Intended for
Energinet

Document type
Report

Date
October 2022

GROUND CONDITIONS RISK ASSESMENT

NORTH SEA – ENERGY ISLAND/WIND FARM AREA

Bright ideas. Sustainable change.

Project name	**Ground Conditions Risk Assessment – North Sea - Energy Island / Wind farm area**
Project no.	**1100051218**
Recipient	**Energinet**
Document type	**Report**
Version	**1**
Date	**October 7th, 2022**
Prepared by	**SIAS, HFCH, MRJK, MJLF, SBMA**
Checked by	**RUBJ, SBMA**
Approved by	**SBMA**
Description	**Report**

Ramboll
Hannemanns Allé 53
DK-2300 Copenhagen S
Denmark

T +45 5161 1000
https://ramboll.com

Rambøll Danmark A/S
DK reg.no. 35128417

Member of FRI

CONTENTS

1. EXECUTIVE SUMMARY

Ramboll has for the Danish transmission system operator (TSO), Energinet, prepared this report entailing the results of an analysis and interpretation of the risk for encountering less suitable seabed conditions based on existing and new geological, geophysical and geotechnical (G&G) data from an investigation area in the North Sea encompassing the 3 GW area and the potential future 10 GW offshore wind area.

The purpose for this extended G&G desktop study has primarily been to evaluate the risk for potential soft soils in the investigation area. Other potential geohazards, including hard soils and layers with high organic content, are also discussed if identified or indicated.

The above integrated analysis and interpretations are eventually presented as 'risk and uncertainty maps'; one set of maps and associated table is prepared for foundations purposes (depths down to c. 30-35m); and another set of maps and associated table relevant for cable burial assessment (depths to c. 6m).

The conclusion in regards of the risk for encountering soft soils is in general assessed to be "Low" or "Probably low" outside buried paleochannels and "Probably medium to high" within and along buried paleochannels. The 'Probably' signifies the uncertainty of this assessment due to often sparse data coverage, however within the Energy Island, where the data coverage is very high, the risk and uncertainty has been assessed to be "Low, not seen".

Similar 'risk and uncertainty maps' are developed for potential hard soils and potential high organic content soils. The latter risk is in general "Probably low" although "Probably medium to high" within and along parts of the large abundance of buried paleochannels. The risk for potentially encountering hard soils, including gravel / gravelly sand, is in general high for large portions of the investigation area; however, "Probably medium" within and along the buried paleochannels.

Based on the assessment, recommendations for future investigations are given:

1) Within the Energy Island and the 3 GW area there is a good data coverage. The major risk identified within the 3 GW area is related to hard soils, which are mainly seen as very dense (and in some cases gravelly) sand. Laboratory data on organic content and thermal conductivity properties, which were not available for this report, is expected to shed light on the risk related to thermal properties for design of inter-array cables.

2) Within the 10 GW area (including the 3 GW area), it is recommended that the shallow paleochannels are investigated further (CPT, boreholes, seismic surveys) to quantify the geology and strength properties of the soils located there.

3) Acoustic blanking has been mapped on the geophysical data associated with seismic unit "U25", indicating a risk of shallow gas in the area. Therefore, it is recommended to carry out further seismic and geotechnical investigations to delineate seismic unit "U25" and to evaluate the geotechnical properties of associated areas of acoustic blanking.

4) Within the 10 GW area, it is recommended to support the interpretation of "Unit U10 – low amplitude reflections" with seismic and geotechnical investigations to classify the soil type and strength to investigate further the risk of encountering soft soils.

Table 1-1 Overview of risk levels

	Area	**Data coverage**	**Risk level Outside channels**	**Risk Level Channels**
Risk factor				
Soft soils	Energy Island	Very high	Low, not seen	Low, not seen
	3 GW area	Good/Medium	Probably low	Probably medium to high
	10 GW area	Low	Probably low*	Probably medium to high
	Northern ECR	Low	Probably low	Probably medium to high
	Southern ECR	Low	Probably medium to high close to shore	Probably medium to high
Hard soils	Energy Island	Very high	High, upper 15 m show very dense sand	Low, not seen
	3 GW area	Good/Medium	High in northern part of area and in NW-SE band. Medium in remaining part	Probably medium
	10 GW area	Low	Probably medium to high	Probably medium
	Northern ECR	Low	Probably medium to high	Probably low
	Southern ECR	Low	Probably high in gravel area	Probably medium
Shallow gas	Eastern part, see map	Medium	High in localized areas, see map	
ECR only:**				
Organic layers/content	Energy Island	Low, no lab data	Probably low	Probably low
	3 GW area	Low, no lab data	Probably low	Probably medium to high
	10 GW area	Low	Probably low	Probably medium to high
	Northern ECR alignment	Low	Probably low	Probably low
	Southern ECR alignment	Low	Probably low, except close to shore	Probably medium to high

*Only based on geophysical data
**Upper 6 m

2. INTRODUCTION

This report entails the results of a desk study conducted by Ramboll for Energinet on the future North Sea Energy Island and associated offshore wind farms (potentially up to 10 GW). The primary objective for this study has been to assess and preliminary quantify the risk of potential soft bottom conditions in the 10 GW area.

2.1 Background

On 30 November 2020, Energinet received an instruction from the Danish Energy Agency (DEA) [Energistyrelsen (ENS)] on behalf of the Minister of Climate, Energy and Utilities to prepare and carry out preliminary studies and surveys at sea for an Energy Island in the North Sea consisting of an artificial island connected to 3 GW of offshore wind. Thus, in the period 2021-2023, Energinet are carrying out geological, geophysical and geotechnical (G&G) pre-investigations and feasibility studies for the 3 GW offshore wind farm area (OWF), including the planned Energy Island, as well as two potential export cable routes (ECR), see Figure 2-1.

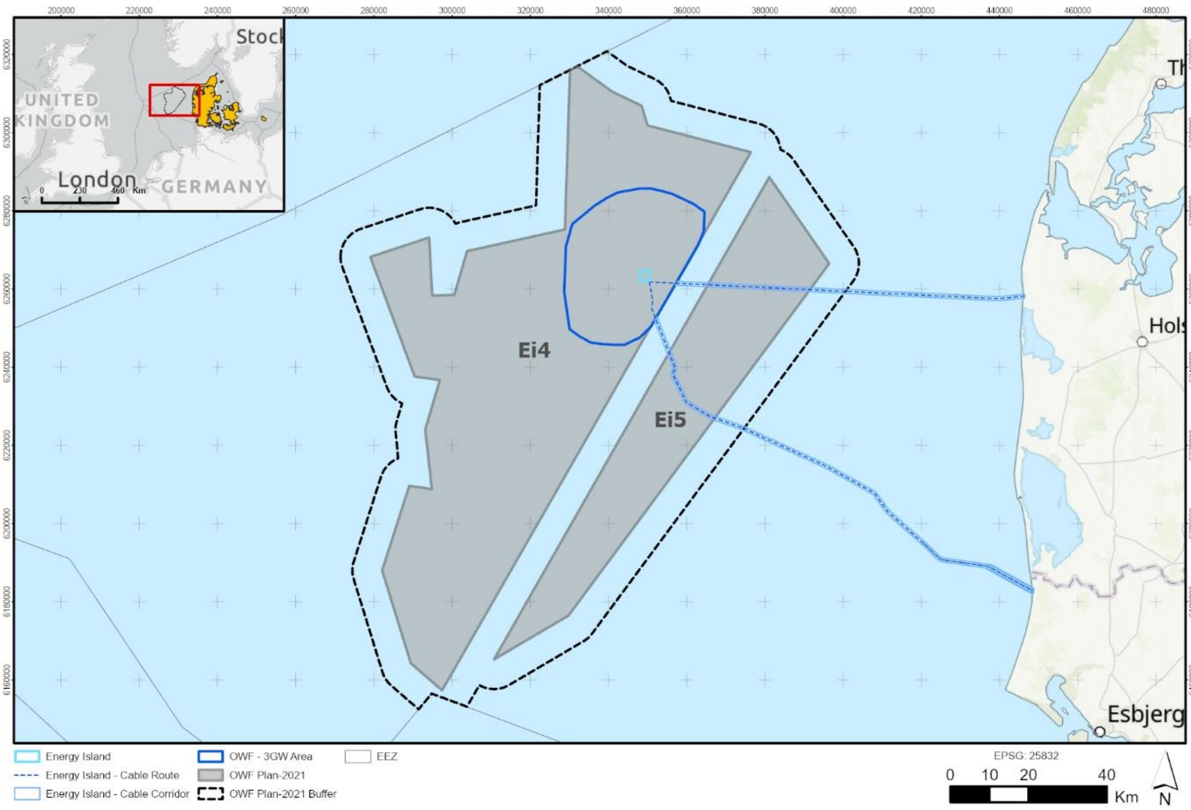

Figure 2-1 Geographical delimitation of areas for the project Energy Islands - North Sea (received by Energinet). The "Ei4" and "Ei5" are so-called development zones mentioned in "Havplan 2021" (will not be referred to in this report).

In continuation of a market dialogue held regarding the ownership of the future artificial Energy Island and associated offshore wind farms in the North Sea (currently planned for up to 10 GW), it turned out that the market wants assurance that it is possible to realize not only 3 GW offshore wind, but in the long run also 10 GW offshore wind. The reason for this is that future market players do not want to own a share of an artificial Energy Island of up to 10 GW if there is uncertainty about the possibility of establishing a similar amount of offshore wind. At the market dialogue the potential bidders referred to the unsuitable soil conditions in large parts of the Hesselø offshore wind project area (soft bottom not feasible for construction/installation), which regrettably first were found and quantified during the geotechnical field surveys. The unfortunate soil conditions at Hesselø have delayed the Hesselø tender round. Most recently it has been informed by the DEA, that the location for Hesselø Offshore Wind Farm is moving south to reduce risk in establishing the wind farm.

Against this background, the Danish Energy Agency has requested Energinet to prepare a study program that can quantify the risk of inappropriate soft bottom conditions in the 10 GW area. On this basis, Energinet has prepared a step-by-step approach to which activities are meaningful to carry out, in order to clarify the uncertainty about a realization of 10 GW in the North Sea:

Step 1. Desk study, geology
Step 2. Geotechnical field investigations (CPTs and boreholes)
Step 3. Geophysical surveys

Step 1 must according to Energinet entail the following tasks and activities:

A. *Provide a summary of the geological development of the area.*
B. *Provide a description of near-surface soil layers that can be expected on the seabed in the area, including lithological composition, formation environment and age.*
C. *The above must be substantiated by using examples from existing data archives with i.e. seismic data as well as in-situ surveys with boreholes and vibrocores.*
D. *The aim is to use archive data so that a geographical coverage is obtained for the entire study area.*
E. *On the basis of the archive data, a rough division of the study area shall be made, which classifies the areas in relation to their risk in relation to the establishment of offshore wind farms. It is important that the classification is transparent in relation to the quality of the data on which the division is based.*
F. *Finally, a program for Step 2. and 3. (geotechnical and geophysical field investigations) must be prepared. Prior to the initiation of this tasks, a meeting is held with Energinet to align expectations on purpose and scope.*

2.2 Scope of work

Ramboll has prepared this report which entails the results of the aforementioned Step 1. In addition to ‘archive data’ Energinet has on Ramboll’s request shared new preliminary geophysical and geotechnical data from the ongoing pre-investigations at the Energy Island site and within the 3 GW OWF area.

2.3 Investigation area

The area of interest for this study is shown in Figure 2-1, where it is called “OWF Plan-2021 Buffer”. This area encompasses not only the agreed 3 GW OWF pre-investigation area, where the planned artificial Energy Island is located, but also the potential future 10 GW offshore wind area (sometimes referred to as development zones Ei5 and Ei4, and other times “Nordsøen II” and “Nordsøen III”, respectively, which in the figure is called “OWF Plan-2021”. For the remainder of this report when referring to “10 GW area” it generally means the area outside the 3 GW area within the “OWF Plan-2021” area.

3. METHODOLOGY

The methodology used for this study are detailed described in the remaining chapters; however, can briefly be described as follows:

1. Data collection: Collection of published / available data and reports, including seismic data and drilling profiles. The primary database is the geophysical and geological data, maps and reports from the Danish Geological Survey (GEUS) Marta / Jupiter databases; however seismic data (multi-channel seismic) from Aarhus University has also been requested and delivered. Secondly, additional available geophysical and geotechnical data from Energinet has also been requested and delivered for the purpose of this study.
2. Loading of available seismic data into IHS Kingdom 2020 for data assessment and interpretation. Primary data types are single-channel seismic sub-bottom profiler SBP (Innomar, chirp) data and to a lesser extent multi-channel seismics (Sparker/Air gun). Data is accessed strategically so that the entire area is screened using a selection of lines. In identifying potential soft-bottom conditions, all surrounding lines are utilized for detailed interpretation:
    a. Seismic stratigraphic understanding (primarily based on multi-channel data).
    b. Identification / evaluation of seismic reflectors and the seismic character of the seismic layers / sequences.
    c. Identification / evaluation of depositional boundaries
3. Assessment of the geotechnical properties based on boreholes including vibrocore and CPT data. The assessment includes both wind turbine generator (WTG) foundations (monopile, upper 35-40 m) and ECR / inter-array cables (upper 6 m).
4. Evaluation of the lithology and age of drilling / sample data as well as interpretation of geotechnical properties. An overall assessment of lithology, formation environment and age will be made for the soil types found, based on the geophysical model compared with the geological descriptions (from vibrocores and boreholes). Preliminary CPT and borehole data from the 3 GW offshore wind area plays an important role in the data review, interpretation and risk assessment. There will be a special focus on the soil conditions outside and inside paleochannels. The paleochannels encompass both deep Quaternary valleys and shallow postglacial/late glacial channels. Further, the depth of postglacial (Holocene) deposits is evaluated.
5. Interpretation of the geological and geophysical model compared with the geotechnical data. Integration of geotechnical results and geophysical results to both increase the geophysical interpretations and to inter- and extrapolate the geotechnical interpretations from single points to 2D and 3D surfaces.
6. Preparation of risk (and uncertainty) maps for the cable routes and the wind farm area, respectively. Based on the integrated results, a geotechnical assessment is made of the risk of finding soft/very soft deposits as well as a division of the area into risk zones. If other potential geohazards are identified, these will also be documented (e.g., shallow gas, hard soils, organic layers etc.).
7. Reporting (this).

.

4. EXISTING CONCEPTUAL MODEL – FROM PREVIOUS STUDIES

When referring to previous conceptual models, including simplified geologic profiles, these are primarily the following:

- ”Havbund og geologiske forhold for BORNHOLM I + II, NORDSØEN II + III OG OMRÅDET VEST FOR NORDSØEN II + III”, ref. [4]
- ”En geologisk screeningundersøgelse af potentielle energiø områder i Dansk Nordsø”, ref. [2]
- ”Energy Island Danish North Sea, Geoarchaeological and geological desk study”, ref. [8]
- ”Baltic Pipe route Denmark, Geoarchaeological and geological desk study”, ref. [9]

In the above and other mentioned references, the geological setting and expected lithologies within depths of relevance for this study are detailed described and documented, so in the following only a brief summary is presented.

During the Neogene period large amount of sediment were deposited in marine and coastal settings resulting in thick clayey to sandy successions throughout the majority of the Danish North Sea area [3]. In a more recent timeframe glacial periods have influenced the deposits in the area resulting in moraine/till deposits and proglacial deposits such as paleochannels, meltwater deposits and sandy outwash.

A conceptual model for the upper 50 m of sediment has been presented in a screening study from 2020 [4], see Figure 4-3, Figure 4-4 and Figure 4-5. Three of the investigated areas (Nordsøen II and III) and the area west of this are of interest for this desk study, cf. Figure 4-1 and Figure 4-2.

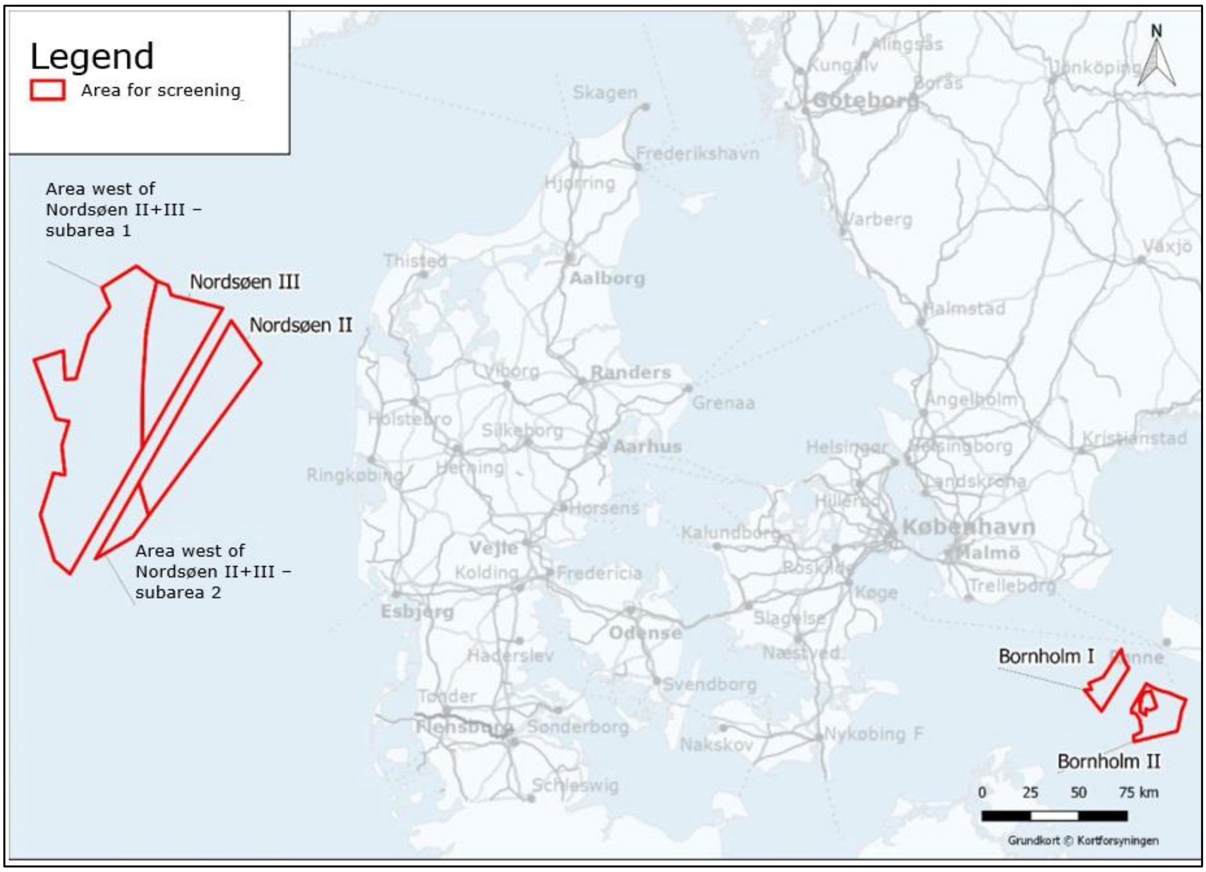

Figure 4-1 Areas Nordsøen II and III and the area west of these, modified from ref. [4].

