $F_r = \frac{f_s}{q_t - \sigma_{v0}}$
- φ' = the angle of internal friction. φ' is defined by

  $N_q = tan^2\left(\frac{\pi}{4} + \frac{\varphi'}{2}\right) \cdot exp\left(\left(\frac{\pi}{3} + 4 \cdot \varphi'\right) \cdot tan(\varphi')\right)$

  According to Lunne and Christoffersen (1983) (ref. 04).
- N_q = bearing capacity factor. N_q is defined by $N_q = \frac{q_t}{\sigma'_{v0}}$
- c_u = derived undrained shear strength. c_u interpretation is described in Section 9.3.3.1
- D_r = derived relative density. D_r interpretation is described in Section 9.3.3.2
- B_q = the pore pressure ratio. B_q is defined by $B_q = \frac{u - u_0}{q_t - \sigma_{v0}}$
- R_{ft} = the ratio of the corrected cone sleeve friction to the corrected cone resistance. R_{ft} is defined by $R_{ft} = \frac{f_t}{q_t} \cdot 100\%$
- Interpretation of soil behaviour. The interpretation is described in Section 9.3.2.

Legend and definitions for the CPTU logs are presented in Enclosure C.02.

9.3.2 Interpretation of Soil Behaviours

The soil type given on the CPTU logs is based on the Soil Classification schemes proposed by Robertson (1986) (ref. 05). The module to be used was discussed and agreed with Energinet during the initial part of the project.

The interpretations of soil behaviours, presented on the CPTU Logs in Enclosure D.02, have all been automatically generated, and are solely based on the empirical model. The soil model is shown in Figure 9.1 and Table 9.2.

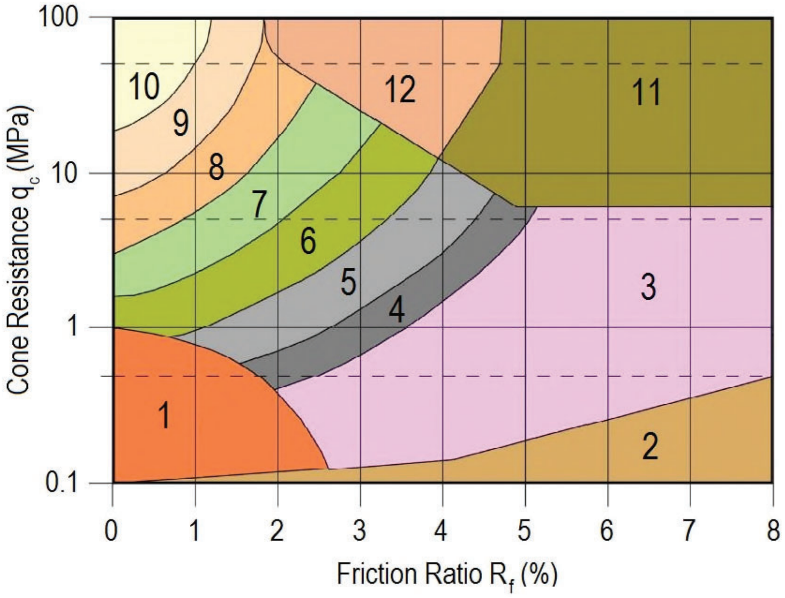

Figure 9.1 – Robertson (1986) CPT Soil Classification

Table 9.2 – Robertson (1986) CPT Soil Classification

Zone	Soil Behaviour Type (SBT)
1	Sensitive, fine grained
2	Organic soils: peat, clay
3	CLAY
4	CLAY - Clay to silty clay
5	SILT mixtures - Clayey silt to silty clay
6	SILT - Sandy silt to clayey silt
7	Fine SAND mixtures - Silty sand to sandy silt
8	SAND - Sand to silty sand
9	SAND - Coarse to medium sand
10	Gravel mixtures - Gravel to gravelly sand
11	(Very stiff fine grained / Hard clay silt weak rock)
12	(Very compact sand to clayey sand)

The soil types should always be considered and compared in relation to adjacent borehole and other geotechnical information from the site, and treated with caution.

9.3.3 Strength Parameters

The geotechnical parameters derived from the cone penetration test results are described in the sections below.

9.3.3.1 Undrained Shear Strength

The undrained shear strength (c_u) has been determined from:

$$c_u = \frac{(q_t - \sigma_{v0})}{N_{kt}}$$

where q_t is the corrected cone resistance (kPa)
σ_{vo} is the vertical stress (kPa)
N_{kt} a cone factor (see comment below).

The undrained shear strength (c_u) has been derived using N_{kt} factors of lower bound 10 and upper bound 20, which are assumed representative of the actual soil. This range of Nkt factors are based on general experience of N_{kt} factors used on adjacent sites and also based on an evaluation of N_{kt} factors based on CAU laboratory tests and CPT data from the site. At specific locations N_{kt} is determined by the above formula where c_u is derived from the laboratory results and q_t and σ_{v0} is derived from the CPT data. A documentation of these N_{kt} determination is included below in Figure 9.2

The interpretation of c_u is presented on the interpreted CPTU logs, Enclosure D.02. The results from c_u are provided for cohesive formations and cohesive mixture soils – zone 6 and 7 on the classification model presented in Figure 9.1 and Table 9.2.

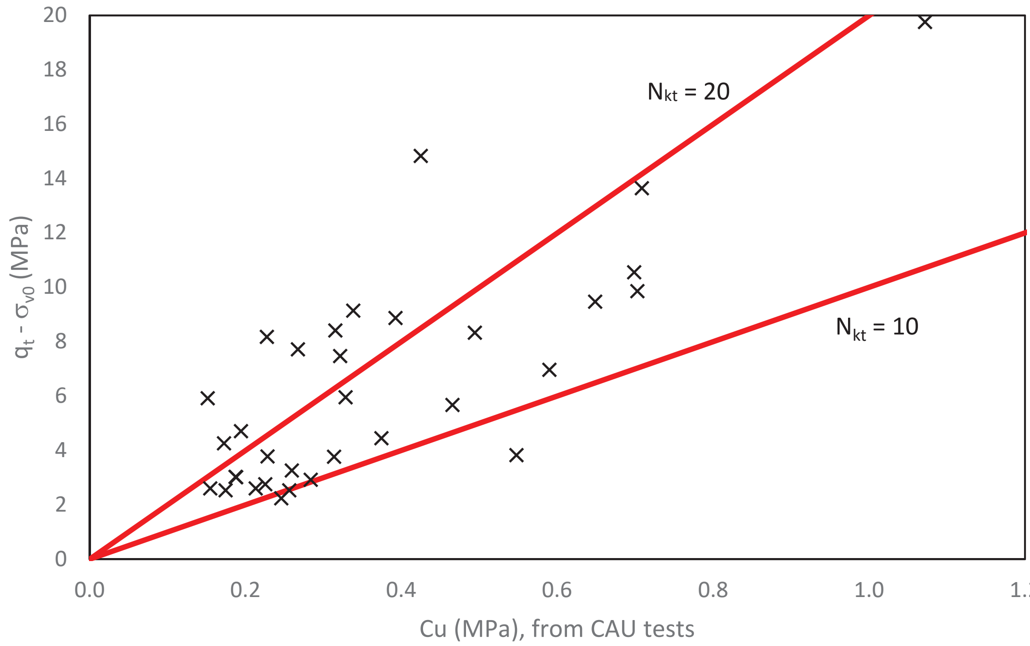

Figure 9.2 – Plot of N_{kt} values determined from a combination of CAU test results and CPTU test results from the site. Red lines indicates range of N_{kt} values from 10 to 20.

9.3.3.2 Relative Density

The relative density (D_r) is estimated by the expression below:

$$D_r = \frac{1}{C_2} \cdot ln \left[\frac{q_c}{C_0 \cdot \left(\sigma'_{v0} \left(\frac{1 + 2 \cdot K_0}{3 \cdot 100} \right) \right)^{C_1}} \right]$$

where	q_c	is the measured cone resistance (MPa)
	σ'_{vo}	is the effective vertical stress (kPa)
	K_0	is the coefficient of earth pressure at rest (see comment below)
	C_0	2.494
	C_1	0.46
	C_2	0.0296

The equation is based upon Jamiolkowski (2003), (ref. 06). In the equation, K_0 has been set to 0.5 and 1.0, which are assumed representative of the actual soil and these K_0 factors have been used on previous investigations on the site.