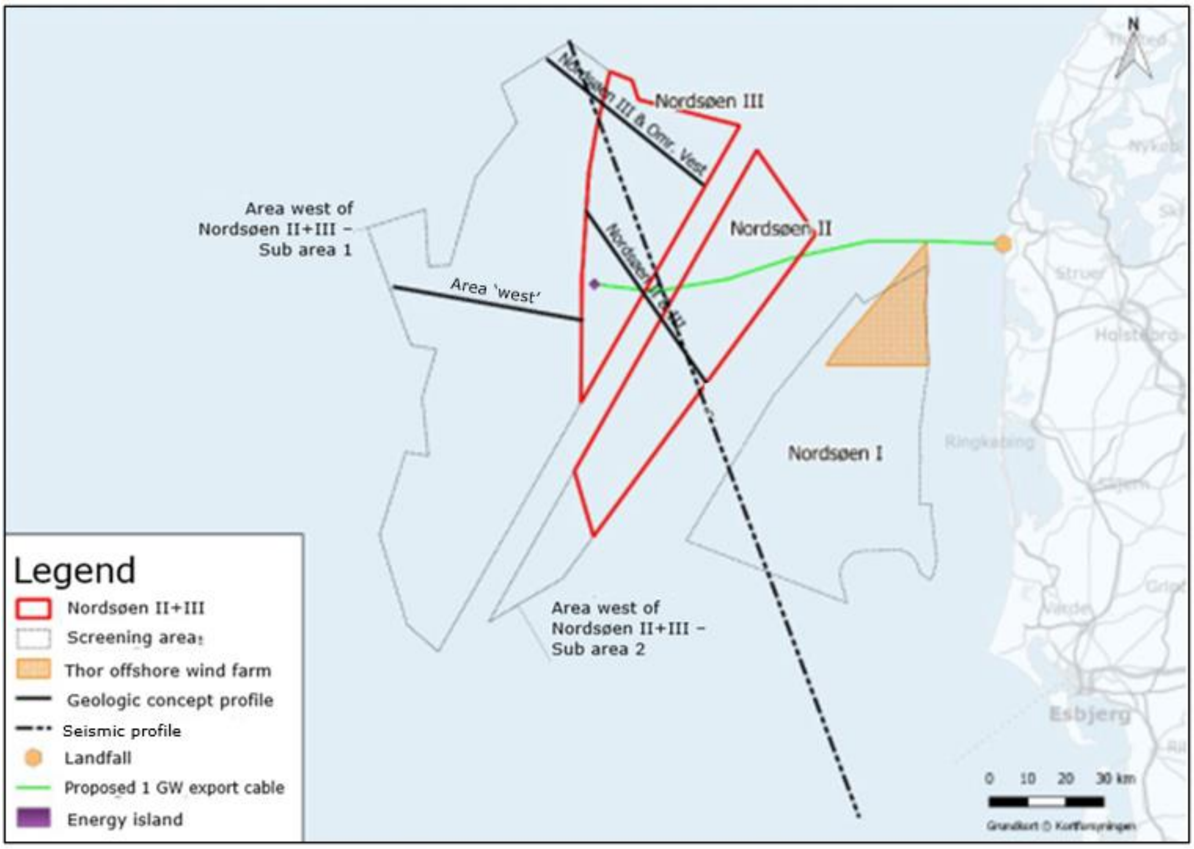

Figure 4-2 Location of seismic profile (dashed line) and conceptual cross sections (black lines), modified from ref. [4].

The further west, the more uncertain the geological model is due to sparser and sparser data coverage. According to the established conceptual models, salt diapirs are expected relatively close to the seabed in the northern part of the Nordsøen III area / the investigation area.

The major part of the area of investigation was ice-free and covered by proglacial river plains and/or Saalian moraine plateaus; however the northernmost of the investigation area was in fact covered by the southern-most maximum extension of the Weichselian ice sheet. Glacial and postglacial channel structures are seen. Below the glacial and postglacial deposits, pre-Quaternary sand, silt and clay is expected. The top Pre-Quaternary surface is an erosional surface.

Buried paleo-valleys, or deep paleochannels, are a characteristic of the Pre-Quaternary surface in the project area as well as for large parts of the North Sea. Such valleys or larger channels are related to the glaciations and weak zones in the Pre-Quaternary sediments. The channels are reused by the ice sheets moving and later filled with glacial, interglacial, and Late Glacial sediments. The thickest Quaternary deposits in the area are registered in the paleo-valleys in the Pre-Quaternary surface and are sometimes, but not always, related to depressions in the present-day bottom relief. Several deep buried valleys are situated in the areas planned for Energy Island and OWF's and in the eastern export cable corridor. On multi-channel seismics it is often seen that the flanks of this valley can be followed almost to the sea floor.

The screening study from 2020 [4] assesses the geological and geotechnical conditions of various areas with respect to establishing wind farms and export cables. The parameters assessed are listed in Table 4-1.

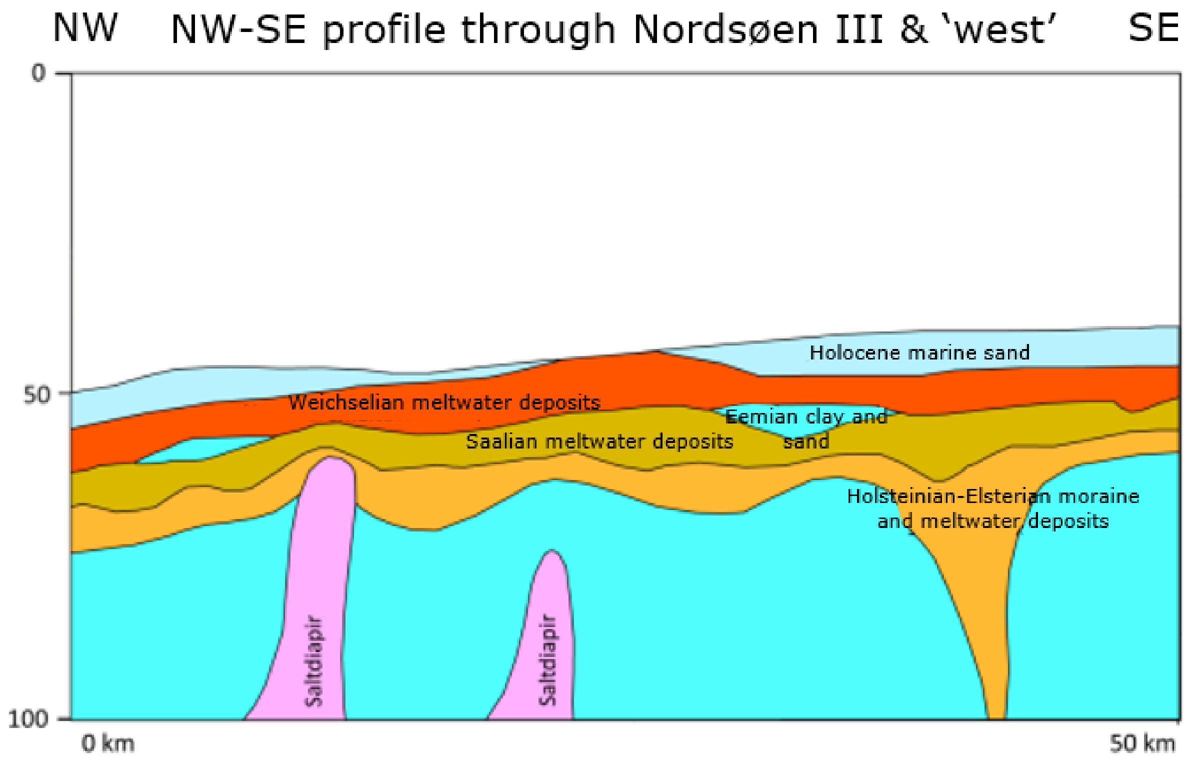

Figure 4-3 NW-SE section across the area Nordsøen III and the area west of this, modified from ref. [4].

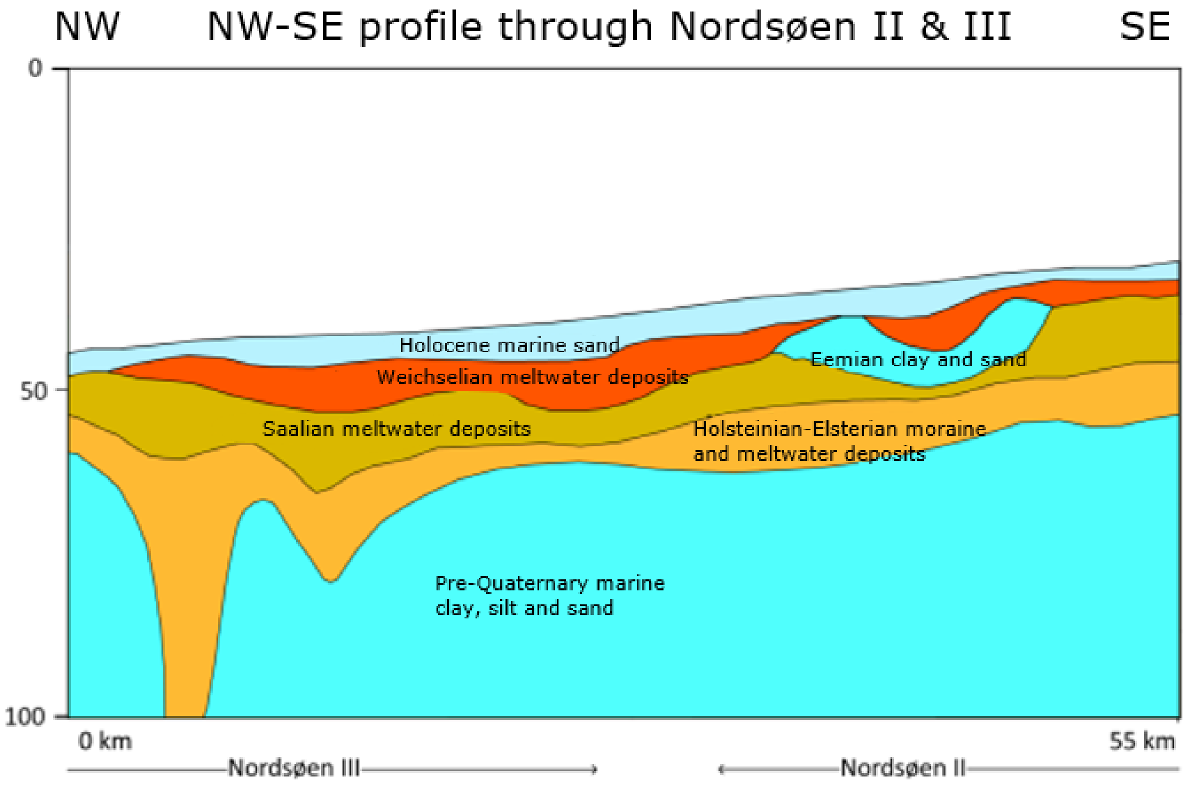

Figure 4-4 NW-SE section across the Nordsøen III and Nordsøen II areas, modified from ref. [4]

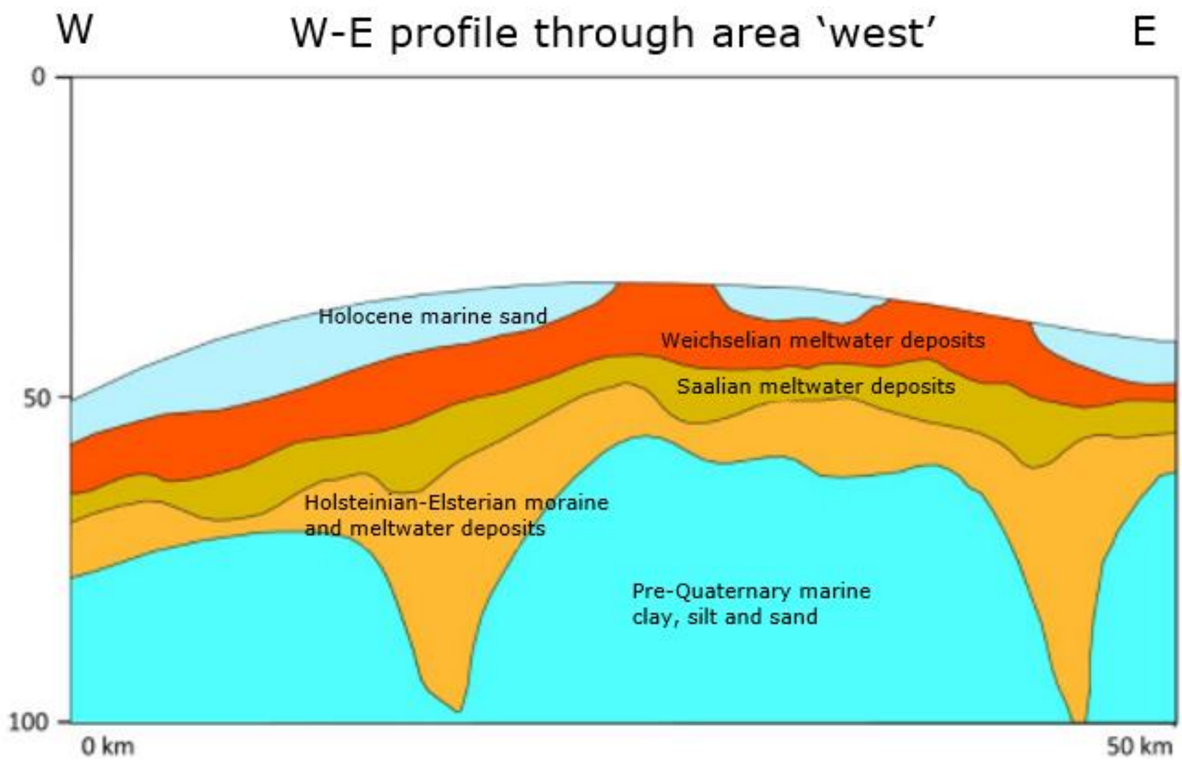

Figure 4-5 W-E section across the area west of Nordsøen III, modified from ref. [4]

Figure 4-6 presents a similar conceptual model of the nearby area, Jyske Rev. This model shows a lot of the same features as shown in Figure 4-3-Figure 4-5, but includes presence of glacial till deposits and smaller Weichselian meltwater features cutting into the till and older glacial deposits.

Based on the mentioned conceptual models in this report will update and incorporate findings from geophysical (seismic) data and especially new geotechnical data to assess the potential hazards related to offshore wind constructions and installations.

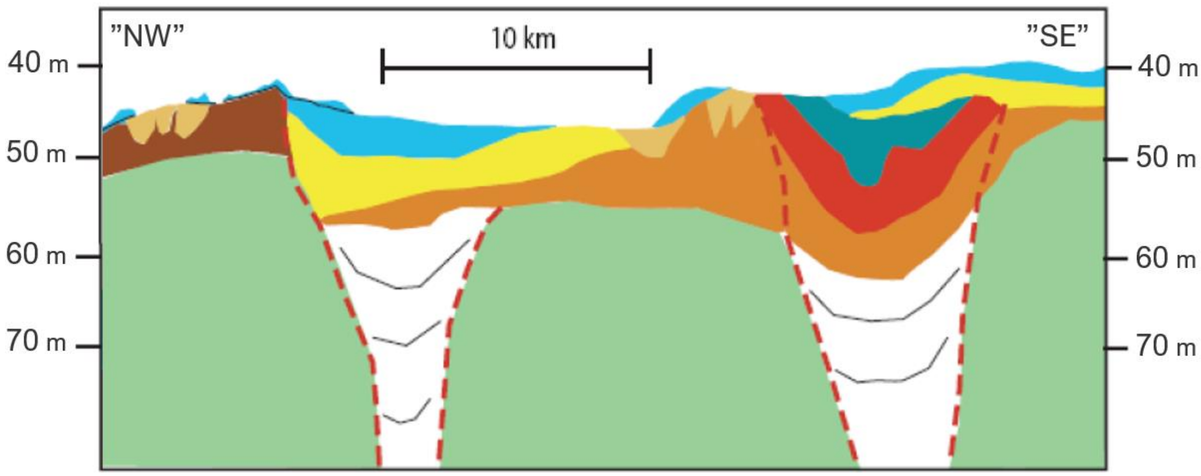

Figure 4-6. Conceptual geological model of the nearby area Jyske Rev. The colours on conceptual geological model correspond to the stratigraphic model shown on Figure 4-7, modified from [6]. Also presented and discussed in [8].

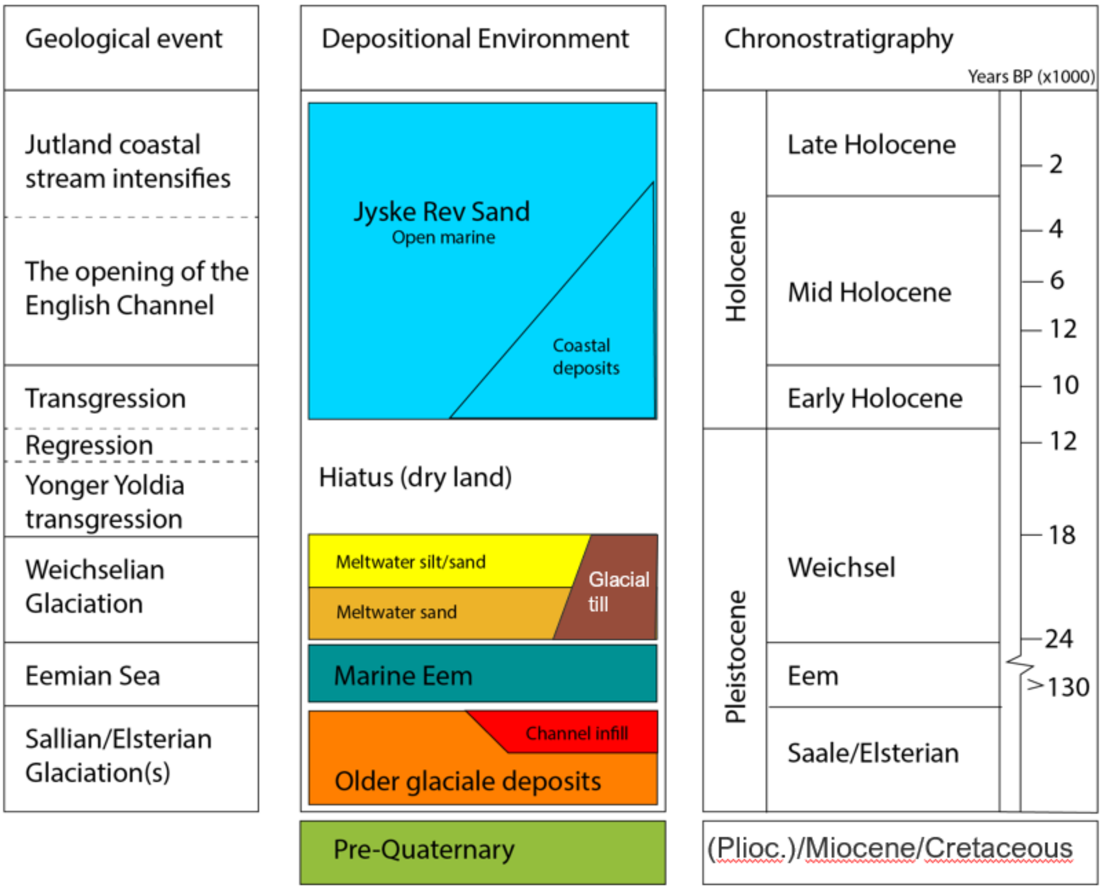

Figure 4-7. Stratigraphic model, modified from [6]. Also presented and discussed in [8].

With respect to geotechnical properties in relation to foundation and export cable, the following is expected:

- Interglacial sediments (clay and sand from Eem) may have high strength
- The glacial till contains boulders and may have high strength
- The pre-quarternary deposits may be as shallow as 15 m and may have high strength

The screening study from 2020 [1] accesses the geological and geotechnical conditions of various areas (shown in Figure 4-1 and Figure 4-2) with respect to establishing wind farms and export cables. The parameters assessed are listed in Table 4-1.

Table 4-1 Assessed parameters in relation to establishing wind farms and export cables

Parameter	**Comment**
Water depth	Limitations in relation to various foundation types
Shallow chalk/bed rock	May prohibit the use of monopiles
Soft sediments at the seabed	Problematic for jack-up operations and foundation
Shallow thin or thick sand layers	Thin sand layers may increase cost of cables. Thick sand layers may favor suction buckets
Current and Sediment transport	Strong currents may increase installation costs Sediment transport is important for cable burial depth (erosion risk)

Design of cable route	Distance from shore, passage of soft soils, glacial sediments or boulder fields
UXO risk	Risk of UXO's increasing costs

In summary, the main risk in the areas seems to be related to hard soil according to the 2020 desk study [4].

5. GEOPHYSICAL DATA

5.1 Data sources

Geophysical data for this assessment is limited to existing data available in publicly available databases. Publicly available geophysical data is stored in the Marta database (managed by GEUS) and lists of relevant data were extracted from this database. Older data were listed in the database but not stored by GEUS, but it was possible to retrieve sets of the data from Aarhus University. This was the case for the Dana94-Dana96, Flyvefisken_1999 and Gribben 1997-1998 surveys, see Table 5-1.

The geophysical data sets are from several vintage surveys and were acquired for a range of different purposes. Therefore, the location of the data is spread unevenly across the area and comprise a range of different data types (i.e. seismic sources). This results in some limitations for the interpretation of the data. The main limitation is in the continuity of interpretations in the deeper penetration seismic data types (sparker and air gun) where the limited extend and uneven distribution limit the possibilities to map the subsurface.

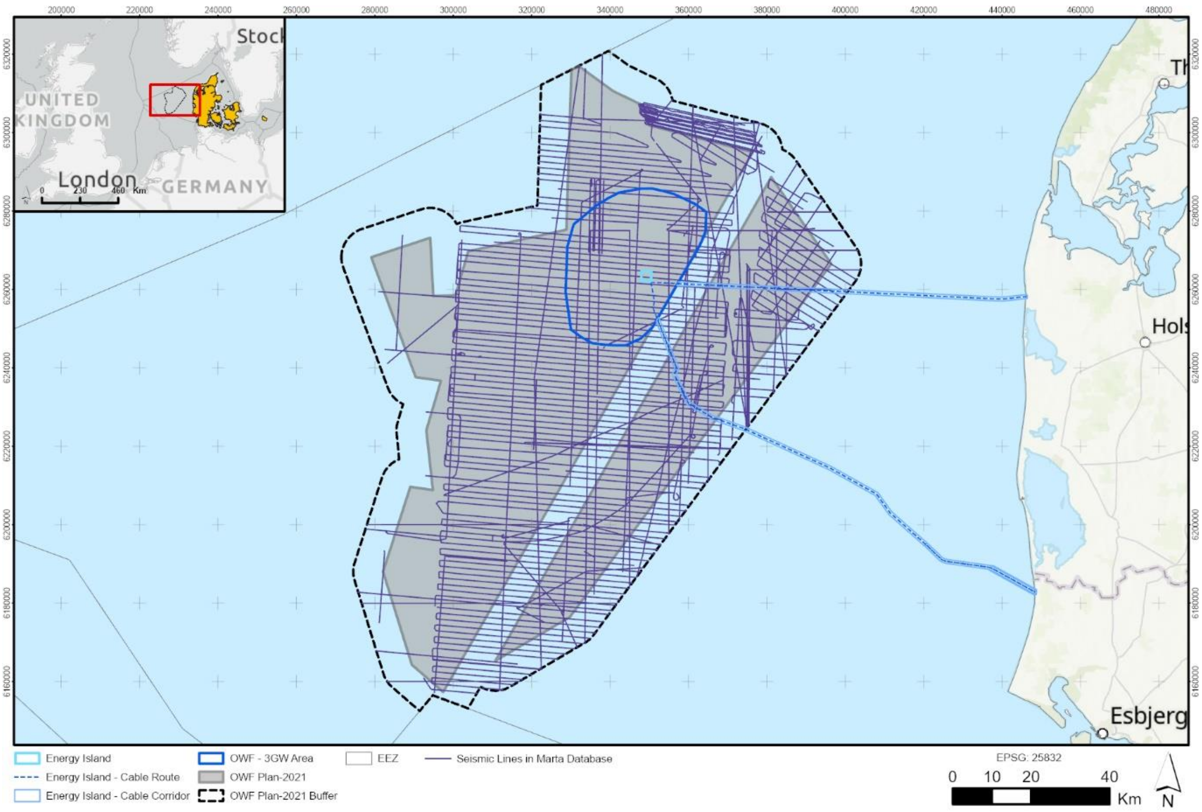

Figure 5-1. Seismic Lines from the Marta Database inside the 10 GW buffer area.

5.2 Available data

As mentioned in section 5.1 the available geophysical data is a compilation of data from the Marta database and additional data received from Aarhus University.

Table 5-1 presents all relevant data from the Marta database that have been considered for this project. Only selected datasets in the list were eventually used in the mapping, but location, data type and quality have been checked for any possible valuable information in relation to this project.

Several of the datasets that were considered were discarded due to different reasons: Often the target depths for the surveys have been significantly deeper than the target for this project, resulting in too low resolution and non-optimal processing of the data for near seabed interpretations. For other datasets limited extent of the survey lines or data format have excluded the datasets.

Table 5-1. Geophysical data from the Marta database that have been considered for this project. Survey names in green indicate surveys that ended up being used for interpretation.

Survey Name (Martha Database)	Instrument	Sum of LENGTH (Km)	Sum of LENGTH - clipped to buffer (Km)	Status according to Marta
GEUS_NORDSOE_2009	Chirp - Sparker	407,69	173,71	*Released*
GEUS_NORDSOE_2010	Chirp - Sparker	533,32	496,43	*Released*
NORDSOEEN_MST_HAB2019	Innomar SES-2000 Medium sub-bottom profiler	5613,06	4428,39	*Confidential*
NORDSOEEN_O2_NST_2012	Sparker:	479,91	196,40	*Released*
NORDSOEN_BLST_F1P2	Sparker - Chirp	470,09	437,45	*Released*
NORDSOEN_BLST_F1P3	Sparker - Chirp	101,75	101,75	*Released*
NORDSOEN_BLST_F2	Chirp - Sparker	1440,66	1440,66	*Released*
Sum		**13942,20**	**9787,95**	
Survey (Aarhus University)	Instrument	Sum of LENGTH (Km)	Sum of LENGTH - clipped to buffer (Km)	Status
Dana_1994	Multi-channel reflection seismic, Airgun	868	86	*Released*
Dana_1995	Multi-channel reflection seismic, Airgun	1382	112	*Released*
Dana_1996	Multi-channel reflection seismic, Airgun	1620	548	*Released*
FLYVEFISKEN_1999	Water gun	1192,18	674,26	*Released*
GRIBBEN_1997	Water gun Sleeve gun	226,95	152,46	*Released*
GRIBBEN_1998	Water gun	916,19	461,10	*Released*
Sum		**3870**	**746**	

In addition to available seismic data Energinet has provided preliminary interpretations and reports from the surveys covering the 3 GW area based on the 2021 geophysical pre-investigation surveys. The surveys were split such that Fugro has covered the western part of the 3 GW area and MMT has covered the eastern part. Horizons mapped on SBP and/or multi-channel seismic data by MMT/Fugro were delivered as subsurface grids (elevation and depth below seabed) and thickness maps (isopachs) of the units were delivered as well. These interpretations have been used in the geophysical assessment to assist the interpretation within the 3 GW area.

5.2.1 Data quality

Both the SBP and multi-channel seismic data included are of high quality. In general, multi-channel seismic data will always have better signal to noise (S/N) ratio compared to single channel data (including SBP) due to the increased amount of recording channels. However, the lower S/N ratio in the SBP data is compensated by high frequencies, and thus higher resolution, for shallow soil interpretations.

The data resolution (vertical seismic resolution) is a key figure for seismic data and interpretation of seismic data as it determines the minimum subsurface structure resolvable in from the data. In general, the vertical resolution of seismic data is considered to be ½ of the wavelength calculated from the dominant frequency in the frequency spectrum of the data. The dominant frequencies and vertical resolution for the three seismic data types are listed below:

SBP:
Dominant frequency: 7900 kHz
Vertical seismic resolution (at seismic velocity of 1500 m/s): <u>0,09 m</u>

Sparker:
Dominant frequency: 600 kHz
Vertical seismic resolution (at seismic velocity of 1500 m/s): <u>1,25 m</u>

Airgun:
Dominant frequency: 55 kHz
Vertical seismic resolution (at seismic velocity of 1500 m/s): <u>13,6 m</u>

The vertical resolutions illustrate the different usability of these three seismic data types. For airgun multi-channel data with a resolution around 13 m only major structures such as very large channels are expected to be visualized. Another disadvantage of the airgun data is the dominating seabed reflector that masks all structures in the upper 10-20 m below the seabed.

The sparker data is very useful for the scope of this study. It has a deeper penetration depth when compared to the SBP data and a vertical resolution of 1,25 m meaning that most structures and layers are resolved. Unfortunately, the 10 GW area have a very limited coverage of sparker data.

The SBP data has the highest vertical resolution of the three seismic data types. However, the SBP is limited in the depth of penetration by the ground conditions and especially in sandy and coarse-grained materials the penetration depth is very limited. The SBP data is mainly from the NORDSOEEN_MST_HAB2019 dataset that has an evenly spaced coverage throughout most of the 10 GW area, resulting in a very useful dataset, despite the limitations in penetration depths.

5.2.2 Data weighting

Sub-bottom Profiler (SBP)

After examination of all datasets, the NORDSOEEN_MST_HAB2019 (Sub-bottom Profiler data) with relatively dense line spacing covering most of the 10 GW area was decided to be the primary dataset. Furthermore, the following datasets were used to confirm location of structures deeper than the range of the SBP data as well as to confirm location of previous mapped valleys: Dana_1994, Dana_1995, Dana_1996, GEUS_NORDSOE_2009, GEUS_NORDSOE_2010 (location of the datasets is shown in Figure 5-3), NORDSOEEN_O2_NST_2012 and NORDSOEN_BLST_F2 (location of the dataset is shown in Figure 5-2).

The NORDSOEEN_MST_HAB2019 data is high-resolution sub-bottom profiler (SBP) data acquired in 2019 by The Danish Environmental Protection Agency. The data has high-resolution in the shallow subsurface but has a low penetration in the order of a few meters to tens of meters. The quality of the data is varied throughout the site and the ability to detect subsurface reflectors has shown to be highly dependent on the shallow sediment types. Thicker, shallow sandy layers reflect most of the incoming seismic signal back and limits the penetration of deeper units.

In some areas where the shallow sand layers are either thin or absent, deeper reflectors can be seen. Throughout the site, fine-grained, paleochannel sequences is penetrated in areas where coarse-grained layers are either thin or absent below the seabed.

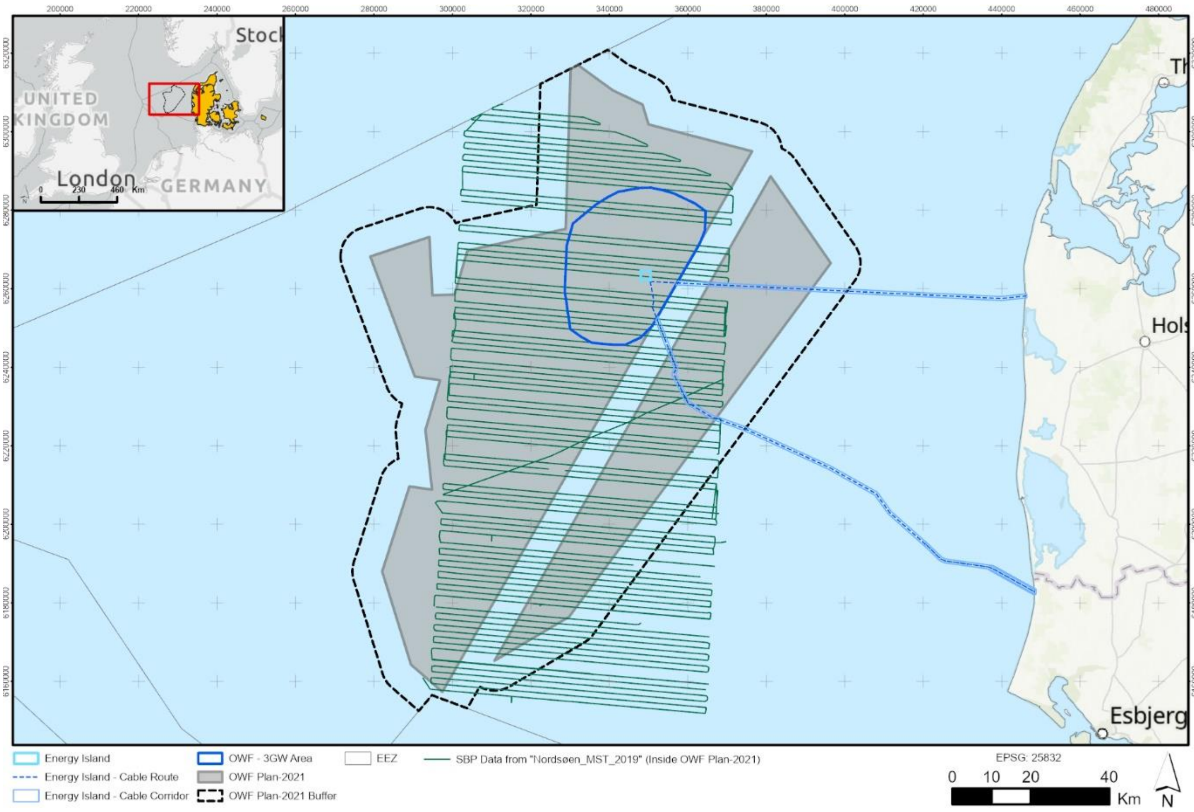

Figure 5-2 Sub-bottom Profiler (SBP) from The Danish Environmental Protection Agency (2019). Only the part of the dataset that covers the "OWF Plan-2021 Buffer" is shown.

Sparker/Multi-channel seismic (MCS)

To work around the limited penetration depth of the SBP, deeper penetrating seismic data from GEUS and AU has been used to support the assessment. From GEUS, sparker data acquired in 2009, 2010 and 2012 has been used to support the interpretation from the SBP because the data sets overlap in many parts of the area. The sparker data has been used in areas where reflectors were too deep to be mapped on the SBP.

From AU, multi-channel seismic reflection data acquired with the DANA vessel in 1994, 1995 and 1996 was also imported to the IHS Kingdom project. However, due to the lower frequency of this data, shallow structures are not resolved, and it did not make sense to continue interpretations carried out on the SBP onto the MCS data. Instead, the MCS was used to confirm presence and location of large paleochannels (buried Quaternary meltwater valleys) previously mapped [7].

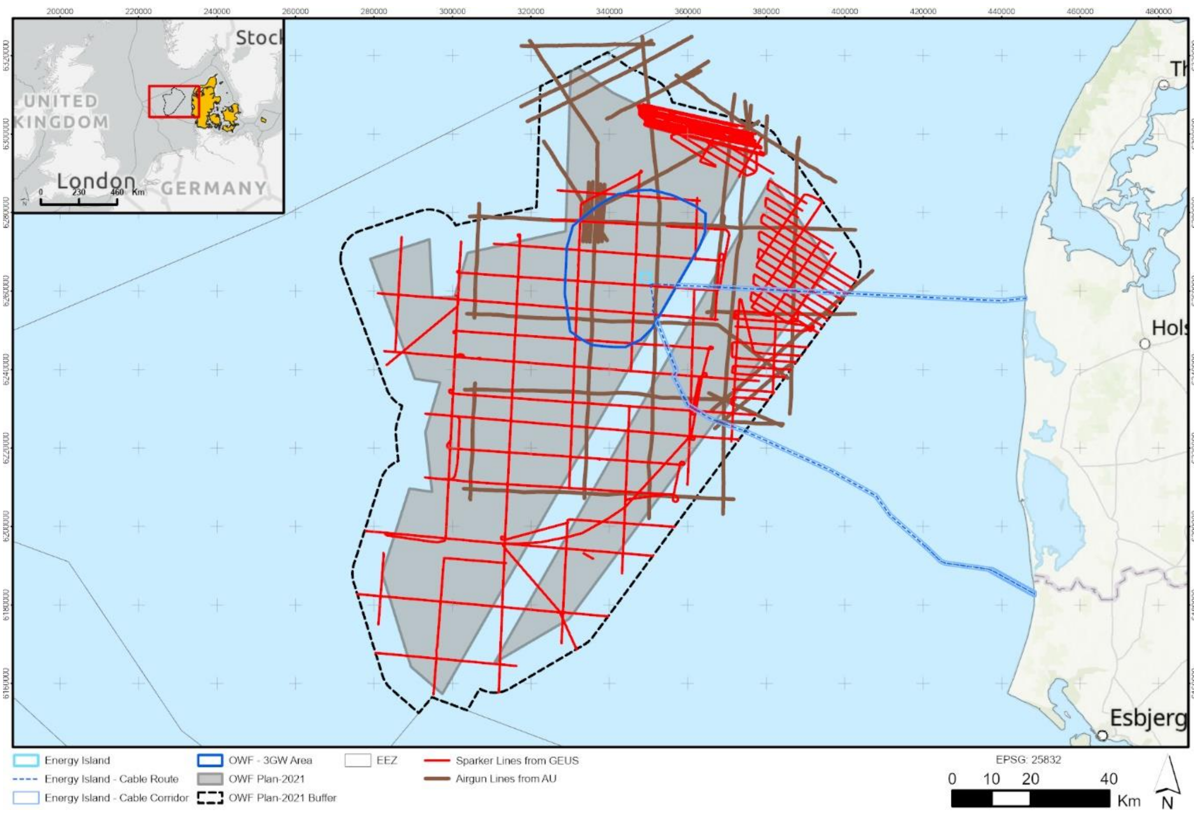

Figure 5-3 Sparker lines from GEUS (red) acquired in 2009, 2010 and 2012 and, Airgun lines from AU (brown) acquired on the DANA vessel in 1994, 1995 and 1996.

6. GEOTECHNICAL DATA

6.1 Available data

The geotechnical evaluation is based on the following data:

Data source	Type of data	Area
Marta database (The Danish marine raw materials database)	Vibrocores, grab samples	Eastern North Sea
Jupiter database (The Danish well / borehole database)	Boreholes, vibrocores, grab samples	Eastern North Sea
Seabed map – Marta database [5]	GIS layer	Eastern North Sea
The Danish Environmental Protection Agency 2019-2020, report ref. [1]	Map of sediments at the seabed	Eastern North Sea and Dogger banke Tail End
Fugro survey 2022	Preliminary CPT and borehole data	Energy Island and 3 GW area

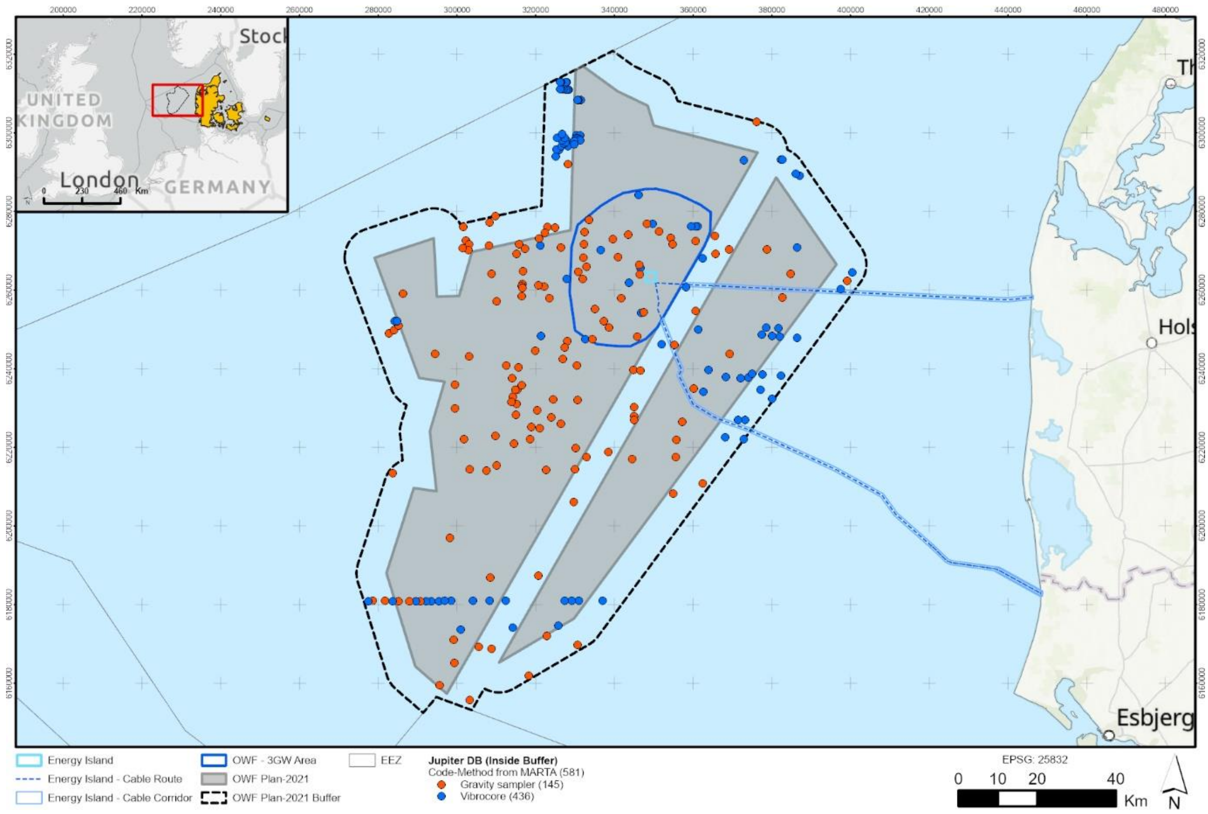

Figure 6-1 Marta database illustrating vibrocores (blue) and grab samples (orange) in the area of interest