The interpretation of D_r is presented on the interpreted CPTU logs, Enclosures D.02. The results from D_r are provided for granular strata and mixture soils – zone 6 and 7 in classification model.

9.4 Dissipation Tests

A total number of 9 dissipation tests were performed during the campaign. The logs are presented in Enclosure D.07.

Table 9.3 – Overview of dissipation tests

CPTU Test	Test Level (mbsb)	Comment
CPT-23	11.47	
CPT-27	21.45	
CPT-35a	43.58	
CPT-36	42.98	
CPT-57	13.73	
CPT-60a	16.90	
CPT-68	11.70	
CPT-83	9.45	Results not valid. Log not presented in report.
CPT-84	30.15	

9.5 Comments to Seabed CPTU Results

The combination of enhanced CPTU and lubrication provided the best basis for reaching the target depth of 50-70 mbsb. Average penetration depth for the campaign was 27.9 m.

The majority of the CPTU tests were carried out successfully. Any specific remarks to the individual tests are included on the CPTU summary, Enclosure B.01.

In order to penetrate the very dense sand the refusal criteria for q_c was occasionally exceeded. The exceeding was performed where the CPT operator deemed the risk for damaging the cone & rods limited and the possibility for further penetration, positive.

At locations where boreholes was also performed, there was in general found a good correlation between the interpreted CPTU results and borehole logs. The main boundaries lie within the same levels for both the CPTU results and the borehole logs, although some discrepancies are seen at some locations. These discrepancies is likely to occur due to the horizontal displacement between the borehole and seabed CPTU locations.

10 RESULTS FROM SEISMIC CPTU'S

10.1 SCPTU Summary

A total of 14 SCPTUs were carried out with penetration depths between 1.1 and 37.0 mbsb. The average penetration depth for the SCPTUs under this campaign was 16.9 m.

A summary of key data for the positions with SCPTUs is presented in Enclosure B.01.

Enclosure B.02 presents relevant information (e.g. positions for GeoThor, GeoScope, test depth etc.) for interpretation of the seismic data from each test.

The accumulated quantities are listed in Table 10.1.

Table 10.1 – Accumulated quantities for seismic CPTUs

Seismic CPTUs (pcs.)	Seismic CPTUs (meters)
14	237

10.2 Data Processing

10.2.1 Raw Data Files

Two A. P. Van Den Berg accelerometers are connected to a CPT cone with a fixed distance of 0.5 m. The accelerometer situated closest to the seabed is labelled 'Upper' (module 2) and the other module situated closest to the cone tip is labelled 'Lower' (module 1). During recording of CPT data, the CPT operator stops the CPT cone at multiple depth positions. At each depth position, a shear wave generator (GeoThor) runs through a series of multiple 'left blows' and 'right blows' generating seismic waves that propagate through the subsurface. The accelerometers records the seismic waves as they passes by at each depth position. The recorded seismic data files are divided into data types based upon which accelerometer recorded the seismic wave, which type of wave was recorded and whether the seismic wave was generated from a left or a right blow. The division is as follows:

A. Lower accelerometer – S-wave, Left Blow.
B. Lower accelerometer – S-wave, Right Blow.
C. Lower accelerometer – P-wave.
D. Upper accelerometer – S-wave, Left Blow.
E. Upper accelerometer – S-wave, Right Blow.
F. Upper accelerometer – P-wave.

The raw seismic data files generated at each SCPT location consist of multiple two-column (array) time-series text files, one for each recording. The first column is time in the unit ms and the second column is the amplitude of the signal expressed as a velocity in the unit cm/s. The sampling period is per default set to 0.2 ms and the recording time is 600 ms. The first row of each data file consists of a string header where the ending of the header is the actual depth of the accelerometer below seabed.

Recordings begins approximately 50 ms prior to the actual seismic blow. The trigger time (i.e. the time at which the shear wave generator (GeoThor) generates a seismic wave) is marked with a 0 in the amplitude column and reflects the moment at which the actual time begins. Ideally, the trigger time should be exactly at 50 ms.

10.2.2 Processing Sequence

Prior to calculating the final Vs log, a series of signal enhancement processing steps are applied to the raw data files. The processing steps are divided into phases and are described below.

10.2.2.1 The Quality Check Phase

The raw seismic data files are imported into SCPT-Geo. SCPT-Geo displays each raw files for one or more data type(s) (i.e., A, B, D or E) at their correct depth, on a time versus depth below seabed plot. Here, the operator dynamically removes erroneous files and/or files where the S-wave signal cannot be traced. Once the data files have passed the quality check phase, the data files are now collectively termed ‘Final Raw Files’.

10.2.2.2 The Signal Correction Phase

In SCPT-Geo, the trigger time for each Final Raw File is automatically identified (ideally, the trigger time should be exactly 50 ms). In cases where the trigger time is offset in a data file (e.g. at 50.4 ms), SCPT-Geo shifts the dataset and corrects the time, so that 50.4 ms will be corrected to 50 ms. This procedure ensures that all Final Raw Files have identical trigger time.

In some cases, Null values are present in the ‘amplitude’ column in some of the Final Raw files. SCPT-Geo will automatically fill out any Null values by using linear interpolation and/or running averages.

The CPT cone can become inclined up to 20 degrees. In such cases of high inclination, the dataset needs to be depth corrected. SCPT-Geo will automatically adjust the depth information embedded in each file from ‘CPT penetration depth’ to ‘Depth below seabed’ as stated in the CPT log. The corrected files are now collectively termed Corrected Final Raw Files

10.2.2.3 The Signal Enhancement Phase

The Corrected Final Raw Files are imported into SPAS 2019 v4 (Signal Processing and Analysis Software). In SPAS, all Corrected Final Raw Files are filtered using a Butterworth Bandpass filter in the frequency range from 20 – 120 Hz. The filtering removes unwanted high frequency and low frequency noise from the Corrected Final Raw Files.

In SPAS, a time window is applied to all Corrected Final Raw Files in order to remove the parts of the signals not related to the first arriving S-wave trace. This procedure enhances the true Vs calculation in SPAS.

SPAS automatically stacks the Corrected Final Raw Files with identical depth position prior to calculating the final Vs log. The stacking procedure enhances the true signal and supress random noise.

10.3 Calculating True-Time Interval Vs

The Vs calculation method in SPAS is based on the cross-correlation method. This method identifies the interval time between two signals (e.g. between recordings from the upper and lower module) by shifting one dataset one time increment at the time and calculating the coefficient of correlation (R^2) between the two arrays. This produces a new array with interval time in the first column and coefficient of correlation R^2 in the second column. The interval time corresponding to the highest R^2 value is assumed the most probable interval time (or transit time).

On the assumption that the generated waves propagate linearly from source (i.e. GeoThor) to receiver (i.e. the accelerometers), and thereby ignoring the effect of refraction, interval Vs between the two stacked signals can be calculated using the formula below:

$$Interval\ V_s = \frac{D_2 - D_1}{\Delta t}$$

Where D_2 is the straight slant distance from source (GeoThor) to receiver at the deepest depth position and D_1 is the straight slant distance from source (GeoThor) to receiver at the shallowest position, and Δt is the transit time between them. D_2 and D_1 can be calculated when knowing the horizontal distance between the source and receiver (H) and the receiver depth below seabed (Z):

$$D_x = \left({H_x}^2 + {Z_x}^2\right)^{0.5}$$

10.4 Calculating G_{max}, Unit Weight, Poissons Ratio and E_{max}

Derivation of the small strain Shear Modulus (G_{max}) from interpreted Vs is carried out using the formula below:

$$G_{max} = \rho {V_s}^2$$

Where ρ is soil density and Vs is shear wave velocity. Soil density (ρ) is an unknown parameter and is not measured directly. Soil density can be derived from Unit Weight (γ) by the following relationship:

$$\rho = \frac{\gamma}{g}$$

Where g is the gravitational acceleration (i.e. approximately 9.81 m/s^2).

The Unit Weight of the soil (γ) is derived using a depth dependent correlation with Vs described below, as proposed by Mayne (2001) (ref. 07):

$$\gamma = 8.32 * \log(V_s) - 1.61 * \log(z)$$

Where z is the depth below seabed in meters.

Derivation of Poissons ratio (v) from interpreted Vs and Vp is carried out using the formula below:

$$v = \frac{\left(\frac{Vp}{Vs}\right)^2 - 2}{2\left(\frac{Vp}{Vs}\right)^2 - 1}$$

Derivation of the small strain Youngs Modulus (E_{max}) is carried out using the formula below:

$$E_{max} = 2G_{max}(1 + v)$$

10.5 Logs

The SCPTU logs are shown in Enclosure D.05, each consisting of three pages (without P-wave interpretations) or six pages (with P-wave interpretations). Vs interpretations are presented as of function of depth in conjunction with the site-specific measured geotechnical parameters q_c, f_s, and u on page 1. In addition to the interpreted interval Vs based on seismic data, Vs derived from two CPT-Vs empirical correlations proposed by Mayne (2006) (ref. 08) and Robertson (2009) (ref. 09) are also shown for comparison on page 1. Logs of interpreted Vs in conjunction with the derived parameters Unit Weight and G_{max} as a function of depth is shown on page 2. Derived G_{max} from empirical CPT-G_{max} correlation proposed by Mayne (2006) (ref. 08) and Robertson (2009) (ref. 09) are also shown for comparison on page 2. Log of interpreted Vs with coloured circles indicating values derived from left shots and right shots individually are shown in conjunction with logs of correlation coefficient and signal to noise ratios for S-waves on page 3. At SCPT locations where P-waves where successfully recorded and interpreted three further pages were added. Here, Vp interpretations are presented as of function of depth in conjunction with the site-specific measured geotechnical parameters q_c, f_s, and u on page 4. Interpreted Vp and Vs are shown on a combined log on page 5 in conjunction with derived parameters small strain Youngs Modulus (E_{max}) and Poissons ratio (v). On page 6, a log of interpreted Vp is shown in conjunction with logs of correlation coefficient and signal to noise ratios for P-waves.

Tabulated data from the SCPTU tests are included in Enclosure D.06.

10.6 Comments to SCPTU tests

Due to induced noise, non-elastic soils and the effect of refraction, shear wave velocities cannot reliably be determined in the upper approximately 5 meters below seabed (re. ISO-199901-8 (8.6.3)). Derived values from these depths, although presented, should be regarded as highly uncertain.

S-waves were interpreted at all SCPT locations. P-waves were interpreted at the following SCPT locations: SCPT-25, SCPT-45, SCPT-51 and SCPT-59. All S-wave interpretations were performed using the True-Time method with a 0.5 m module spacing. All P-wave interpretations were made using the Pseudo-Time method with a 4 m module spacing. SCPT interpretations were generally performed until refusal at all SCPT locations except for at SCPT-43, here, interpretations was stopped at 20.37 m below seabed due to insufficient signal at greater depths.

The signal to noise ratio (S/N ratio) differed substantially between the SCPT locations. At SCPT-21, SCPT-33ac, SCPT-35a and SCPT-43 the S/N ratio decayed unexpectedly rapidly with depth, whereas at SCPT-25, SCPT-45, SCPT-51, SCPT-55, SCPT-55a, and SCPT-59 the S/N ratio decayed with depth as expected.

11 GEOTECHNICAL DRILLING AND SAMPLING RESULTS

11.1 Borehole Summary

A total of 18 sample boreholes were performed in 18 locations. Boreholes BH-01 to BH-17 were performed to depths between 69.3 and 70.5 meters. BH-18 was terminated at 67.8 m mbsb due to a stuck inner tube in the drill string. 2 DTH-CPTU boreholes, BH-12a and BH-17a was performed on separate locations next to the adjacent sampling boreholes and seabed CPTs.

The final drilling depths, coordinates, seabed levels etc. are listed in a summary of boreholes in Enclosure B.04.

The performed boreholes are plotted and presented on the General Location Plan in Enclosure A.01 and on the Detailed Location Plan in Enclosure A.02.

The accumulated quantities are listed in Table 11.1.

Table 11.1 – Accumulated quantities for boreholes

Sample boreholes (pcs.)	DTH-CPTU boreholes (pcs.)
18	2

11.2 Presentation of Borehole Logs

The preliminary geotechnical borehole logs with onshore classification data are available in Enclosure D.08.

On all borehole logs, the water depths relative to MSL registered during the borehole campaign have been used as level for the seabed.

The boundaries, presented on the borehole logs, between the different soil layers have been registered by the driller and the geologist during the offshore sampling and the geological description of samples.

The tip resistance (q_c) from the adjacent seabed CPTUs and DTH-CPTUs have been included on the logs.

Definitions and symbols shown on the borehole logs are listed in Enclosure C.03.

11.3 P-S Logging

P-S Logging was performed in 4 boreholes. Key data for the P-S logging are presented in the summary sheet in Enclosure B.07. Detailed P-S logging results are presented in a separate report from Robertson Geologging Ltd. in Enclosure E.01.

11.4 General Comments to the Geotechnical Drilling

The Boreholes were completed successfully with the following remarks below.

In BH-09, due to upcoming weather and no working DTH-CPT unit, it was decided to proceed with sampling while repairing CPT unit from 50 to 70 m, to ensure that the borehole could be completed before deadline for transit for shelter in Hvide Sande. The timing allowed for 3 pcs. of DTH CPTs from 68.4 m to 70 m.

In BH-18 the inner tube was stuck in the Geobor-S string at 68 m, and the entire drill string had to be recovered. The borehole was therefore abandoned at 68 m after acceptance of the Client.

12 DTH-CPTU RESULTS

12.1 DTH-CPTU Summary

The final penetration depths, coordinates, seabed levels, termination reason, identification and size of cone used are listed in the summary in Enclosure B.05.

12.2 DTH-CPTU Logs (measured values)

The measured values for the DTH-CPTU tests are presented according to the details given for presentation of the seabed CPTUs (see Section 9.2).

A combined log for all the individual CPTU strokes for each location are presented together with data from the adjacent seabed CPTU in Enclosure D.03.

12.3 DTH-CPTU Logs (interpreted values)

The interpreted values for the DTH-CPTU tests are presented according to the details given for presentation of the seabed CPTUs (see Section 9.3).

A combined interpretive log of soil behaviours for all the individual CPTU strokes at each location are presented together with data from the adjacent seabed CPTU in Enclosure D.04.

12.4 Comments to DTH-CPTU Results

Any specific remarks to the individual tests are included in the Summary in Enclosure B.05.

13 LABORATORY TEST RESULTS

13.1 General

The laboratory tests are conducted to describe the state of the soil as well as for determining the fundamental characteristics of the ground conditions.

Onshore laboratory testing has been carried out according to the Scope of Work and the laboratory guidance note, established in the beginning of the project.

During geological description of the samples they have been photographed and photos is included in Enclosure F.01.

13.2 Laboratory Test Overview

An overview of all tests carried out on the boreholes is presented in Table 13.1. and Table 13.2.

Table 13.1 – Overview of quantity of classification tests

Test Type	Moisture Content	Bulk and Dry Density	Pocket Pen	Tor Vane	Atterberg Limits	Sieve	Sieve + Hydrometer	Particle density	Maximum and Minimum Dry Density	Microfaunal and Palynofloral dating	Loss on Ignition	Carbonate Content	Chemical Testing (Acid Soluble Sulphide/Chloride)	Angularity	Thermal Conductivity
Tests in Total	609	123	484	480	121	51	154	138	61	19	36	40	36	24	18

Table 13.2 - Overview of quantity of advanced tests

Test Type	Triaxial Test, UU	Direct Simple Shear, DSS	Triaxial Test, CID	Triaxial Test, CIU	Triaxial Test, CAU	Cyclic Triaxial Test, CAUcy	Oedometer, Incremental Loading, IL
Tests in Total	55	12	42	6	33	10	50

13.3 Laboratory Testing – Index Tests

13.3.1 Tor Vane

Tor Vane (TV) has been carried out on cohesive material for determination of undrained shear strength. It should be noted that the maximum value that can be measured by the TV is 250 kPa. The tests have been carried out according to Dgf Bulletin 15, Clause 6.2.