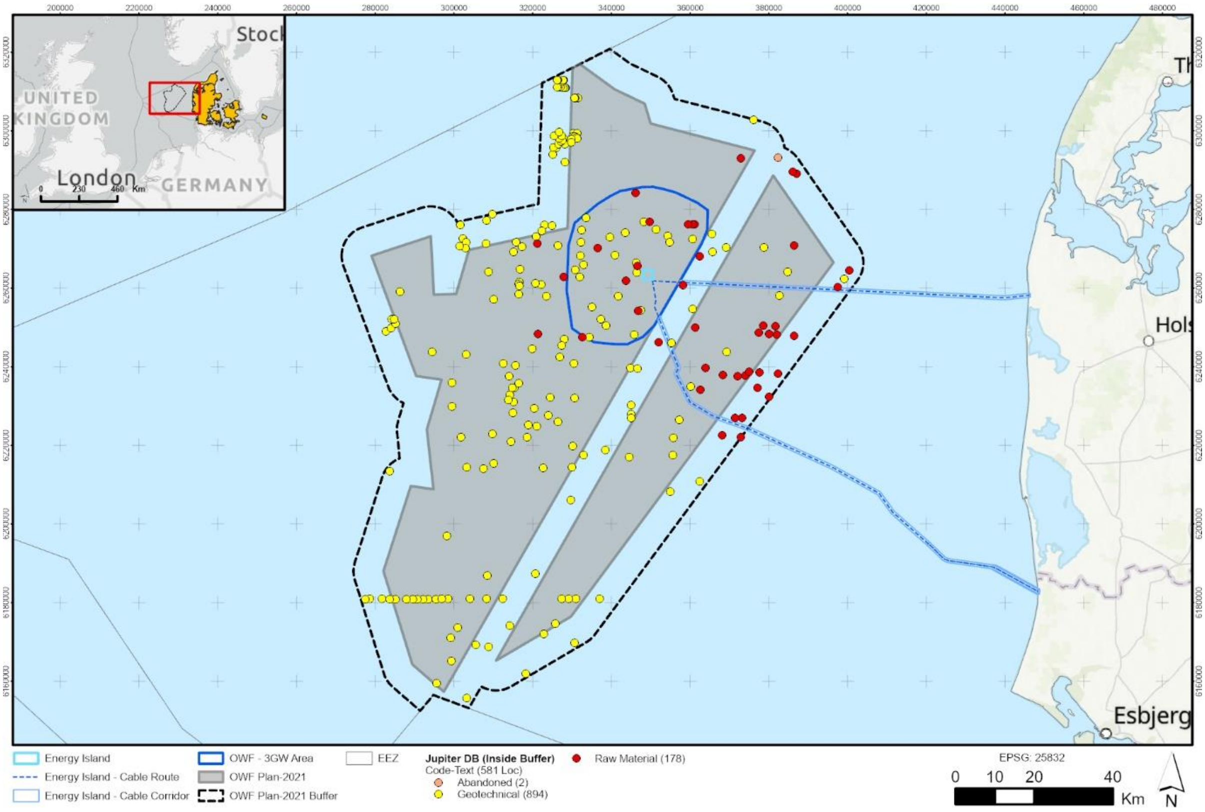

Figure 6-2 Jupiter database illustrating "geotechnical" (yellow) and "raw materials" (red) boreholes

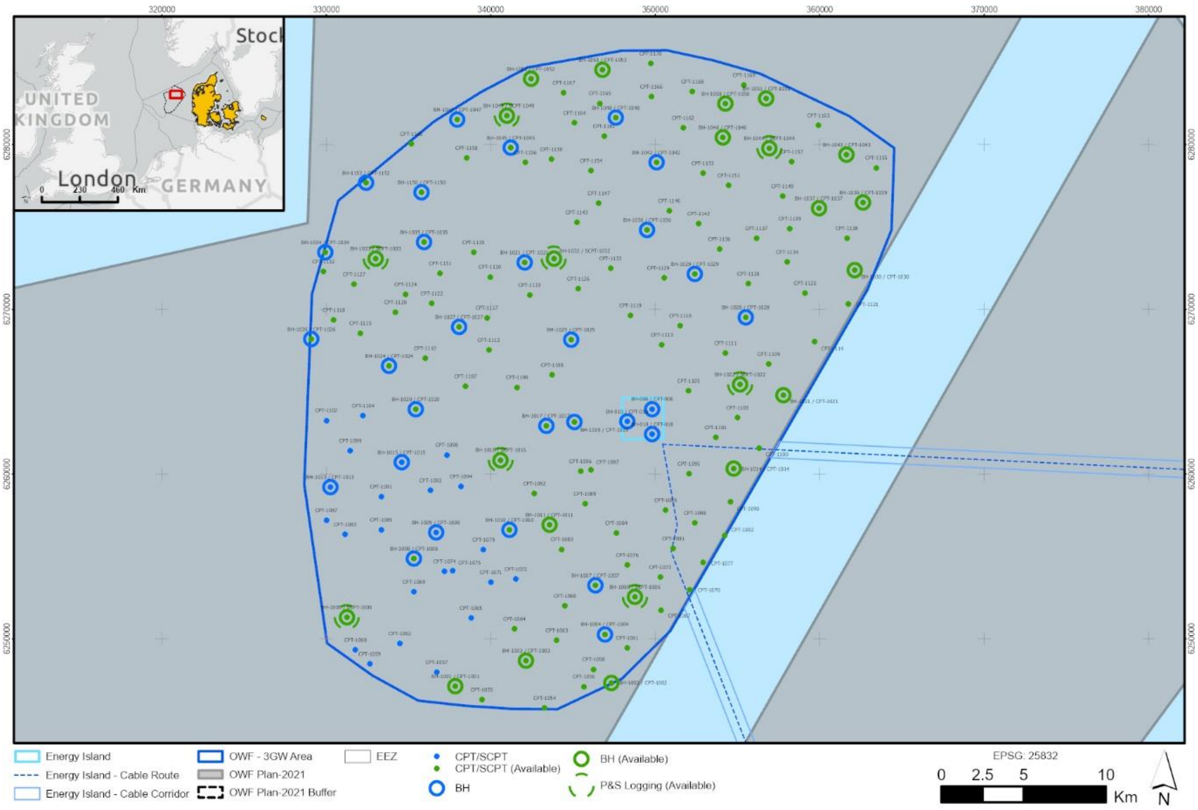

Figure 6-3 Windfarm area, location of the 25 geotechnical boreholes relative to the CPT's (Green dots=available CPT, Green circle=available borehole, blue dots and circles=CPT's and boreholes planned but not available)

6.2 Data quality

The data from the Jupiter database varies in quality and a number of deficiencies and errors have been found. For some samples, the sample type was not given. However, based on the entered data (depth and description) it was possible to determine whether the sample type should be gravity sample, vibrocore or borehole.

Also, for a number of grab samples the water depth was entered instead of the depth below seabed. In these cases, the depth below seabed was set to 0.2 m, which is the normal depth assumed for a grab sample. A corrected version of the dataset was used for this project.

The preliminary Fugro CPT and borehole data was of good quality, except for the geological age missing on the borehole logs. An assessment of this was made by a Rambøll geologist, based on general knowledge of the area. For the CPT’s, the preliminary interpretations made by Fugro has been used.

7. RESULTS

7.1 Geophysical data and their interpretation

Load/work process:
All seismic data was imported to the interpretation software IHS Kingdom as SEG-Y files. Most of the Sub-Bottom Profiler (SBP) was delivered as .raw files and were converted to .segy files using the SESConvert (version 2.330) software prior to the import.

The seismic data is in two-way-travel time [s] and all seismic interpretations have been carried out in the time domain. To visualize the geotechnical data (CPTs, vibrocores and boreholes) on the seismic profiles, a simple time-depth conversion was carried out. The seafloor horizon was gridded and converted to depth [m] using a seismic velocity of 1495 m/s. Afterwards, a simple Dynamic Depth Conversion (DDC) was carried out by using the seafloor grid in depth and a seismic velocity of 1600 m/s for the underlying shallow sediments. Formation tops created from boreholes, CPTs and vibrocores were then imported and visualized on the seismic profiles for correlation.

Before initiating the interpretation, elevation maps delivered from Energinet were converted into grids in two-way-time. These grids covering the eastern and western part of the 3 GW area were then merged into horizon grids covering the entire 3 GW site. The horizon grids maps were then visualized on the SBP profiles acquired by The Danish Environmental Protection Agency in 2019.

Interpretation methodology:

The interpretation methodology can be summarized as following:

1) The seismic interpretation was initiated within the 3 GW area previously (2021) mapped by Fugro (west) and MMT (east) on SBP and multi-channel seismic data.
2) The horizon grids (Fugro/MMT) were visualized on the SBP profiles (The Danish Environmental Protection Agency 2019). Three reflectors matching three MMT/Fugro horizons, namely the H10, H20 and H25 could to a large extent be followed on the SBP data. The rest of the horizon grids were too deep to be within the penetration depth of The Danish Environmental Protection Agency's SBP data.
3) H10, H20 and H25 were then mapped by Rambøll on the SBP data (The Danish Environmental Protection Agency), first throughout the 3 GW area and later extended across the entire study area (see Figure 7-1 and Figure 7-2). Furthermore, the location of shallow paleochannels were mapped with the horizon "Shallow_Paleochannels".
4) Finally, grids were created from these horizons with 500 m buffers for visualization purposes around interpretation points along the SBP profiles

The seismic interpretation has led to the establishment of a simple model of the shallow subsurface consisting of three units (Table 7-1). In the following section, the horizons and units will be described.

Table 7-1 Seismic Units

Seismic Unit	Base Horizon
U10	H10
U20	H20
U25	H25

A shallow reflector, covering most of the site, H10, is in general interpreted as the base of the Postglacial sediments by Ramboll. Thereby, Unit U10 is interpreted as Postglacial sediments. In some parts of the area (mostly in the eastern part of the 10 GW area), H10 is defined on the seismic data as a transition from high-amplitude reflections to either low-amplitude reflections or the end of the seismic signal (where signal-to-noise ratio makes interpretation impossible). In other parts (especially within the western parts of the 10 GW area), H10 forms a distinct surface separating upper, low amplitude/transparent seismic reflections from underlying higher amplitude seismic reflections.

A deeper, undulating reflector, H20, was interpreted on the SBP data where the penetration depth was deep enough to resolve it, or where H10 was not interpreted to be present. H20 defines the base of Unit U20 that in some parts is characterized by semi-horizontal and stratified internal reflections (possibly representing meltwater deposits). Elsewhere, the sequence represents paleo-channels/-valleys cutting into the substratum. In some areas, only the upper part of Unit U20 was penetrated, and in those areas the depth to H20 (and the thickness of Unit U20) is unknown. H20 is in general interpreted to be an erosive surface of Late Pleistocene age.

Figure 7-1 shows a representative profile with the interpreted horizons H10 and H20.

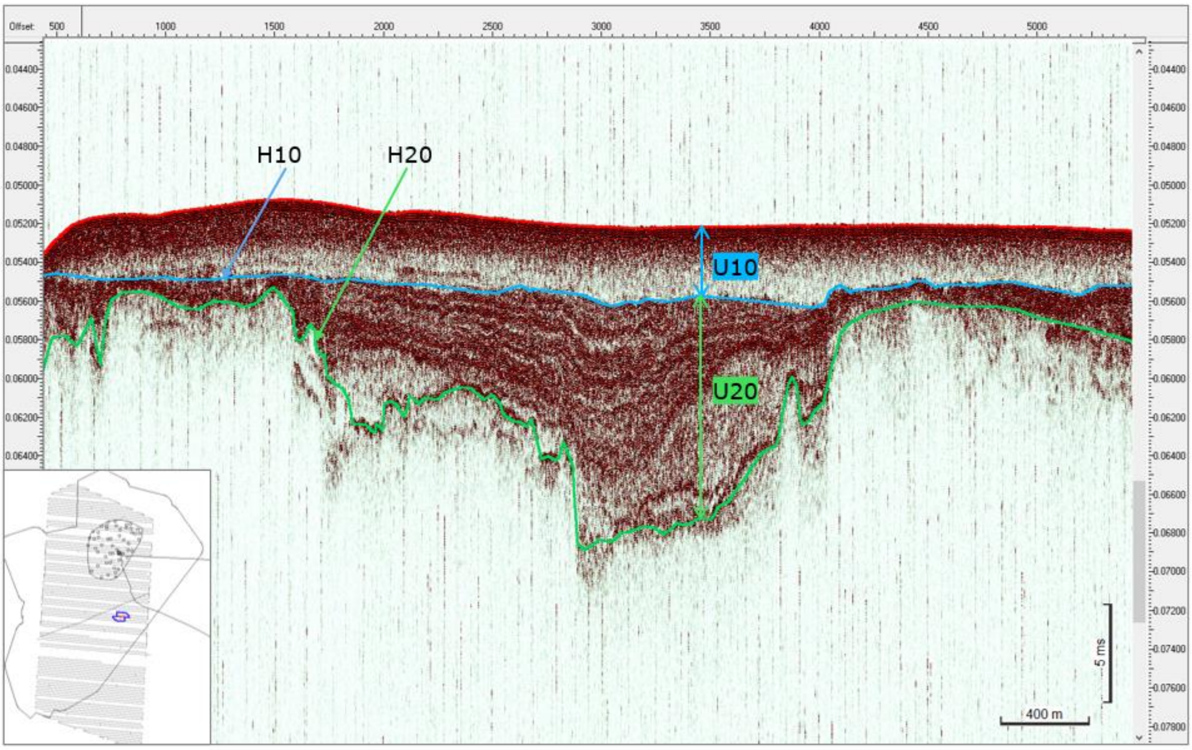

Figure 7-1 Representative profile showing the interpretation of H10 and H20 and the units U10 and U20.

In the eastern part of the 3 GW area, a seismic unit U25 has a base defined by the H25 reflector. This horizon, previously mapped by MMT, showed to delineate an interval in The Danish Environmental Protection Agency's SBP data that has a distinct seismic signature: stratification (layering) and areas/spots of acoustic blanking. The base of U25 (H25) was often below penetration of The Danish Environmental Protection Agency's SBP data which meant that H25 could not always be mapped in this assessment. However, as the internal seismic character is so distinct, an approximate base (H25) was mapped in this study to get the spatial extent of U25. H25 was resolved on some of GEUS' sparker lines (2009, 2010 and 2012 datasets), but the internal character is not as distinct on these profiles when comparing to the SBP.

Figure 7-2 shows a representative profile of Unit U25 delineated by H25. The unit has horizontal layers of high- and low amplitude reflections and spots/bands of acoustic blanking are present. The blanking occurs both as vertical bands across the unit and, as spots of acoustic blanking mostly distributed in the top of the unit (just below H10).

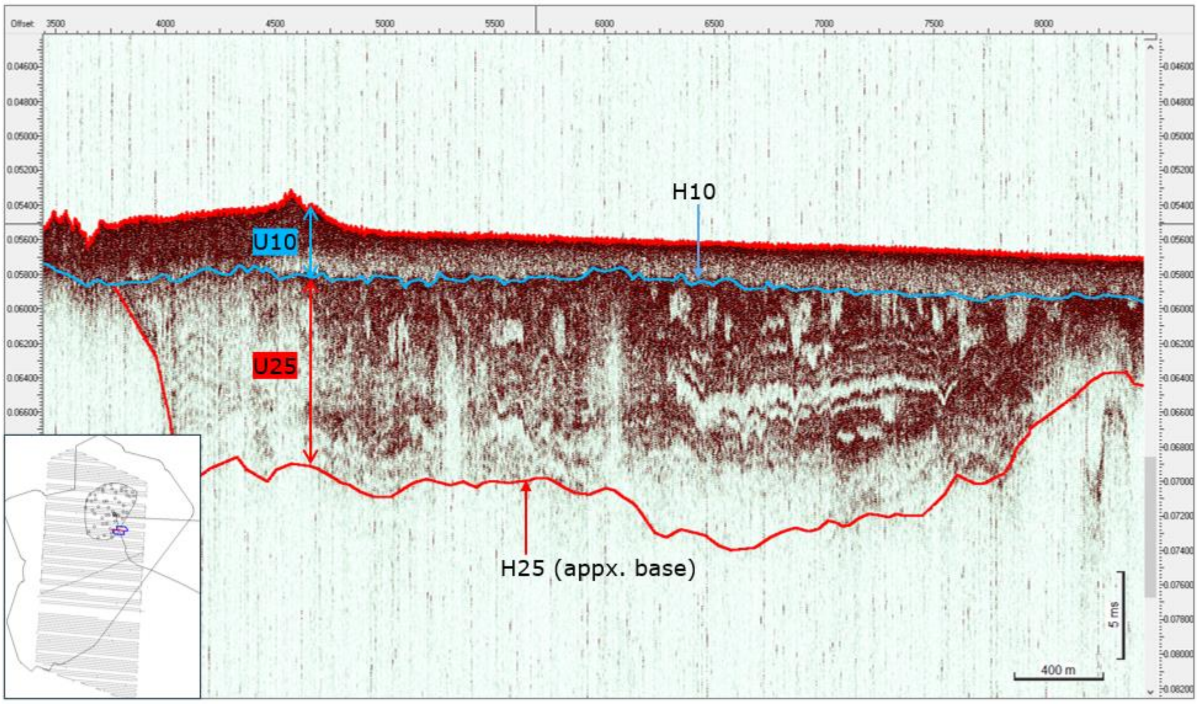

Figure 7-2 H10 and H25 (delineating units U10 and U25) mapped on MST-2019 SBP W-E profile in SE-part of 3 GW area. Evident acoustic blanking in unit U25.

Furthermore, distinct paleochannels along horizon H20 and deeper were mapped separately on the SBP lines by the horizon "Shallow_Paleochannels" to show an overview of where shallow paleochannels are present in the subsurface. Often, the pathways of the channels are not complete in map view due to the shallow penetration of the SBP that only allow penetration on some seismic lines. Furthermore, the lack of seismic lines crossing the E-W trending SBP lines prevented complete spatial mapping.

Figure 7-3 shows the shallow paleochannel pathways as mapped in this study (left) and deeper, regional paleochannels (right) mapped by [7]. The figure highlights that the paleochannels mapped in this study and in the study by [7] are found in different scales/dimensions that date to different periods in the geological history in the study area. This can also be seen in Figure 7-5, where shallow paleochannels as mapped in this study and deeper paleochannels are represented on a MCS profile.

Figure 7-4 shows a representative profile of how shallow paleochannels were defined along the H20 reflector.

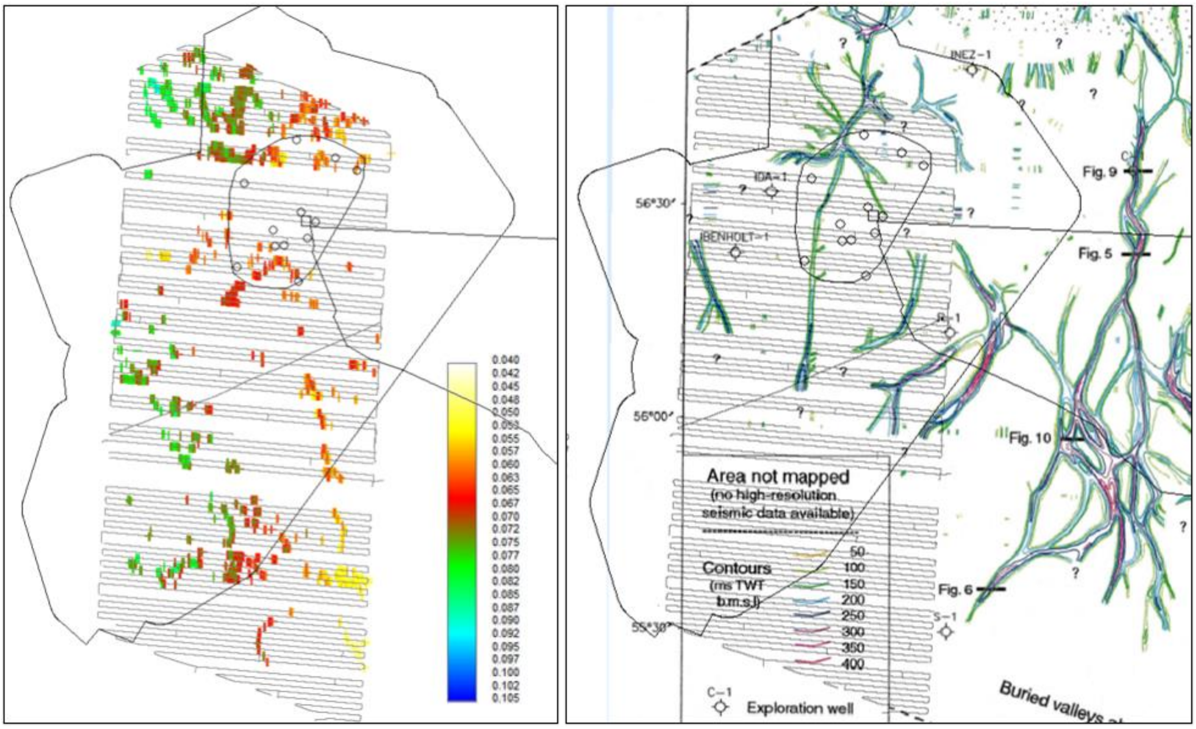

Figure 7-3 Left: Map view of paleochannels mapped on the SBP in this study. Right: regional buried paleochannels/-valleys mapped using multi-channel seismic data by [7]. The two sets of interpreted channels are not of same age and represent two different scales of paleochannels. The left are smaller scale and more recent channels compared to the larger and deeper channels shown to the right.