The results from these tests are provided on the borehole logs in Enclosure D.08 and in the summary table in Enclosure G.01.

13.3.2 Pocket Pen

Pocket Penetrometer (PP) has been carried out on cohesive material for the determination of undrained shear strength. It should be noted that the minimum and maximum value that can be measured by the pocket penetrometer are 25 kPa and 1000 kPa, respectively. The tests have been carried out according to Dgf Bulletin 15, Clause 6.3.

The results from these tests are provided on the borehole logs in Enclosure D.08 and values are included in the summary table in Enclosure G.01.

13.4 Laboratory Testing – Classification Tests

13.4.1 Moisture Content

Moisture content has been measured following the test procedures described by CEN ISO/TS 17892-1:2014. Moisture content was determined on cohesive and organic soil types retrieved from the boreholes.

The results of the water content determination tests are considered reliable and representative of the different types of material encountered across the site.

The results of these tests are plotted on the borehole logs given in Enclosure D.08 and values are included in the summary table in Enclosure G.01.

13.4.2 Bulk and Dry Density

Bulk and Dry Density have been measured following the test procedures described by CEN ISO/TS 17892-2:2014. Bulk and Dry Density were determined on cohesive and organic materials retrieved from the boreholes. A total of 123 tests were carried out.

The results of these tests are plotted on the borehole logs given in Enclosure D.08 and values are included in the summary table in Enclosure G.01.

13.4.3 Particle Size Distribution

Particle size distributions were determined onshore according to CEN ISO/TS 17892-4: 2016. When the content of fines exceeds 10 %, a hydrometer analysis was performed. A total of 205 Particle Size Distribution analysis were carried out.

In general, the results from the particle size distribution test confirmed the visual descriptions that were made offshore; however, some sample descriptions had to be updated to reflect additional data provided by the particle size distribution. For some of the samples the laminated nature of the soil can lead to what seems to be a discrepancy between the geological description and the measured content of sand, silt and clay. Here an overall comparison of the description to the particle size distribution have been made, in order to give the best impression of the soil behaviour.

The samples tested are marked on the borehole logs given in Enclosure D.08. Main results (D_{10}, D_{50} D_{60}, $D_{90,}$ Cu) are included in the summary table in Enclosure G.01. Detailed test results from the individual tests are found in Enclosure G.02.

13.4.4 Atterberg Limits

The liquid and plastic limits were determined onshore according to CEN ISO/TS 17892-12:2018. A total of 121 tests were carried out.

The plasticity index, I_p varies from 8 % to 61 % between the soil types. The variation in plasticity index in some of the units (e.g. the meltwater deposits and Neogene soils) can be explained by the lamination of the soil. Within few centimetres, these soils can vary from streaks of sand to clay parts/layers. The geological description is generally made to correspond with the dominant clay type. The results of Atterberg Limit testing is taken into consideration for the soil classification, but also the lamination of the soil is taken into account when comparing the testing result with the soil classification.

The results of the plasticity determinations are considered reliable and representative of the material encountered across the site.

The results are plotted on the borehole logs given in Enclosure D.08 and values are included in the summary table in Enclosure G.01.

13.4.5 Organic Content (Loss on Ignition)

The organic content was determined onshore by loss on ignition according to ASTM D2974 – 07a. A total of 36 tests were carried out. The organic content has been conducted in organic soil types and varies between 1 and 43 %. The Neogene deposits has shown quite high values, which confirms the visual inspection of the cores, where most sections seemed rather organic, especially the clays. In meltwater clays, where the content of iron sulphide was dominant, the tests also confirmed the organic origin of these deposits.

The results of the organic content determination tests are therefore considered reliable and representative of the material encountered across the site.

The results are plotted on the borehole logs given in Enclosure D.08 and values are included in the summary table in Enclosure G.01.

13.4.6 Calcium Carbonate Content

The calcium carbonate contents were determined onshore according to BS 1377-3:6 1990. A total of 40 determinations were carried out. Calcium carbonate content has been conducted in all soil types, most of them within the top 10 meters of the borehole and in association with chemical tests. The results varies between 0 and 17.8 %.

Locally, the carbonate content is fairly high, though still within the limit for calcareous material. The high carbonate content in the marine postglacial clay is evaluated to be caused by shells and shell fragments.

The results are plotted on the borehole logs given in Enclosure D.08 and values are included in the summary table in Enclosure G.01.

13.4.7 Thermal Conductivity

Thermal conductivity measurements were determined onshore according to ASTM D5334-14. A total of 18 tests were carried out, one in each borehole in an approximate depth of 1 m below seabed. The results vary between 1.13 and 3.52 W/mK.

The results are considered reliable and representative of the material encountered across the site.

The results are plotted in the borehole logs given in Enclosure D.08. Detailed test results from the individual tests are found in Enclosure G.03.

13.4.8 Maximum and Minimum Dry Density

The maximum and minimum density were determined onshore according to DGF Bulletin 15. A total of 61 determinations were carried out.

The results are plotted in the borehole logs given in Enclosure D.08. Detailed test results from the individual tests are found in Enclosure G.04.

13.4.9 Angularity Test

The angularity tests were carried out according to Powers 1953. A total of 24 soil samples were examined, mostly with the fractions from 0.063 – 0.25 mm , 0.25 – 1 mm and 1 - 16 mm in focus.
Approximately 100 grains were evaluated per fraction, and only fractions that exceeded this number has been included in the test. In total 60 individual fractions within the above mentioned grain size ranges were tested on the 24 selected samples. For each sample, the average angularity for all fractions is added and hence the dominant angularity of the particles was found for each sample. The angularity tests were generally performed in connection to CID tests.

Detailed test results from the individual tests are found in Enclosure G.05.

13.5 Laboratory Testing – Advanced Tests

13.5.1 Triaxial Test – Unconsolidated Undrained (UU)

Unconsolidated Undrained triaxial tests (UU) have been carried out on intact fine grained material according to CEN ISO/TS 17892-8:2018 to determine the undrained shear strength. A total of 55 tests have been carried out.

Test specimens were prepared from core samples to a height / diameter ratio of 2:1. The tests was carried out at a stress level corresponding to the total in-situ stress, evaluated as:

> Total in-situ stress = Depth below seabed [m] x 20 kN/m^3 + mean seafloor depth [m] x 10 kN/m^3.
> For all tests, the shear phase was carried out at a strain rate of 1 %/minute until 15% additional strain.
> The resulting undrained shear strength is presented as the maximum shear strength within 15% additional strain.

A test was unintentionally carried out at stresses that varied from in-situ stresses:

BH-10_7.2	Tested at σR=397 kPa and not the in-situ stress of 415 kPa. This is believed to have insignificant effect on the determined undrained shear strength and the result is considered representative.

Two tests reached maximum limit of axial stress for the load frame:

BH-02_42.1	The load frame reached its maximum limit. The test ended at this shear stress level (cu > 1374 kPa)
BH-09_46.1	The load frame reached its maximum limit. The test ended at this shear stress level. (cu>1099 kPa)

The results are plotted in the borehole logs given in Enclosure D.08. Furthermore, the results of the individual UU tests are given in Enclosure G.08.

13.5.2 Triaxial Test – Consolidated Isotropic Drained (CID)

The triaxial CID tests have been carried out on frictional soil according to ISO/TS 17892-9:2018 to determine the drained strength parameters. The tested material was reconstituted to a target density determined from the relative density from the CPT profile together with the maximum and minimum dry density. Reconstitution was carried out by tamping, with 2% undercompaction over 7 layers.

A total of 42 tests have been carried out.