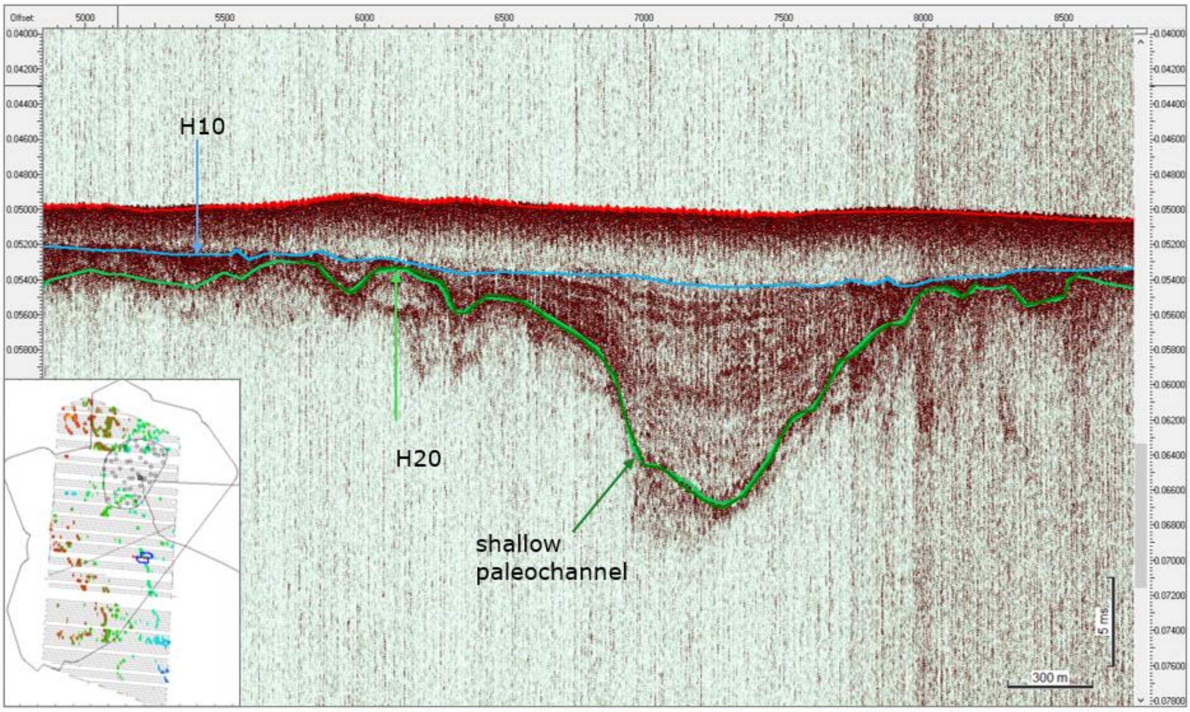

Figure 7-4 SBP profile showing how paleochannels have been defined along the H20 horizon.

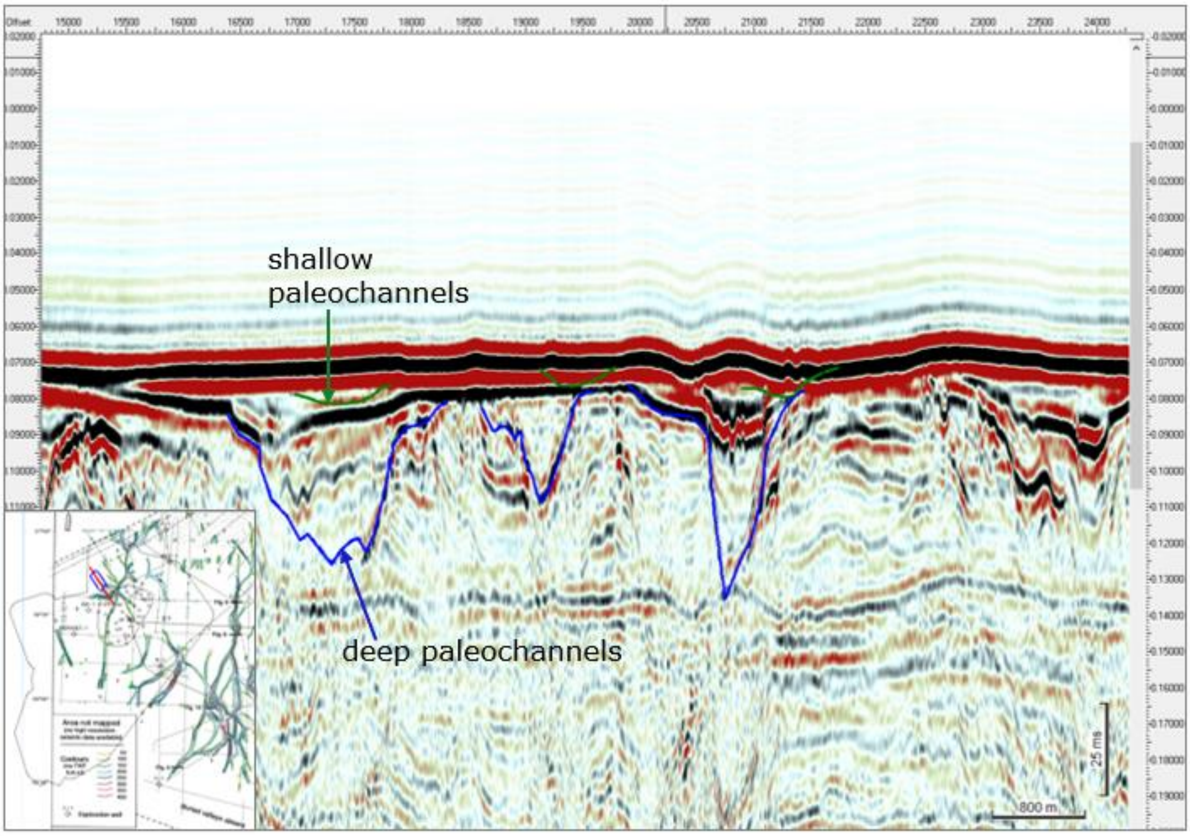

Figure 7-5 Paleochannels. Paleochannels (blue) on MCS data overlain by H20 (green) paleochannel originally mapped on SBP.

7.2 Geotechnical evaluation

The purpose of the geotechnical evaluation is to determine the soil properties in relation to e.g. foundation and cable burial. The boreholes and vibrocores provide detailed soil descriptions, whereas the CPT's provide the soil strength and stiffness. When combining the geotechnical data with the established geophysical ground model, a risk assessment can be made.

The strength of the soils can be assessed from CPT data, indicating the location of hard and soft soils in the upper 6 m (for cables) and in the upper ~30-35 m (for e.g. pile installation).

The soil properties are described on the basis of the undrained shear strength for fine grained materials and the relative density for coarse grained materials (based mainly on CPT data and borehole log when available). The following criteria have been used:

Soft soil:
- All layers of Gyttja or Peat Clay respectively.
- "Very soft" or "Very soft to soft", or "Extremely low strength", or "Very low strength" or "Very low strength to low strength" cohesive sediments (clay, mud, gyttja etc.), evaluated as having undrained shear strength < 20 kPa.

Hard soil:
- All layers described or interpreted as 'clay till' or 'gravel'
- 'Firm' clay, having undrained shear strength > 40-75 kPa
- 'Stiff' clay, having undrained shear strength >75 kPa
- Very dense granular soils (sand or gravel), having a relative density D >85%.

The occurrence of soft and hard soils is illustrated using the color coding showed in Figure 7-6:

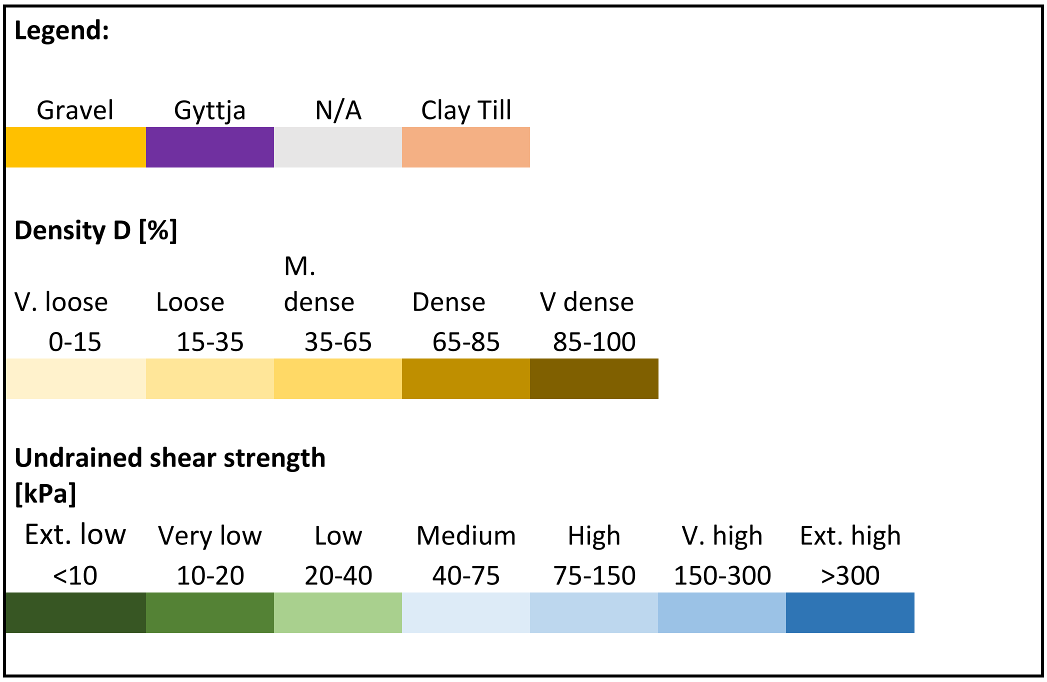

Figure 7-6 Color coding for illustrating hard and soft soils

7.2.1 Energy Island

The soil conditions at the Energy Island are defined based on three boreholes and 97 CPT's.

The location of the three boreholes relative to the CPT's is seen in Figure 7-7 (boreholes marked with green ring). Borehole BH-005 and BH-011 are located at the center, while BH-015 is located in the south-eastern part. The soil conditions found in the three boreholes are summarized in Table 7-2.

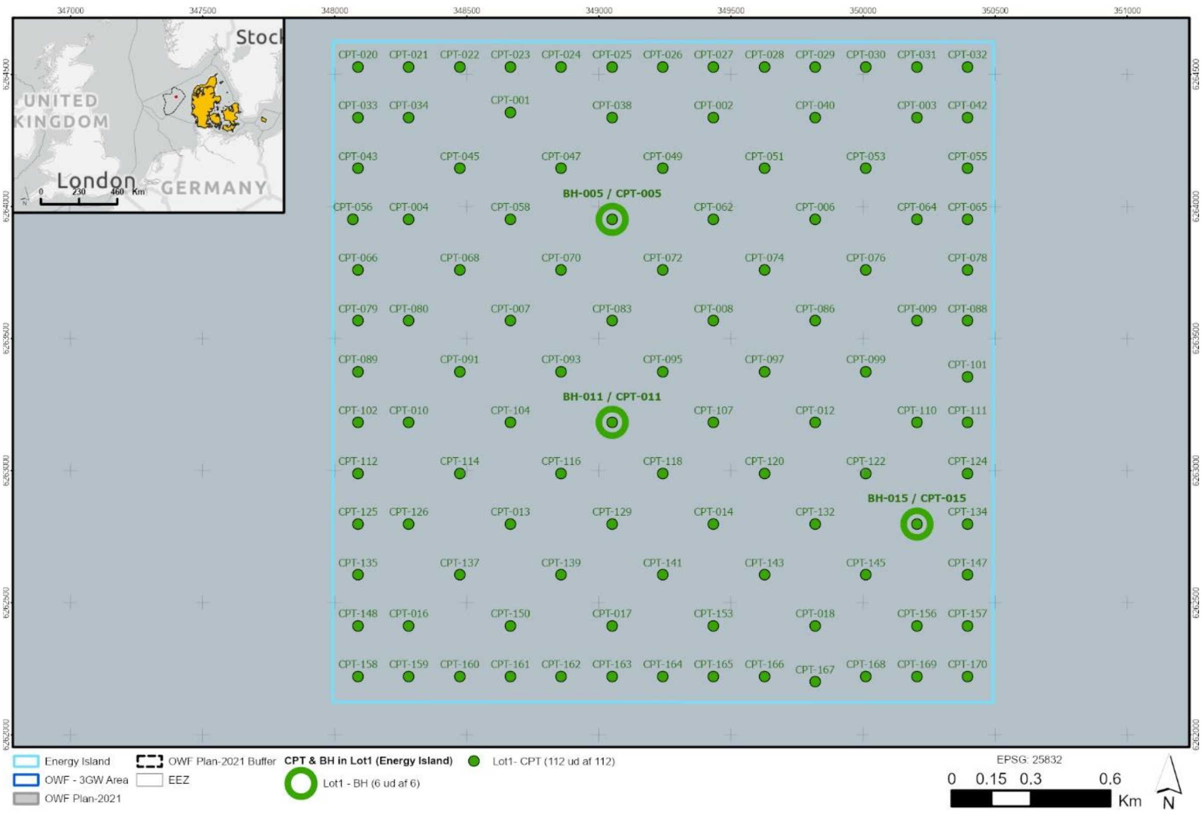

Figure 7-7 Energy Island, location of the three geotechnical boreholes relative to the CPT's

Table 7-2 Energy Island, summary of soil conditions from boreholes

Borehole	Soil conditions, upper 30 m
BH-005	12.8 m of Postglacial sand, followed by Glacial meltwater silt, clay and sand
BH-011	17.2 m of Postglacial sand, followed by Glacial meltwater clay and sand
BH-015	12.9 m of Postglacial sand, followed by Glacial meltwater clay and sand

Comparing the geological assessment from the boreholes and the interpretation of the CPT's, the depth of the base of the postglacial deposits (and top of meltwater deposition) are not always fully in accordance. For borehole BH-005, the borehole and CPT interpretation agrees that the meltwater layers start at 12.8 m, cf. Figure 7-8. However, for borehole BH-011, the interpretation of the borehole puts the base postglacial at 17.2 m, whereas the CPT signal indicates a depth of 13.5 m. The examples show that even for very homogeneous soil conditions as seen at this location, identifying the base of the postglacial deposits is challenging, when these layers are hard instead of soft.