The tests were carried out with the following stages:

- Installation and saturation
- Isotropic consolidation at effective in-situ stress
- Shear phase at effective in-situ stress

The results of the CID test are given in Enclosure G.10

The consolidation and shear phase in CID tests on samples BH-14 34.1D and BH-14 35.1D were carried out at ½ and 1 x in-situ effective stress respectively. This was done in agreement with the client, in order to cover a larger stress range in this formation.

13.5.3 Direct Simple Shear Tests

The Direct Simple Shear tests have been carried out on frictional and fine-grained soil according to ASTM D6528-07. A total of 12 tests have been carried out, 6 tests on reconstituted frictional soils, 6 tests on intact fine-grained material.

The intact specimens from fine-grained soil were prepared by trimming.

The specimens from frictional soil were prepared by reconstitution to a target density, based on the maximum and minimum density and the relative density determined from the CPTs.

The tests on frictional soils were conducted with the following phases:

- Installation
- Loading to in-situ stress.
- Shear phase with constant volume

Before shearing, the specimens were consolidated to 80% of the estimated pre-consolidation stress determined from the oedometer tests, then unloaded to a normal stress corresponding to the effective vertical in-situ stress. The shear rate was evaluated according to the time curve from the consolidation phase at 80% of the estimated pre-consolidation stress.

In the test on sample BH-03, 15.2U, the data logging of the test malfunctioning during the consolidation phase. Documentation from the first three consolidation phases was therefore lost. However, based on technician notes the consolidation phase has been performed according to plan. Therefore, the test results from the shearing phase are deemed valid and included in the test results.

The results of the Direct Simple Shear tests are given in Enclosure G.09.

13.5.4 Oedometer, Incremental Loading (IL)

Incremental Loading (IL) tests have been carried out on fine-grained material according to ISO 17892-5:2017. A total of 50 tests have been carried out.

The tests were conducted to determine the preconsolidation stress, the compression index and the stiffness during unloading-reloading.

Where possible, the preconsolidation stress is determined according to Casagrande, Becker and Janbu methods.

26 samples were tested for preconsolidation stress by incremental loading. The load increments were 10, 20, 40, 80, 150, 300, 600, 1200, 2400, 4800 kPa. If swell tendencies was observed, the next load-step was initiated. Below is a summary of tests that showed indications of swell. The lowest axial stress level, at which swell was no longer observed, is stated in the summary.

Sample BH-04, 34.2U swell was prevented at 20 kPa.
Sample BH-04, 45.2U swell was prevented at 80 kPa
Sample BH-05, 19.2U swell was prevented at 40 kPa
Sample BH-06, 30.2U swell was prevented at 80 kPa
Sample BH-07, 38.3U swell was prevented at 80 kPa
Sample BH-05, 48.1U swell was prevented at 80 kPa
Sample BH-08, 16.2U swell was prevented at 40 kPa
Sample BH-09, 16.2U swell was prevented at 80 kPa
Sample BH-09, 28.2U swell was prevented at 40 kPa
Sample BH-09, 34.1U swell was prevented at 80 kPa
Sample BH-10, 27.1U swell was prevented at 40 kPa
Sample BH-12, 33.1U swell was prevented at 300 kPa
Sample BH-13, 26.2U swell was prevented at 80 kPa
Sample BH-14, 15.2U swell was prevented at 80 kPa
Sample BH-14, 23.1U swell was prevented at 80 kPa
Sample BH-15, 5.1U swell was prevented at 80 kPa
Sample BH-16, 30.2U swell was prevented at 40 kPa

In 24 of the samples tested for pre-consolidation there was also performed a stiffness test on adjacent material with the following phases by incremental loading:

- Loading to estimated pre-consolidation stress
- unloading to in-situ stress
- reloading to maximum stress (4800 kPa).

The oedometric modulus for the test on sample BH-15, 5.1U_2 was interpreted starting from stress interval of σ'_v=120 kPa due to possible swell effects at σ'_v=60 kPa

The results of the Incremental loading tests are given in Enclosure G.13.

13.5.5 Triaxial Test – Consolidated Anisotropic Undrained compression test (CAU)

The triaxial CAU tests have been carried out according to DS/EN ISO 17892-9:2018. The tests were carried out to determine the undrained shear strength and if possible the drained strength parameters. A total of 33 tests have been carried out.

The tests were conducted with the following phases:

- Installation and saturation
- Area-constant loading to an axial stress of 80% estimated pre-consolidation from Incremental Loading.
- Area-constant unloading to estimated axial in-situ effective stress level
- Undrained shear phase in compression

The loading to 80% pre-consolidation stress was limited at fixed stress ratios (σ'_R / σ'_A) depending on the geological description of the soil, to reduce the risk of failure before reaching maximum consolidation stress level. These limits were modified during the execution of the test programme, to take the properties of the actual soil unit in to account.
For meltwater deposits, the stress ratio limit was increased to 0.80, as some specimens from this soil unit failed at a lower stress ratio limit.
For Till deposits, the stress ratio limit was increased to 0.40, as some specimens from this soil unit failed at a lower stress ratio limit.

Sample BH-04, 34.2U showed a local shear failure at σA - σR = 565 kPa, σ'R = 200 kPa, and cu = 282 kPa prior to the maximum shear stress within 10% additional axial strain.

For samples, BH-12_32.1U, BH-12_33.1U, BH-14_17, and BH-14_21.1U, the effective stresses were raised during saturation in order to prevent swell.

The loading to consolidation in the tests on sample BH-06, 13.2U was carried out in three phases, first area-constant loading, then constant stress ratio until onset of failure, then loading to estimated isotropic pre-consolidation stress of 917 kPa, assuming a coefficient of earth pressure at rest, k0 = 0.3. Failure was likely initiated during the consolidation phase (phase 3b). This might have affected the undrained shear strength.
In sample BH-17, 19.2U the last part of loading to pre-consolidation was carried out at σ'_R/σ'_A = 0.29.

The results of the CAU test are given in Enclosure G.12

13.5.6 Triaxial Test – Consolidated Isotropic Undrained (CIU)

The triaxial CIU tests have been carried out according to DS/EN ISO 17892-9:2018. The tests were carried out to determine the undrained shear strength and if possible the drained strength parameters. A total of 6 tests have been carried out.

The tests were conducted with the following phases:

- Installation and saturation
- Isotropic consolidation
- Undrained shear phase

For BH-17, 4.2U, the effective stresses was raised during saturation in order to prevent swell.

The results of the triaxial CIU tests are given in Enclosure G.11.

13.5.7 Cyclic Triaxial Test - Consolidated Anisotropic Undrained Cyclic Triaxial Compression Test (CAUcy)

The Cyclic triaxial tests have been carried out in accordance with ASTM D5311 for the cyclic part and EN ISO 17892-9:2018 for the static part. A total of 10 tests have been carried out.

The tests were performed on the three main soil types: Meltwater deposits, Till, and Sand.

The tests were carried out to investigate the response to undrained cyclic shear at various degrees of utilization. The post-cyclic shear strength has not been investigated.

The tests were generally conducted with the following phases:

- Installation and saturation
- Loading and consolidation:
    - Meltwater specimens: to the mean effective preconsolidation stress corresponding to the static reference CAU test.
    - Clay Till: to the effective pre-consolidation stress state derived based on the K0=0.5 and the mean pre-consolidation stress from the in area constant loading in reference static test
- Unloading and consolidation to the in situ stress state.
- Undrained cyclic shear to a maximum of 5000 cycles at 0.1 Hz.

In the initial tests on meltwater clay, it is observed that the stress controlled consolidation (opposite to the area constant consolidation in static reference tests) may cause activation of slickensides in the material. Due to this, and in agreement with the client, the loading and consolidation is made to the mean effective preconsolidation stress.

The majority of tests were planned as symmetric, i.e. with 0 average shear stress, generally in line to the unloading consolidation levels from the static reference tests.

The CAUcy test on Clay till sample BH-12 19.1U was conducted as a symmetric test with τ_{cy} of 360 kPa. The test ended due to a rupture in the membrane after 25 cycles. A re-run of the test was conducted twice, with all the tests ending in membrane rupture. This was likely caused by a contact of the membrane and sharper sand grains within the till sample. The test reported is the last conducted test, where double membrane was used in an attempt to avoid the rupture of the membrane. In conclusion, an asymmetric test with lower τ_{cy} could be considered, to minimize the risk of membrane failure, if future tests are planned on the clay till.

The results of the CAUcy test are given in Enclosure G.14.

13.6 Laboratory Testing – Other Tests

13.6.1 Acid Soluble Chloride

A total of 36 tests were carried out.

The results of the Acid Soluble Chloride are considered reliable and representative of the material encountered across the site.

The Acid Soluble Chloride were determined by GSTL according to the BS 1377-3:7 1990. Detailed test results from the individual tests are found in Enclosure G.06.

13.6.2 Acid Soluble Sulphate

A total of 36 tests were carried out.

The results of the Acid Soluble Sulphate are considered reliable and representative of the material encountered across the site.

The Acid Soluble Sulphate were determined by GSTL according to BS 1377-3:5 1990. Detailed test results from the individual tests are found in Enclosure G.06.

13.6.3 Microfaunal and Palynofloral Dating

The microfaunal and palynofloral dating was performed on selected samples across the site. A total of 19 samples were tested by Network Stratigraphic Consulting Ltd. The testing was performed in order to aid the interpretation of the depositional age and environment on selected samples. Samples was selected for specific soil units where the interpretation of depositional age and environment was uncertain. Especially with regards to if the soils was of Miocene or of Quaternary age.

The test results dates most of the soils to be of Late to Early Miocene age. Among others, the classification showed assemblages of different ages, which have led to the interpretation of the original age of the deposits. Other aspects of the site specific information illustrate some deposits have been reworked as reworked debris has been identified (i.e. Late Miocene, Middle Miocene, Eocene and Late Cretaceous).
This leaves the interpretation of the microfaunal and palynofloral tests inconclusive. All tests included, the faunal and floral assembly found in most of the specimens are concluded to represent redeposited soil with origin from older deposits, i.e. Miocene deposits.

Generally, the results from the dating analysis cannot be used as a stand-alone result to determine depositional age and environment of the tested soils. The test results has been used to support the geologists interpretation of depositional age and environment, but is has not been possible to deduct this information from the tests alone.

A report and detailed test results are found in Enclosure G.07

13.7 Comments to Laboratory Work

Laboratory tests have been carried out as ordered in the extent possible. Test that for some reason are changed or cancelled after the approval of the testing programme, has been done with acceptance from Energinet.

Effort has been made to ensure that geological descriptions are in agreement with results of classification tests, following the guidelines of the standards. The results of the classification testing was used to evaluate the geological description of the soil.

Differences are observed between the strength determined from the UU tests and the index tests (Pocket Pen & Tor Vanes). Generally, the index tests show lower values than the UU tests. UU tests are deemed most reliable. Index tests are more uncertain determinations due to the simple nature of the tests and very limited volume of soil tested.

13.8 Digital Delivery

An AGS file with relevant borehole- and CPTU data has been uploaded in connection with the report delivery. The AGS file has been uploaded to a project specific Share Point Site.

14 SOIL CONDITIONS

14.1 General

In the Danish North Sea, the Quaternary consists of deposits from the Elsterian, Saalian and Weichselian glaciations, as well as the interglacials Holstein, Eem and Holocene.

The Quaternary layers reach thicknesses of more than 1000 m in the middle of the North Sea but is thinning towards the Danish west coast (ref. 10). The present investigation area has not been covered by the Weichel glaciation, but both Elsterian and Saalian ice sheets have covered the area (ref. 11). Quaternary deposits consist mainly of glacial till deposits and glaciofluvial sand and clay deposits from meltwater deposition, which drained areas in Scandinavia and carried meltwater from the ice-margins in Denmark and Norway out into the North Sea (ref. 12). Marine Neogene deposits and locally Neogene freshwater deposits have also been described and found onshore at the Danish west coast.

14.2 Soil Types

The investigated sequence of layers in the area is comprised of various types of sand and clay with subordinate amounts of gravel layers, marine organic deposits and Neogene marine and freshwater deposits. Based on contents of minor constituents and similar macroscopic petrographic characteristics, the sequence of layers has been divided into the geological soil units, shown in Table 14.1. Photographic examples of each soil type can be found in Enclosure F.02.

Table 14.1 - Soil types in the boreholes.

Geological soil unit	Petrographic Characteristics	Occurrence	Code and colour
Holocene marine gravel	GRAVEL, very sandy, non-calcareous, w. few stones, often with shell fragments and plant remains, grey. Sometimes with iron sulphide, and high plasticity clay parts	BH-01, BH-06, BH-09, BH-10, BH-13, BH-14, BH-16, BH-17 & BH-18	Ma Pg

Holocene marine sand	SAND, fine-medium, sorted, (sometimes very silty and gravelly), (non-) calcareous, w. shell fragments, grey-light greyish brown. Often with clay streaks, iron sulphide stains and plant remains	All boreholes except BH-01, BH-12 & BH-15	Ma Pg
Holocene marine silt	SILT, sl. clayey, sandy, sl. gravelly, calcareous, w. shell fragments, w. few plant remains, dark greenish grey. Sometimes w. mica, clay and sand laminae, charcoal and sl. organic	BH-01, BH-03, BH-05, BH-06, BH-07, BH-09, BH-11 & BH-12	Ma Pg
Holocene marine clay	CLAY, medium-high plasticity, sandy, calcareous, w. iron sulphide specks, greyish brown. Sometimes organic and rich in silt and fine sand laminae and sometimes with gravelly layers	BH-02, BH-04, BH-06, BH-07, BH-09, BH-10,BH-11, BH-12, BH-17 & BH-18	Ma Pg
Holocene marine gyttja and peat	GYTTJA, silty, sandy, calcareous, w. shell fragments, w. plant remains, w. iron sulphide, w. sand layers, rich in shell fragments, grey. PEAT, non-calcareous, brown to black	BH-04	Ma Pg
Meltwater gravel and cobbles	GRAVEL, sl. sandy, non-calcareous and COBBLES, sandy, multi-coloured. Sometimes with charcoal fragments and shell fragments	BH-04, BH-12, BH-13, BH-14 & BH-17	Mw Gc
Meltwater sand	SAND, fine to coarse, sorted - poorly graded, sl. clayey, silty, sl. gravelly, calcareous, and grey. Sometimes with iron sulphide stains, mica, few shell fragments, charcoal pieces, plant remains and very high plasticity clay parts	All boreholes except BH-05, BH-15 & BH-16	Mw Gc
Meltwater silt	SILT, (sl.) clayey, sandy, calcareous, often w. shell fragments and w. few plant remains, dark greyish olive. Sometimes laminated with high plasticity clay layers and mica	BH-01, BH-03, BH-04, BH-05, BH-06, BH-09, BH-10, BH-11, BH-12, BH-13 & BH-14	Mw Gc

Meltwater clay	CLAY, medium - high plasticity, silty, sandy, calcareous, often rich in silt and fine sand laminae, w. few sand parts, w. few shell fragments, w. mica, w. few gravel grains ,w. iron sulphide laminae, greyish brown - dark grey. Sometimes organic – associated with high amounts of iron sulphide	All boreholes except BH-15 & BH-16	Mw Gc
Cobble	COBBLE, very dark grey	BH-10	Gl Gc
Sand till	SAND TILL, clayey to very clayey, gravelly, calcareous, greyish brown. Sometimes with sandparts	BH-01, BH-07, BH-09, BH-10, BH-13, BH-14 & BH-17	Gl Gc
Silt till	SILT TILL, sl. clayey, very sandy, gravelly, calcareous, w. sand smears, dark greyish brown. Sometimes with few shell fragments	BH-10	Gl Gc
Clay till	CLAY TILL, medium - high plasticity, sandy, sl. gravelly, calcareous, greyish brown. Sometimes with few shell fragments	All boreholes except BH-11, BH-13, BH-15 & BH-16	Gl Gc
Interglacial clay	CLAY , high plasticity, silty, sl. sandy, calcareous, high-organic, w. few shell fragments, w. few iron sulphide stains, w. few sand smears, very dark grey	BH-13	Fw Ig
Marine Neogene gravel	GRAVEL, very sandy, non-calcareous, grey	BH-15 & BH-16	Ma Ng
Marine Neogene sand	SAND, fine to medium, sorted to graded, sometimes clayey and very silty, non-calcareous, w. mica and sometimes organic, w. clay/silt laminae, w. plant remains and a few charcoal fragments, grey	BH-01, BH-02, BH-05, BH-07, BH-10, BH-14, BH-15, BH-16 & BH-18	Ma Ng