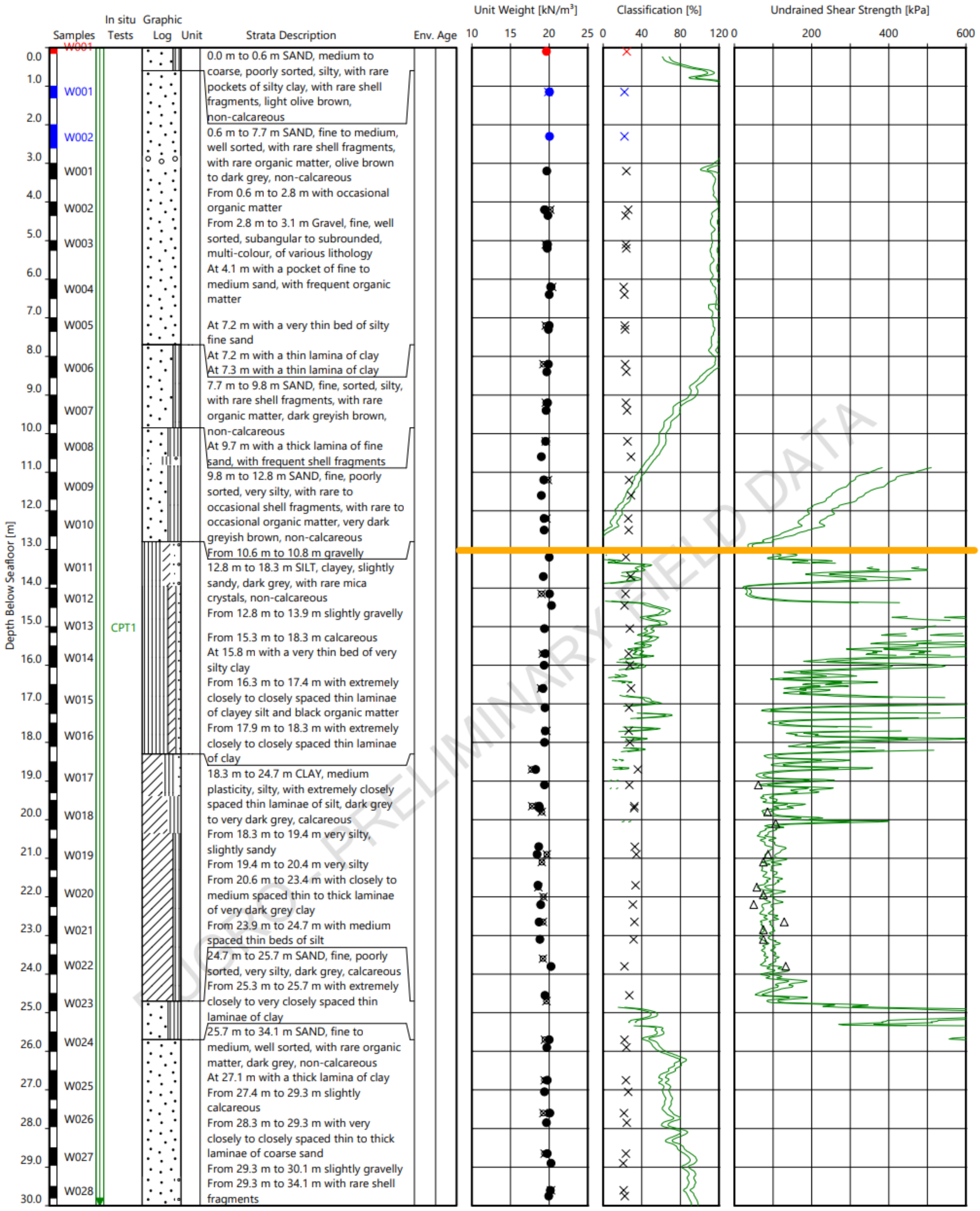

Figure 7-8 BH-005 – Example of good correlation between CPT and Borehole

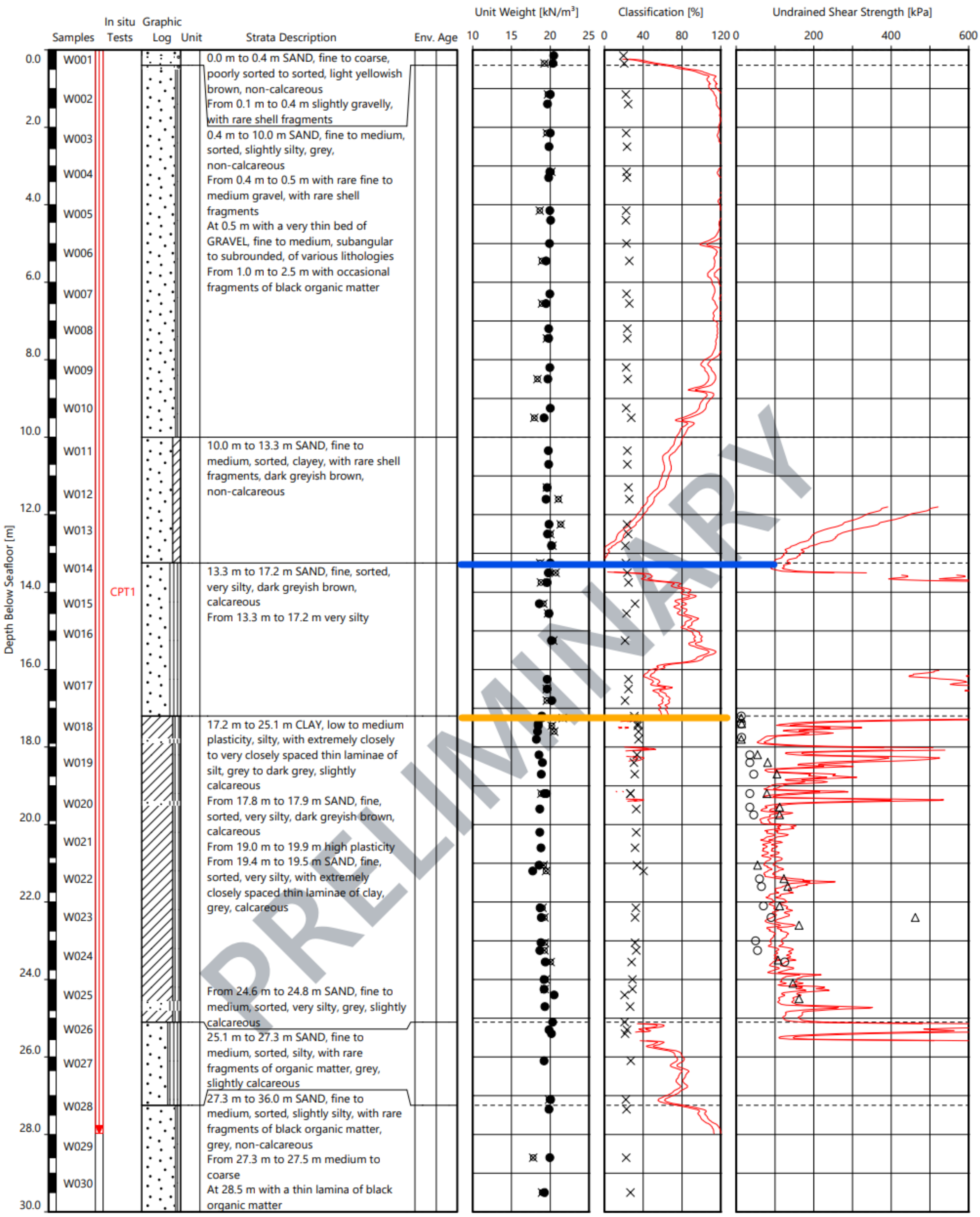

Figure 7-9 BH-011 – Example of uncertainty between CPT and Borehole

Examples of the CPT interpretation with regards to hard and soft soils are seen in Figure 7-10 and Figure 7-11 for the cable and foundation depth interval, respectively.

The examples show that the upper postglacial sands in this area are characterized as very dense with a relative density of D=85-100 % and thus a hard soil. This implies that hard soil is expected for the cable burial (top 6 m) in the entire Energy Island area. Below the dense sand, various layers of clay and sand is seen, followed by another layer of very dense sand. No soft soils are encountered in this area.

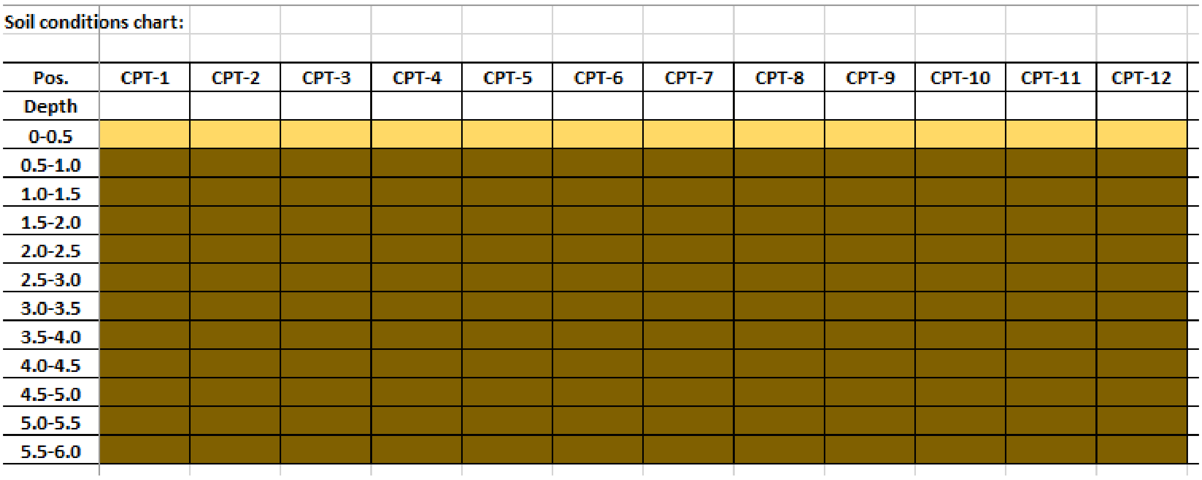

Figure 7-10 Example of CPT interpretation in relation to hard and soft soil conditions, cable depth (0-6 m bsb)

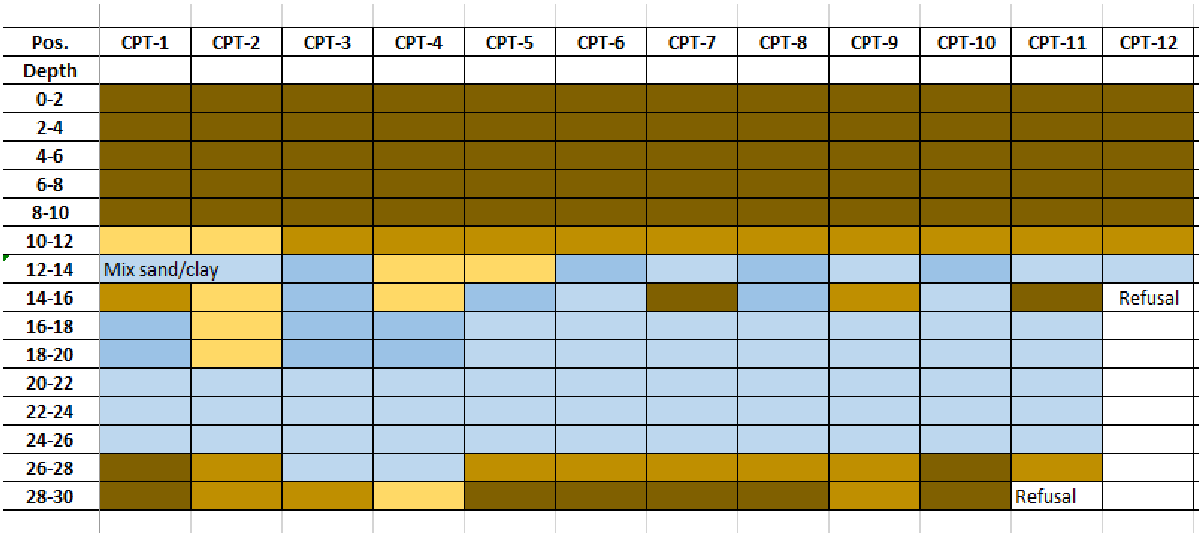

Figure 7-11 Example of CPT interpretation in relation to hard and soft soil conditions, foundation depth (0-30 m bsb)

Out of the 97 CPT's, five show refusal before reaching 30 m depth, cf. Table 7-3. Four of the five CPT refuses at a depth corresponding to the lower, very dense layer. A single CPT (CPT-12) refuses at a higher level, possible in an interbedded dense sand layer also seen in nearby CPT's.

Table 7-3 Energy Island, refusal depth for CPT's

CPT number	Refusal depth
CPT-011	27.5
CPT-012	14.9
CPT-038	27.0
CPT-112	27.6
CPT-169	26.3

By comparing the CPT and borehole data, it is seen that a 30 cm thick gravel layer is found in position BH-005, cf. Figure 7-12. No other gravel layers are found in the three boreholes.

Pos.	CPT-005	CPT-011	CPT-015
Depth			
0-2			
2-4	2.8-3.1		
4-6			
6-8			
8-10			
10-12			
12-14			
14-16			
16-18			
18-20			
20-22			
22-24			
24-26			
26-28			
28-30		Refusal	

Figure 7-12 Location of gravel layers, Energy Island, cable and foundation depth

With regards to organic content, occasional organic content is observed from 0.6-2.8m depth in BH-005, followed by rare organic content. Occasional organic content is also seen in BH-011, whereas no organic content is observed in the samples from BH-015, cf. Figure 7-13.

Pos.	CPT-005	CPT-011	CPT-015
Depth			
0-0.5			
0.5-1.0			
1.0-1.5			
1.5-2.0	0.6-2.8	1-2.5	
2.0-2.5			
2.5-3.0			
3.0-3.5			
3.5-4.0	At 4.1		
4.0-4.5			
4.5-5.0			
5.0-5.5			
5.5-6.0			

Organic content:

- Rare
- Occasional
- Frequent
- Peat

Figure 7-13 Organic content, Energy Island, cable depth

In summary, for the cables, the risk is related to hard soil conditions (hard sand layer) seen in the entire area and potential gravel layers. Further, organic content should be expected in the postglacial sand layers. For foundation, the risk is related to a hard sand layer in the upper 10 meters and again starting at approx. 26-28 m bsb seen in the entire area.

7.2.2 3 GW area

The soil conditions in the 3 GW windfarm area are defined by 25 boreholes and 102 CPT's (Figure 7-14).

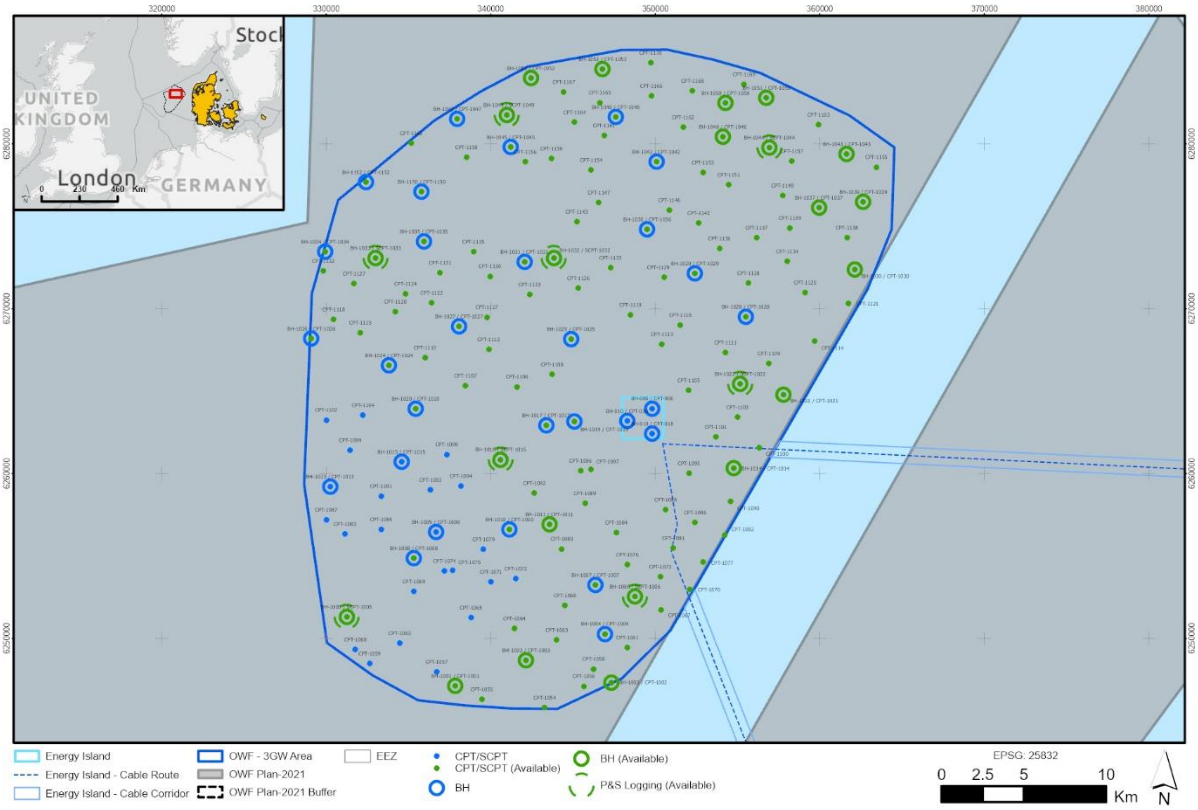

Figure 7-14 Windfarm area, location of the 25 geotechnical boreholes relative to the CPT's (Green dots=available CPT, Green circle=available borehole, blue dots and circles=CPT's and boreholes planned but not available)

It should be noted that the south-western area is sparsely covered (boreholes only), as this desk study only considers the data marked in green (presently available, as the survey is on-going).

The estimated depth of the postglacial deposits has been evaluated in each of the 25 boreholes. The results of this evaluation are found in Table 7-4. In general, it is seen that in this case the age determination does not provide a good guideline for the location of the boundary between softer and more competent units. In many cases, the postglacial layer consists of dense and very dense sand. The exception from this is borehole BH-1006 and BH-1010, where 6-7 m of soft clay is found.

Table 7-4 Estimated depth of postglacial (PG) unit

Position	Base PG [bsb]	Composition of PG layer
BH-1001	3.0	Very dense and dense sand
BH-1002	3.3	Very dense and medium dense sand
BH-1003	1.0	Very dense sand
BH-1005	5.0	Medium strength clay and dense sand
BH-1006	7.3	Extremely low strength clay
BH-1010	6.6	0-3.3 Very dense and dense sand, 3.3-6.6 Low strength clay
BH-1011	2.0	Loose
BH-1012	6.2	Dense and medium dense sand
BH-1014	1.1	Low strength clay
BH-1016	3.3	Medium dense sand and high strength clay
BH-1018	12.8	Very dense sand
BH-1021	10.2	Very dense sand
BH-1022	4.0	Medium dense sand and high strength clay
BH-1023	15.7	Very dense sand
BH-1030	1.6	Medium dense sand and high strength clay
BH-1032	0.0	-
BH-1033	1.6	Medium and very dense sand
BH-1037	1.8	0.9 m very low strength clay (from CPT), followed by dense sand
BH-1039	1.9	Dense and very dense sand
BH-1043	3.5	Dense and very dense sand
BH-1044	1.8	Medium dense sand
BH-1046	1.9	Medium dense and dense sand
BH-1049	0.0	-
BH-1050	0.0	-
BH-1053	3.5	Dense and very dense sand

The borehole positions where the base of the postglacial deposits have been determined are illustrated in Figure 7-15. As seen from Table 7-4, the base of postglacial are misleading with regards to determining the extent of soft soils, as the majority of positions represent dense to very dense postglacial sands. Only two positions (marked with green circles) represent soft soil conditions.

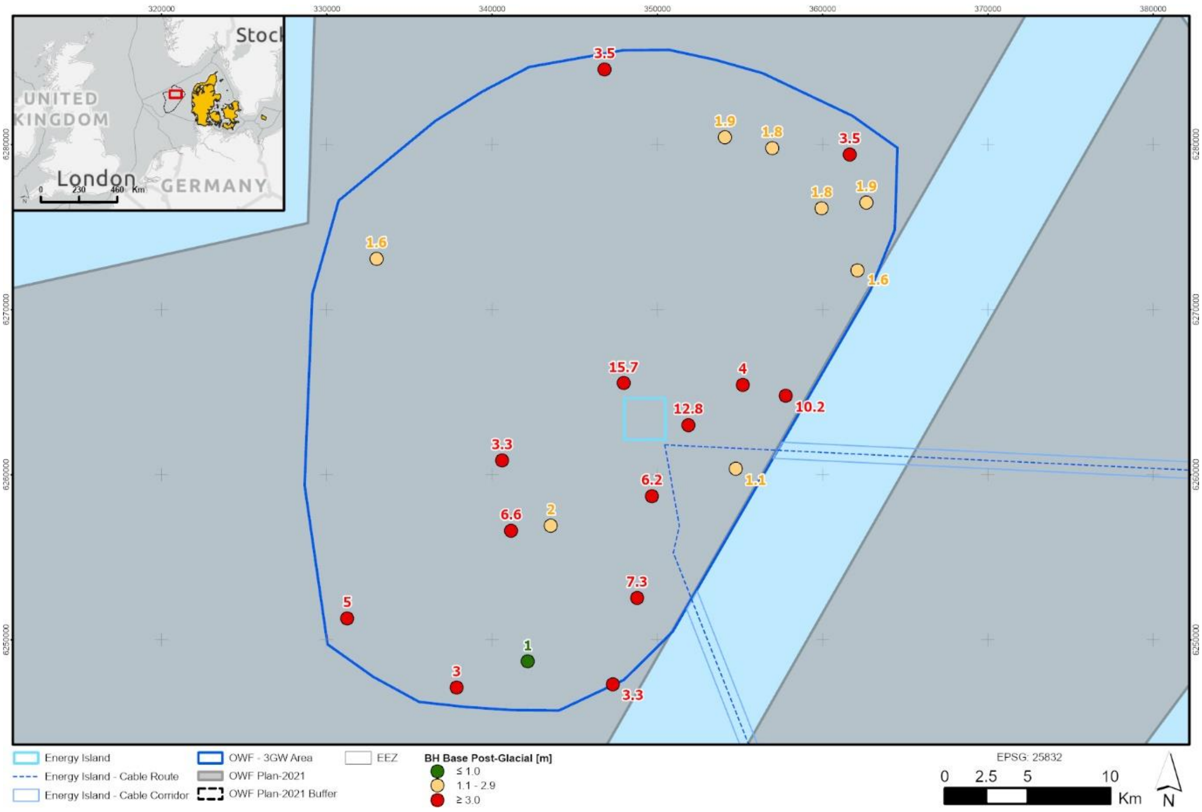

Figure 7-15 Base postglacial deposits from boreholes (soft soil positions in green circles)

The soil conditions evaluated based on CPT-data is illustrated in Appendix 1. The top part shows the occurrence of hard and soft soils in the top 6 m (relevant for cable burial assessment), while the lower part shows the same for the top 30 m relevant for foundation. The soil conditions vary significantly, but as for the Energy Island, hard soil is encountered in many positions, illustrated by the dark brown color (very dense sand) and many refused CPT's. On the other hand, relatively soft soil is encountered at some locations, illustrated by the green colors.

Gravel layers:

Combining the borehole and CPT data, it is seen that in some places the very dense sand layers contain layers of gravel (or sand, very gravelly). Figure 7-16 and Figure 7-17 show the observed gravel layers and their thickness in the 25 boreholes:

Pos.	CPT-1003	CPT-1005	CPT-1006	CPT-1014	CPT-1016c	CPT-1023	CPT-1032	CPT-1033	CPT-1037	CPT-1044	CPT-1050
Depth											
0-0.5							0-0.1 Gravel				0-0.1 Gravel
0.5-1.0											
1.0-1.5											
1.5-2.0											
2.0-2.5		2.2-5 Gravel									
2.5-3.0											
3.0-3.5											
3.5-4.0											
4.0-4.5											
4.5-5.0											
5.0-5.5				5-5.1 Gravel							
5.5-6.0											

Figure 7-16 Gravel layers at cable depth, 0-6m

Pos.	CPT-1003	CPT-1005	CPT-1006	CPT-1014	CPT-1016c	CPT-1023	CPT-1032	CPT-1033	CPT-1037	CPT-1044	CPT-1050
Depth											
0-2											
2-4		2.2-5.0 Gravel									
4-6		5-6.1 Peat									
6-8			7.3-8.2 Peat							7.6-8.6 Stones	Refusal
8-10						8-8.8 Clay v. gravelly				Refusal	
10-12			Refusal								
12-14				Sand							
14-16			15.8-18.6 Sand, v. gravelly	Refusal							17-18 Sand v. gravelly
16-18								Sand			
18-20	Refusal	Refusal	18.6-20.1 Gravel					Refusal			
20-22											21-22.6 Sand v. gravelly
22-24											
24-26	24.5-26.6 Sand,v. gravelly							25.5-26.6 Gravel	Sand		
26-28									Refusal 27.2. At 27.5-27.6 Gravel		
28-30				31.3-35.3 Sand, v. gravelly	29.4-29.8 Stones			28.8-29.6 Gravel		33.6-34.5 Gravel	32.8-36.5 Stone

Figure 7-17 Gravel layers at foundation depth, 0 to ~30 m.

The gravel layers and their thicknesses are also listed in Table 7-5. Shallow gravel is only seen in a single position (BH-1005), so in summary the gravelly (dense) sands seem to be the main risk with regards to hard soils.

From the CPT's it is not possible to distinguish between dense sand, very gravelly sand and stones. However, the refusal depth may be an indication of such layers being present.

Table 7-5 Observed thickness of layers of gravel, very gravelly sand and stones in boreholes

Position	Location of gravel layer	Thickness [m]
BH-1003	24.5-26.6 (sand, v. gravelly)	2.1
BH-1005	2.2-5.0	2.8
BH-1006	15.8-18.6(sand, v. gravelly) 18.6-20.1	2.8 1.5
BH-1014	5.5.1 31.1-35.3 (sand, v. gravelly)	0.1 4.2
BH-1016	29.4-29-8 (stones)	0.4
BH-1023	8-8.8 (clay, v. gravelly)	0.8
BH-1032	0-0.1	0.1
BH-1033	25.5-26.6 28.8-29.6	1.1 0.8
BH-1037	27.5-27.6	0.1
BH-1044	7.6-8.6 (stones)	1.0
BH-1050	0-0.1 17-18 (sand, v. gravelly) 21-22.6 (sand, v. gravelly)	0.1 1.0 1.6

Refusal depth:

The refusal depths are recorded in Table 7-6. When more than one push has been made, the longest is counted. The target depth for the 102 CPT's where more than 30 m and 60 showed refusal before reaching 30 m. The data shows that 30 CPT's refuse within the first 15 m, 22 CPT's have refusals depth from 15 to 25 m and 8 CPT's refuses between 25 and 30 m. The refusal depth may also be an indication of hard soil layers such as dense sand, gravel or stones. Comparing the refusal depth with the borehole data, when possible, it is seen that in all cases refusal occurs in layers where the main description is sand, which is slightly silty to silty and in some cases slightly gravelly.

Table 7-6 Refusal depth for CPT's

CPT no.	Refusal depth [m]	Soil type at refusal depth (from borehole) [if blank no corresponding borehole]
CPT-1042	3.5	
CPT-1051	6.0	
CPT-1050	6.1	Sand, slightly silty, slightly gravelly
CPT-1115	6.3	
CPT-1168	6.3	
CPT-1161	6.8	
CPT-1110	6.9	
CPT-1044	7.0	Sand, silty w. mica
CPT-1137	7.4	
CPT-1149	7.6	
CPT-1131	7.7	
CPT-1118	9.2	
CPT-1006	10.2	Sand, slightly gravelly to gravelly
CPT-1048	10.6	
CPT-1163	10.9	
CPT-1011	11.0	Sand, slightly silty
CPT-1155	11.0	
CPT-1010	11.9	Sand, silty to very silty
CPT-1167	12.1	
CPT-1151	12.3	
CPT-1053	13.1	Sand, slightly gravelly, slightly silty
CPT-1017	13.3	
CPT-1154	13.7	
CPT-1004	13.8	
CPT-1162	13.8	
CPT-1152	14.1	
CPT-1014	14.2	Sand, slightly silty
CPT-1002	14.3	Sand, slightly gravelly
CPT-1028	14.3	
CPT-012	15.0	
CPT-1043	16.0	Sand, slightly silty, with laminae of black organic matter
CPT-1160	16.5	
CPT-1165	16.7	
CPT-1007	17.2	
CPT-1003	17.4	Sand, slightly silty, with laminae of clay
CPT-1033	17.4	Sand, slightly gravelly to gravelly
CPT-1015	17.5	

CPT-1030	17.5	Sand, silty, with laminae of dark organic matter, mica
CPT-1128	18.0	
CPT-1138	18.2	
CPT-1008	18.7	
CPT-1005	18.8	Sand, silty, clayey, with laminae of clay
CPT-1012	18.8	Sand
CPT-1125	19.4	
CPT-1166	19.8	
CPT-1039	21.0	Sand, silty to very silty
CPT-1142	21.3	
CPT-1139	21.5	
CPT-1018	22.0	Sand, silty
CPT-1153	22.8	
CPT-1020	23.2	
CPT-1024	24.3	
CPT-1025	25.5	
CPT-1046	25.9	Sand, silty, mica
CPT-169	26.3	
CPT-1037	26.7	Sand, slightly gravelly
CPT-038	27.0	
CPT-011	28.0	
CPT-1035	28.7	
CPT-1016	29.0	Sand, silty, slightly clayey

The positions of the CPT refusals are illustrated in Figure 7-18. The red dots represent refusal within the upper 15 meters. The refusals at this depth seem to be located in the northern part of the area as well as in a band stretching NW-SE.

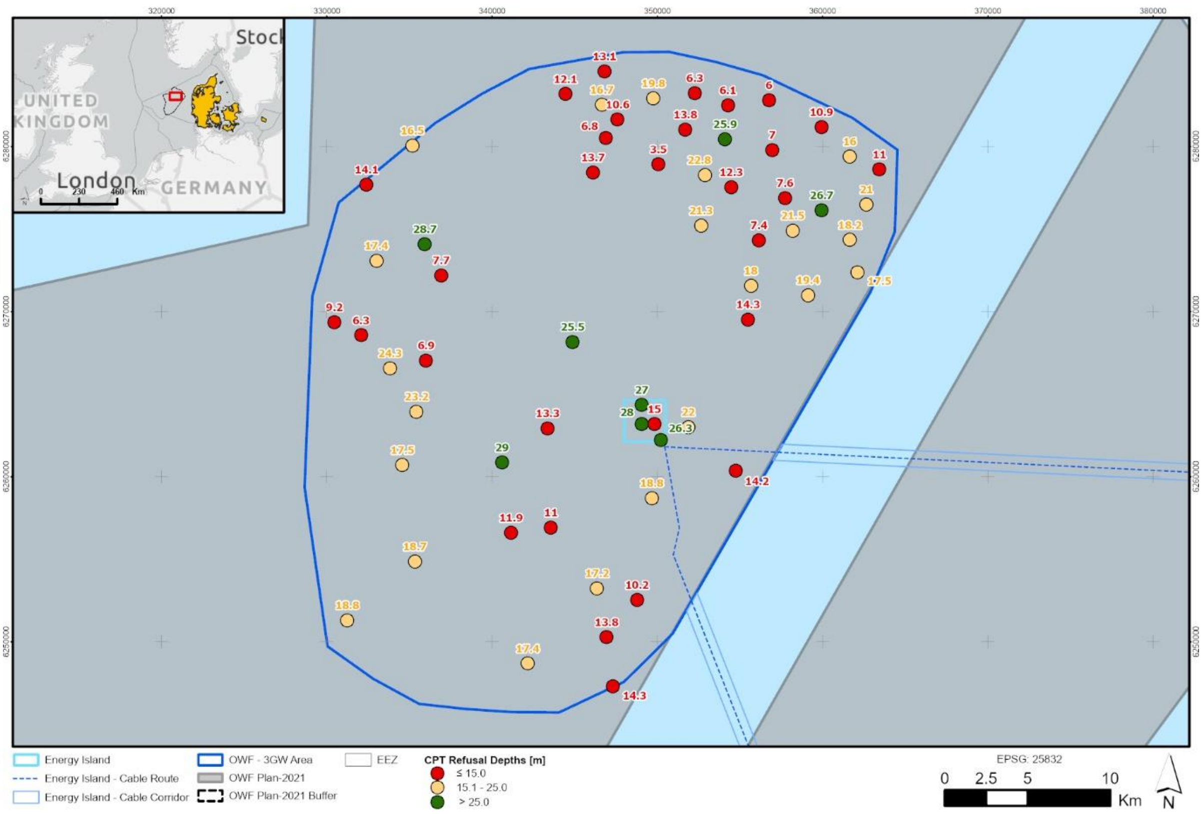

Figure 7-18 Positions with CPT refusal within the 3 GW area

Soft layers:

Soft layers are defined as layers with an undrained shear strength cu<20 kPa and all layers described as gyttja or Peat. Positions where soft clay has been encountered are illustrated in Figure 7-19 and Figure 7-20. The estimated depth of postglacial deposits (based on the borehole logs) is also indicated. In general, there is a poor correlation between this, and the soft layers observed by the CPT's. This may be due to the very dense sand layers being postglacial, while the underlying late glacial/glacial meltwater deposits may also consist of relatively low strength clay. However, soft soil is only encountered in 15 of the 102 CPT's and in six of these the layer is less than 2 m thick.

Pos.	CPT-1006	CPT-1007	CPT-1010	CPT-1014	CPT-1023	CPT-1028	CPT-1037	CPT-1039	CPT-1106	CPT-1125	CPT-1126	CPT-1128	CPT-1152	CPT-1155	CPT-1160
Depth															
0-0.5							Clay ?								
0.5-1.0				PG 1.1											
1.0-1.5															
1.5-2.0							PG 1.8	PG 1.9							
2.0-2.5															
2.5-3.0															
3.0-3.5															
3.5-4.0															
4.0-4.5															
4.5-5.0															
5.0-5.5															
5.5-6.0	PG 7.3		PG 6.6		PG 15.7										

Figure 7-19 Soft layers, cable depth 0-6 m. Depth of base postglacial deposits is indicated where known

Pos.	CPT-1006	CPT-1007	CPT-1010	CPT-1014	CPT-1023	CPT-1028	CPT-1037	CPT-1039	CPT-1106	CPT-1125	CPT-1126	CPT-1128	CPT-1152	CPT-1155	CPT-1160
Depth															
0-2				PG 1.1											
2-4							PG 1.8	PG 1.9							
4-6	PG 7.3		PG 6.6												
6-8															
8-10															
10-12	Refusal								mix						
12-14			Refusal											Refusal	
14-16				Refusal	PG 15.7	Refusal							Refusal		
16-18		Refusal													Refusal
18-20												Refusal			
20-22								Refusal		Refusal					
22-24															
24-26															
26-28							Refusal								
28-30															

Figure 7-20 Soft layers, foundation depth 0-30 m. Depth of base postglacial deposits is indicated where known

The base of the soft layers is listed in Table 7-7. It should be noted that at position CPT-1023, the soft clay is overlain by approx. 8 m of dense sand, while at CPT-1039, 1.4 m sand is seen on top of the soft clay. The positions of the base soft layers according to CPT data is illustrated in Figure 7-21.

Table 7-7 Base soft layers according to CPT data

CPT No.	Base soft layer	Note
CPT-1006	5.9	
CPT-1007	1.8	
CPT-1010	6.7	
CPT-1014	2	
CPT-1023	(10.6)	8 meters of dense sand on top of soft clay
CPT-1028	2.1	
CPT-1037	1.4	Borehole log says sand
CPT-1039	5.9	with 1.4 m sand layer on top
CPT-1106	1	with 1 m sand on top
CPT-1125	1.5	
CPT-1126	1	
CPT-1128	2.3	
CPT-1152	2.9	Stronger clay below, down to 4.7m
CPT-1155	1	
CPT-1160	0.8	

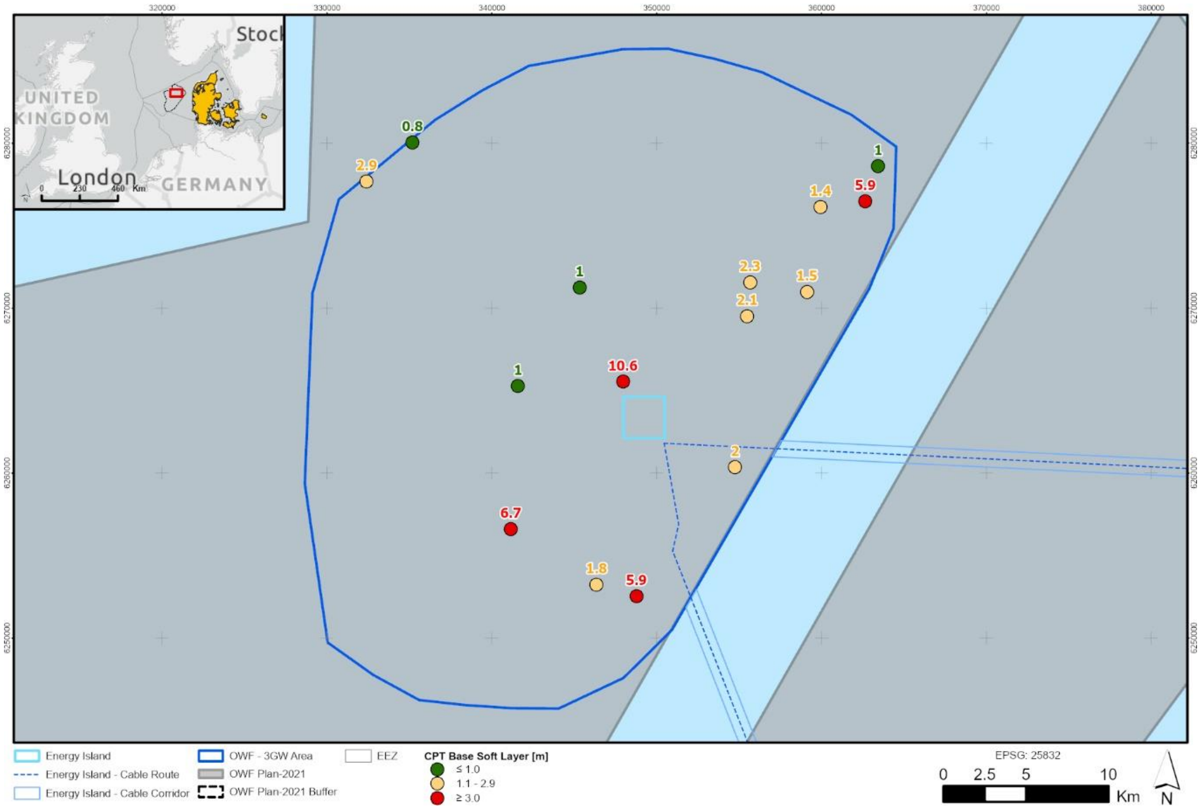

Figure 7-21 Base soft layer in the 3 GW area, according to CPT data

It should be noted that the two positions to the North corresponds to the two boreholes where base postglacial deposits were deepest, cf. Figure 7-15.

Organic matter:

The presence of organic matter is evaluated based on the borehole logs, as no laboratory test data is available on this. The amount of organic matter is described using the color coding shown in Figure 7-22, describing it as either peat or being rare, occasional or frequent. The description is done for the upper 6m, as the organic matter is not relevant for the foundation concept. However, it is very relevant for the ECR and inter-array cables, as it affects the thermal properties. An overview of the boreholes with occurrence of organic matter and peat is seen in Figure 7-23 and Figure 7-24.

Organic content:

Rare
Occasional
Frequent
Peat

Figure 7-22 Color coding for the presence of organic matter

Pos.	CPT-1001	CPT-1002	CPT-1003	CPT-1005	CPT-1006	CPT-1010	CPT-1011	CPT-1012	CPT-1014	CPT-1016c	CPT-1018	CPT-1021	CPT-1022
Depth													
0-0.5					0-1.1					0-0.1			
0.5-1.0													
1.0-1.5		0-3.3									0.5-2.5		
1.5-2.0							1.7-2			0.8-3.3 Black staining			
2.0-2.5									2-2.4				
2.5-3.0													
3.0-3.5													
3.5-4.0													
4.0-4.5		From 3.3							From 3.5				
4.5-5.0					4.2-5.7								
5.0-5.5				5-6.1									From 4.8 Black staining
5.5-6.0													

Figure 7-23 Occurrence of organic matter, upper 6m, boreholes BH-1001- BH-1022

Pos.	CPT-1023	CPT-1030	CPT-1032	CPT-1033	CPT-1037	CPT-1039	CPT-1043	CPT-1044	CPT-1046	CPT-1049	CPT-1050	CPT-1053
Depth												
0-0.5		0.2-0.4		From 0.0		From 0.0	From 0.0	0-0.8				
0.5-1.0												
1.0-1.5												
1.5-2.0					From 1.8			0.8-1.8				
2.0-2.5												
2.5-3.0					2-2.8			1.8-3				
3.0-3.5												
3.5-4.0							From 3.5					
4.0-4.5											4-4.3	
4.5-5.0	At 4.6							3-5.8	4.8-5			
5.0-5.5		From 4.8										5-6.1
5.5-6.0								From 5.8				

Figure 7-24 Occurrence of organic matter, upper 6m, boreholes BH-1023- BH-1053

The location, frequency and thickness of the organic layers and peat is given in Table 7-8. The color coding given reflects a combination of the frequency (rare, occasional or frequent) and the thickness of the layer. The location of positions with observed organic content is illustrated in Figure 7-25.

Table 7-8 Location and thickness of organic layer/peat. Layers of 0.1m and less are not included

Position	Location of layer w. organic content/Peat	Frequency	Thickness
BH-1002	0 – 3.3		3.3
BH-1002	3.3 - 6		2.7
BH-1005	5 – 6.1		1.1
BH-1006	0 – 1.1		1.1
BH-1006	4.2 – 5.7		1.5
BH-1011	1.7 – 2.0		0.3
BH-1014	2.0-2.4		0.4
BH-1004	3.5 – 6.0		2.5
BH-1016	0.8 - 3.3		2.5
BH-1018	0.5 – 2.5		2.5
BH-1022	4.8 – 6.0		1.2
BH-1030	0.2 – 0.4		0.2
BH-1030	4.8 – 6.0		1.2

BH-1033	0.0 – 6.0		6.0
BH-1037	1.8 - 2.0		0.2
BH-1037	2.0 – 2.8		0.8
BH-1037	2.8 – 6.0		3.1
BH-1039	0.0 – 6.0		6.0
BH-1043	0.0 – 3.5		3.5
BH-1043	3.5 – 6.0		2.5
BH-1044	0.0 – 0.8		0.8
BH-1044	0.8 – 1.8		1.0
BH-1044	1.8 – 3.0		1.2
BH-1044	3.0 – 5.8		2.8
BH-1044	5.8 – 6.0		0.2
BH-1046	4.8 – 5.0		0.2
BH-1050	4.0 – 4.3		0.3
BH-1053	5.0 – 6.1		1.1

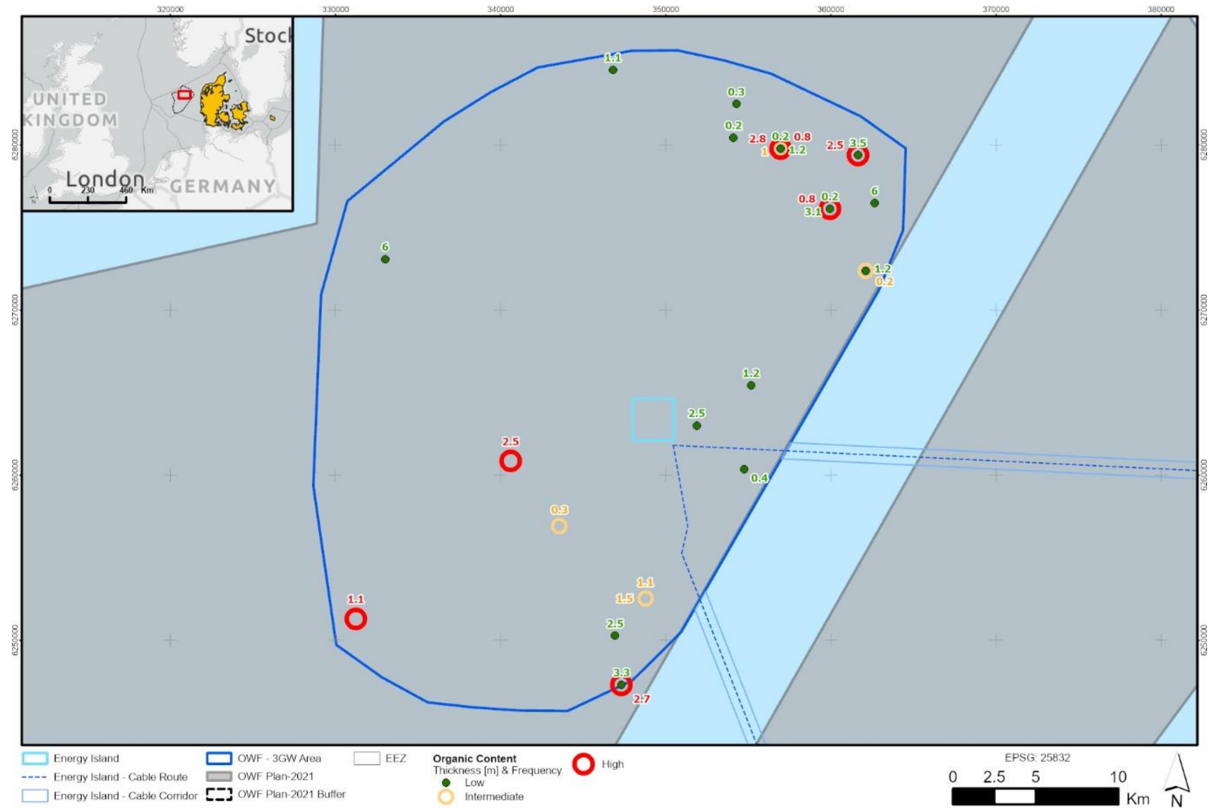

Figure 7-25 Organic content in 3 GW area, thickness of layer/frequency of organic content observed

7.2.3 10 GW area and ECR alignments

For the 10 GW area and the export cable routes (ECR), the main source of geotechnical information is provided by GEUS.