Marine Neogene silt	SILT, (sl.) clayey, sl. sandy, non-calcareous, w. mica, sometimes high -organic, rich in clay and fine sand laminae, olive grey-dark brown	BH-01, BH-02, BH-06, BH-09, BH-10 & BH-15	Ma Ng
Marine Neogene clay	CLAY, high to very high plasticity, sl. calcareous, (high-)organic, w. silt and sand laminae and smears, w. mica, dark brown. Sometimes with few gravel grains, shell fragments and slickensides	BH-01, BH-02, BH-05, BH-06, BH-09, BH-10, BH-14 BH-15, BH-16 & BH-18	Ma Ng
Freshwater neogene high organic sand	SAND, fine, silty, non-calcareous, high-organic, w. peat laminae and high plasticity clay layer, brownish black	BH-15 & BH-16	Fw Ng
Freshwater neogene Lignite	LIGNITE, brownish black	BH-15	Fw Ng
Freshwater neogene peat	PEAT, non-calcareous, sl. charred, w. sand laminae, brown	BH-16	Fw Ng
Freshwater neogene clay	CLAY, high plasticity, silty, sl. sandy, non-calcareous, rich in mica, organic, w. fine silt and sand laminae, dark brown, w. peat layers	BH-16	Fw Ng

The above characteristics and diagnostic features of units are solely based on macroscopic visual inspection of sample material carried out during drilling work, and not on any seismic or CPTU data. The descriptions of the soils in table 14.1 are meant to be representative of the general soils encountered across the site, and all observed feature will not appear in the overall descriptions.

14.3 Comments on Soil Types

Holocene marine sand and gravel

With the Holocene transgression followed deposition of sand and gravel deposits, with shells, plant remains, iron sulphate and clay parts. These deposits occurs throughout the wind farm area, in a quite variable thickness between 0.2 m and 17.0 m.

Holocene marine silt and clay
Both clay and silt deposits are observed throughout the area, mostly as minor layers between 0.1m and 3m. At one location, in the northernmost part of the area, BH-18, 10m of clay is observed.

Holocene marine gyttja and peat
The marine organic deposits are only observed in a single borehole, BH-04, in the southwestern corner of the area.

Meltwater deposits

Meltwater deposits are found in all boreholes in the area, except BH-15 and BH-16. The meltwater deposits dominates in a channel structure running from north to south in the middle of the area.
These sand deposits were probably mainly deposited by rivers draining the pro-glacial areas of central Europe. At this time, the North Sea area was dry land, except for the deeper parts of the Norwegian Trench. (ref. 12).

Till deposits
Till deposits are found in very variable thickness between 0.1m and 10m. No glacial till deposits are found in BH-08 and BH-11, which are located within the channel structure in the middle of the area. Till deposits are found elsewhere in the channel, but only as minor layers with up to 3 meters thickness. No till deposits are observed in BH-15 and BH-16.

Inter glacial deposits
Interglacial deposits are only observed in BH-13 as two layers of high organic clay, of 20 m and 7 m in extent, the latter being to bottom of the borehole, so the full length is not recorded. The organic layer indicate a warmer period during the glaciation, possibly deposited in between meltwater channels on the meltwater plain.

Neogene deposits
The marine Neogene sediments were deposited in a fairly deep sea, with depths up to 100 m (ref. 13). The deposits vary between clay, silt and sand with minor layers of gravel. They are often thinly laminated and rich in mica. The deposits are seen in most of the boreholes, although Neogene deposits are not observed in the boreholes situated in the north southern oriented channel structure in the centre of the area. BH-15 and BH-16 is entirely comprised of Neogene deposits with a very thin cover of Holocene deposits.

Neogene freshwater deposits as organic clay, peat and organic sand and lignite are only observed in borehole BH06, BH15 and BH-16.

14.4 Soil Conditions – Cross sections

Geological Cross Sections are presented in Enclosure A.04 and shows the soil types along six cross sections through the wind farm area. Section A to C are west-east oriented, D to E are north-south oriented. The location for the presented cross sections is marked on the location plan given in Enclosure A.03. Table 14.2 sums up the boreholes in the cross sections.

The distribution of soil types in six cross sections (Section A to F) shown in Enclosure A.04 is commented below.

In addition to the listed boreholes above, there is also included main soil behaviour deducted from selected seabed CPTUs, positioned adjacent to the cross sections. It should be noted that soil behaviour is not to be confused with determined geology from the boreholes, and soil behaviour information should be used with caution.

Table 14.2 – Boreholes represented in the cross sections

Section no	Borehole no.	Length of section (km)
A	BH-12, BH-13, BH-14	7.9
B	BH-07, BH-08, BH-10, BH-09	14.9
C	BH-04, BH-01, BH-03, BH-05, BH-02	19.9
D	BH-12, BH-11, BH-08	9.4
E	BH-18, BH-17, BH-16, BH-15, BH-14	9.9
F	BH-10, BH-09, BH-06, BH-05, BH-02	10.4

Section A

Marine postglacial deposits are recognized in all boreholes, covering either meltwater deposits or till deposits. Meltwater and till deposits are present in all three boreholes, in alternating depths and quantities. In BH-13 deposits of freshwater interglacial origin is found. This is also confirmed from the geophysical surveys made in the area, where a north-south oriented valley is present in the investigated area (ref. 14). There are two sets of interglacial deposits in BH-13, both covered by meltwater deposits. Neogene deposits are only found in BH-14.

Section B

Marine postglacial deposits are found in in topmost part of all boreholes in this section. Underlying deposits are of meltwater deposits, mostly dominated by clay. Till deposits are present in all four boreholes, although to a minor extent in BH-08. In BH-09 and BH-10 the till is cutting Neogene deposits, which are present in three out of four boreholes, with largest extent towards the east.

Section C

Organic marine postglacial deposits, as gyttja and peat are found in the westernmost borehole BH-04. The other marine postglacial deposits are dominated by sand, which is found in all boreholes. A thick package of meltwater deposits are present in all boreholes, only cut by minor till deposits at alternating depths. Neogene deposits are found in three boreholes and missing in BH-03 and BH-04. BH-03 is placed in the southern part of the incised valley shown in the geophysical survey, which could explain the lack of Neogene deposits here (ref.14).

Section D

All three boreholes are situated in or just up to the incised valley observed in the geophysical survey (ref.14). Marine sand and clay deposits of postglacial age are found in all boreholes, together with meltwater deposits of gravel, sand and clay. Towards the south the meltwater deposits are fining, indicating a quieter depositional environment here. No Neogene and only minor till deposits are observed in the boreholes.

Section E

Marine postglacial deposits are found in all boreholes in this section, with largest extent in BH-18. Meltwater and till deposits are located in three out of five boreholes. Till deposits of alternating sand till and clay till is found in large quantities in BH-17. In borehole BH-15 and BH-16 Neogene deposits comprises most of the boreholes, with minor amounts of freshwater Neogene deposits.

Section F

This section quite homogeneous with similar geology in the present boreholes, all with marine postglacial sand deposits on top of meltwater deposits mostly consisting of laminated clay. Till deposits are intersecting and underlying the meltwater deposits throughout the area, with Neogene deposits underneath, forming the base of all five boreholes.

15 TYPICAL GEOTECHNICAL CHARACTERISTICS

The laboratory classification tests have been listed and related to the corresponding geological soil type to form a “mini database” of the measured geotechnical parameters. Based on this database, the minimum, maximum and average values of the geotechnical parameters have been identified and tabulated. The values are presented in Table 15.1a and 15.1b.

The values presented is not a statistical work up of all the data for the individual parameters and is not a determination of characteristic design values for each soil type. The presentation of data in Table 15.1a and 15.1b is prepared as a guide to get a quick overview of the measured geotechnical parameter variation for each geological soil type to be used for initial engineering purposes.

Table 15.1a – Range of measured Geotechnical Parameters (minimum, average, maximum) for the various geological units identified. Average is not included if less than 3 test results are available. For some parameters outliers has been neglected.

Parameter	Unit	Marine Postglacial Clay	Marine Postglacial Silt	Marine Postglacial Sand/Gravel	Marine Postglacial Gyttja and Peat	Meltwater Clay	Meltwater Silt	Meltwater Sand/Gravel	Clay Till	Sand Till	Freshwater Interglacial Clay	Marine Neogene Clay	Marine Neogene Silt	Marine Neogene Sand/Gravel	Freshwater Neogene Clay	Freshwater Neogene Sand	Neogene freshwater lignite and peat
Moisture Content (w)	%	12 24 35	19 26 34	29 33	35 86 238	13 27 49	17 24 28	11 21 28	9 14 24	9 13 22	20 118 747	19 31 50	8 28 38	16 24 30	38	46 48	49 93 137
Bulk Density	kN/m3	1.68 1.93 2.17	1.95 2.02	-	1.14 1.53 1.82	1.52 1.95 3.14	1.70 1.92	-	2.08 2.31 2.77	2.01 2.08 2.15	1.75 1.81	1.46 1.77 1.96	1.89	1.54 1.78 199	-	-	-
Dry Density	kN/m3	1.35 1.61 1.91	1.57 1.64	-	0.34 0.90 1.34	1.12 1.56 2.49	1.42 1.53	-	1.76 2.03 2.51	1.66 1.84 1.89	1.30 1.37	1.12 1.36 1.55	1.50	1.25 1.43 1.63	-	-	-
Pocket Pen	kPa	37 98 200	50 72 100	-	12 15 25	38 251 1000	50 274 550	75 153 300	25 418 1000	200 377 950	100 219 350	100 367 600	50 119 200	87	-	-	-
Tor Vane	kPa	7 67 219	2 26 37	-	10 15 18	5 127 250	16 107 240	25 66 170	25 120 250	19 72 250	50 154 225	37 161 250	15 33 52	19	-	-	-
Atterberg Limits (Ip)	%	9 17 28	13	8	25	12 30 61	15 23	-	8 17 30	21	30 46	16 31 60	25	-	-	-	-
Particle density	Mg/m3	2.64 2.66 2.69	2.66 2.67	2.65 2.66 2.74	2.66 2.79	2.65 2.69 2.77	2.71	2.64 2.65 2.67	2.65 2.67 2.74	2.66 2.67	2.66	2.39 2.56 2.71	2.59	2.63 2.65 2.70	-	-	-
Density of non-cohesive soils minimum and maximum	emin-emax	-	-	0.33/0.65 - 0.50/1.19	-	-	-	0.37/0.69 - 0.67/1.36	-	-	-	-	-	0.32/0.70 - 0.72/1.40	-	-	-
Loss on Ignition	%	1.4 4.2 6.5	1.8 3.0 5.5	5.6	3.5 15 30.9	2.4 5.2 7.9	-	1.5 4.4	-	-	5.1 5.8	11.7 14.3 20.0	5.2 8.3	1 2.7	10.7	4.5	42.7
Carbonate Content	%	6.2 6.9 7.4	4.4 15.1	0.0 1.5 4.9	12.7	13.6 17.8	-	0 1.7 3.2	6.5 12.2 17.3	6	-	0.8	-	0.4	-	-	-
Thermal Conductivity	W/mK	1.44 2.60 3.52	2.20	1.20 2.15 3.49	1.13	-	-	-	-	-	-	1.69	-	1.74	-	-	-

Table 15.1b – Range of Geotechnical Parameters (minimum, average, maximum) for the various geological units identified. Average is not included if less than 3 test results are available. For some parameters outliers has been neglected.

Test type	Parameter	Unit	Marine Postglacial Clay	Marine Postglacial Silt	Marine Postglacial Sand/Gravel	Meltwater Clay	Meltwater Sand/Gravel	Clay Till	Freshwater Interglacial Clay	Marine Neogene Clay	Marine Neogene Sand/Gravel
UU	Cu	[kPa]	139 187	87	-	39 183 577	-	49 464 1374	329	104	-
DSS	Cu_{DSS}	[kPa]	134	-	328	129 179 258	190 - 498	-	-	358	177 - 258
Triax, CID (c' = 0 kPa)	φ	[°]	-	-	32 37 46	-	32 38 44	-	-	-	33 37 45
Triax, CIU	Cu	[kPa]	85 104 131	-	-	310 453 558	-	-	-	-	-
Triax, CAU	Cu	[kPa]	-	-	-	154 307 702	-	338 638 1071	374	151 425	-
IL1	σ_{pc}	[kPa]	1200-2400	-	-	1200 - 2400/4800	-	1200-2400 - 2400-4800	2400	600 - 2400-4800	-
IL2	E_{oed}	[Mpa]	61	-	-	33 115 269	-	201 256 355	93	21 - 138	-

16 REFERENCES

No.	Reference
01	ISO. OGP DIS 19901-8. Petroleum and natural gas industries. Specific requirements for offshore structures. Part 8: Marine soil investigations. TP1 recommended DIS. July 2014
02	Geo Operational Report – Seabed CPT Campaign. Report 1.
03	Geo Operational Report – Borehole Campaign. Report 2.
04	Lunne and Christoffersen (1983), Interpretation of Cone Penetrometer Data for Offshore Sands, Offshore Technology Conference OTC 4464
05	Robertson. P.K., Campanella, R.G., Gillespie, D., and Greig, J. (1986). Use of Piezometer Cone data. In-Situ'86 Use of In-situ testing in Geotechnical Engineering, GSP 6 , ASCE, Reston, VA, Specialty Publication
06	Jamiolkowski, M., Lo Presti, D.C.F. and Manassero, M. (2003). "Evaluation of relative density and shear strength of sands from CPT and DMT", Germaine, J.T et al (Eds), Soil behavior and soft ground construction: proceedings of the symposium, October 5-6, 2001, Cambridge, Massachusetts, Geotech Spec Pub, No. 119, Am Soc of Civ Eng, Reston, pp. 201,238
07	Mayne, P. W. (2001). Stress-strain-strength-flow parameters from seismic cone tests. Proceedings, Intl. Conf. on In-Situ Measurement of Soil Properties & Case Histories, Bali, Indonesia: 27-48.
08	Mayne, P. W. (2006). In-situ test calibrations for evaluating soil parameters. Characterisation and Engineering Properties of Natural Soils.
09	Robertson, P. K. (2009). Interpretation of cone penetration tests—a unified approach. Canadian geotechnical journal, 46(11), 1337-1355.
10	EG (2014): Danish Wind Farm Site Surveys Volume 2: Interprative Report Site 2 – Vesterhav Nord, Revision 3 - Final
11	Streif, H. (2004): Sedimentary record of Pleistocene and Holocene marine inundations along the North Sea coast of Lower Saxony, Germany. Quaternary International 112, p. 3-28
12	Graham et al. (2011): (draft): http://nora.nerc.ac.uk/16652/1/Graham_ et_al_North_Sea_Glaciations_2011_Final.pdf
13	Sand-Jensen, Kaj, and Merete Binderup (2006): Naturen i Danmark, bd. 2. Vol. 2. Gyldendal A/S p. 227-236
14	MMT (2020): Geophysical Survey Report. THOR OFFSHORE WIND FARM SITE INVESTIGATION. LOT 1. DANISH NORTH SEA. AUGUST-DECEMBER 2019. 103282-ENN-MMT-SUR-REP-SURVLOT1. REVISION 02. FOR CLIENT REVIEW. FEBRUARY 2020.