The data from the Marta database is illustrated in Figure 7-26, showing the location of vibrocore samples and Jupiter data points. The data from the Jupiter database is seen in Figure 7-27 and is divided into geotechnical and raw material data and contains a brief geological description of the soils found at each sample position. The data varies in quality, from drillers log to quality assured borehole logs.

Another source of geotechnical information has been the map of sediments at the seabed provided by The Danish Environmental Protection Agency, cf. Figure 7-28. The light and dark green sediments may have a significant organic content. At the Energy Island area, the seabed seems to consist of sand, while sand, gravel/coarse sand and till is expected in the 10 GW area.

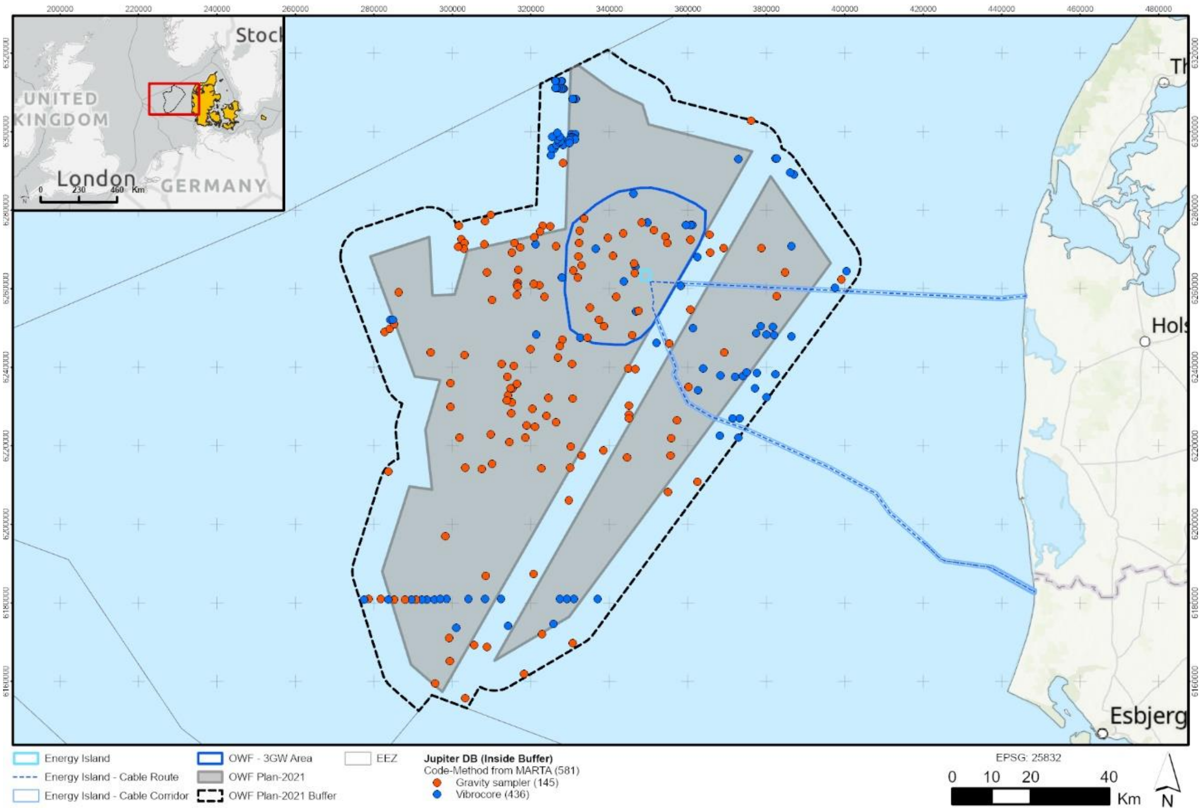

Figure 7-26 Marta database illustrating vibrocores (blue) and grab samples (orange) in the area of interest

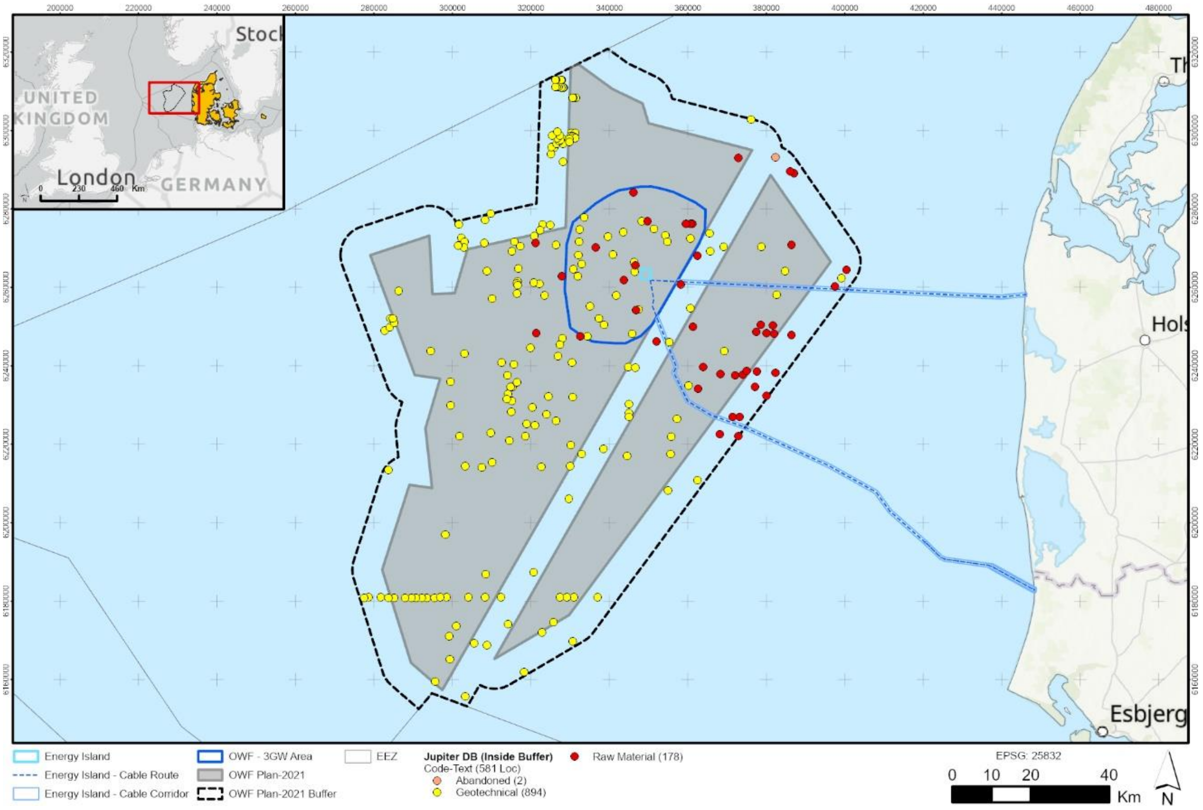

Figure 7-27 Jupiter database illustrating "geotechnical" (yellow) and "raw materials" (red) boreholes

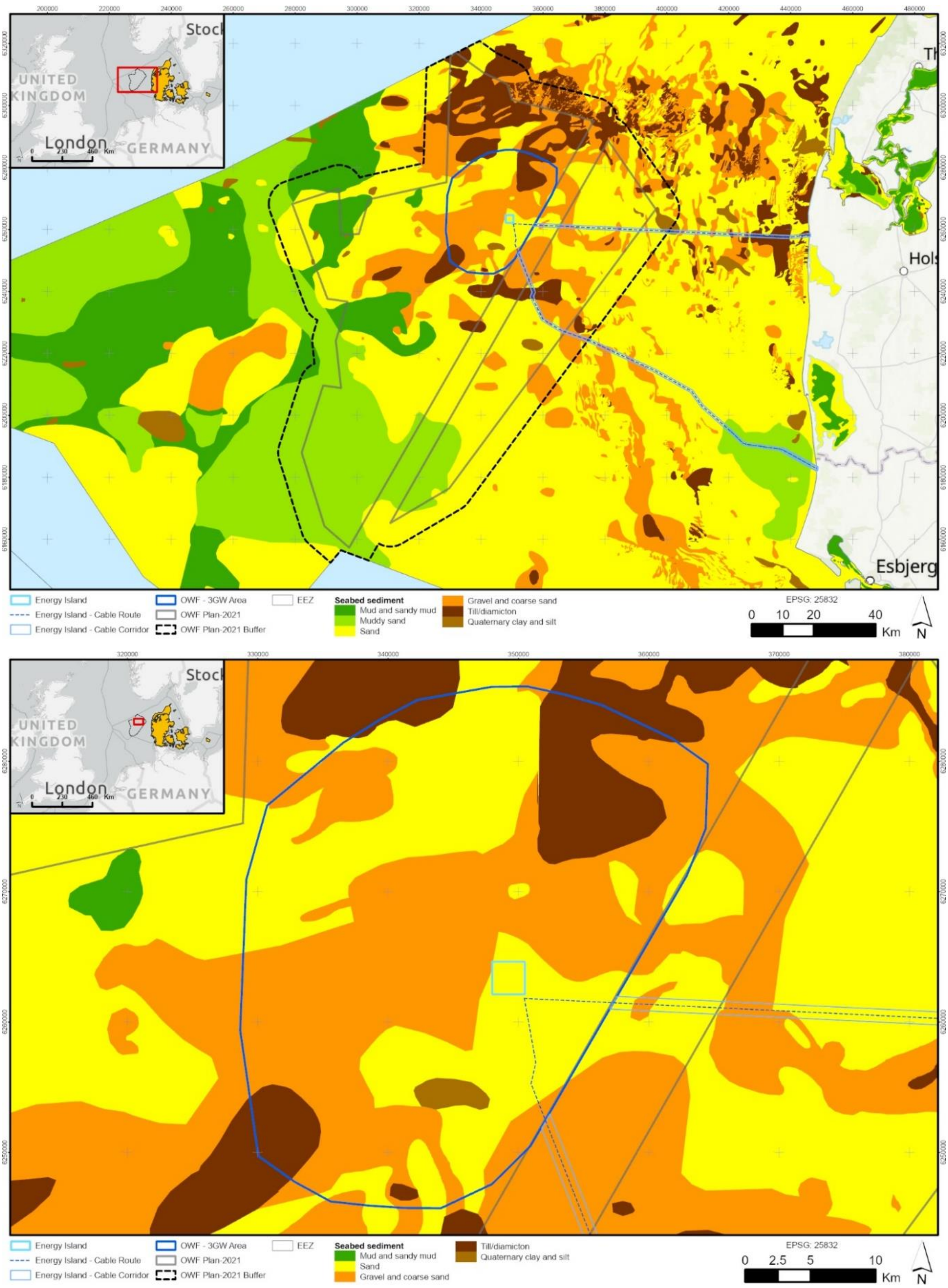

Figure 7-28 Sediment types at and close to the seabed. The top image is related to the 10 GW Area, and below for the 3 GW Area. From ref. [5].

On the basis of the geological descriptions given in the Jupiter database, the following potential geotechnical features are identified:

- Layers described as gyttja and peat
- Layers described as gravel

The occurrence of gyttja and peat in the 10 GW area is illustrated in Figure 7-29. Two positions are found inside the 10 GW area, while several positions are seen just outside the area. These positions seem to correlate well with the deep, regional paleochannels. For the export cable routes, the Northern ECR seems to be crossing a single channel, while the Southern ECR passes a system of channels.

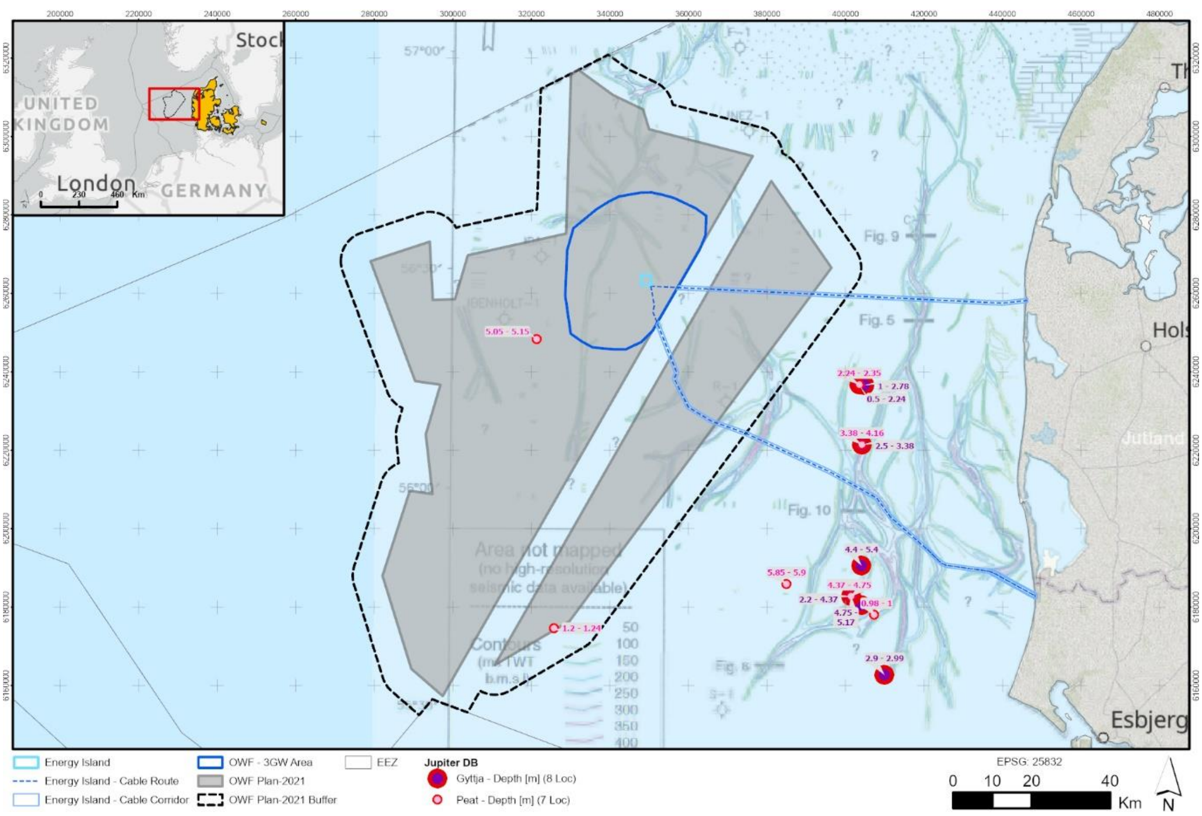

Figure 7-29 Layers with gyttja and peat, from the Jupiter database. Regional buried paleochannels/-valleys mapped using multi-channel seismic data by [7].

The occurrence of gravel is seen in Figure 7-30. For the 3 GW area, the gravel layers do not coincide with the hard sand layers indicated by the CPT refusal depths. It is also noted that the Southern ECR passes just North of an area with gravel.

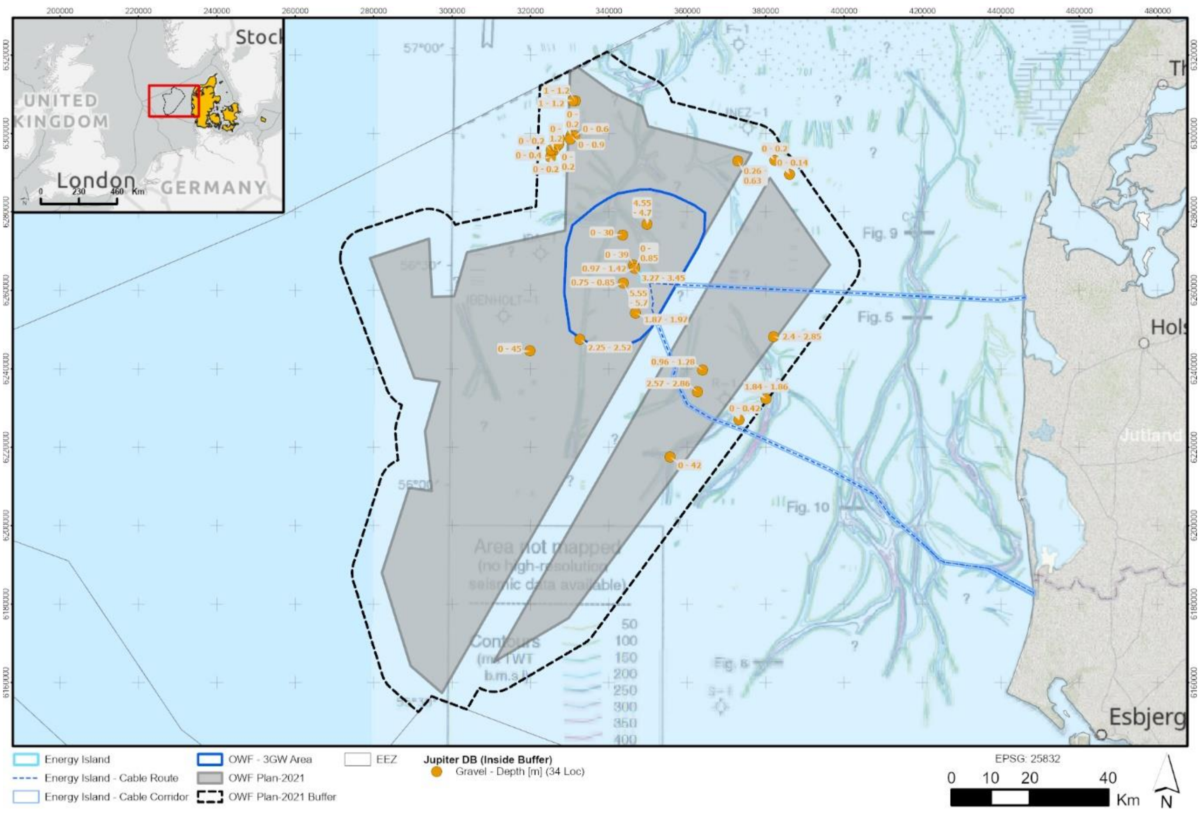

Figure 7-30 Layers of gravel, from the Jupiter database. The paleochannels shown in these figures have thicknesses of up to more the 100 m. Regional buried paleochannels/-valleys mapped using multi-channel seismic data by [7].

7.3 Integrated interpretation of the above methods

By integrating the results from the geophysical and the geotechnical data, a better understanding of the shallow subsurface throughout the study area can be established. In the correlation process, the advantages of the larger spatial coverage of the geophysical data and the very detailed information at the geotechnical locations (boreholes, vibrocores and CPTs) are used. The correlation is done by comparing the different types of geotechnical soil layers with the interpretations carried out on the seismic data. This evaluation showed that for some geotechnical soil boundaries (e.g. the base of the postglacial sediments) the geophysical interpretations could often be correlated with the geotechnical boundaries.

Base of postglacial sediments:

The lower boundary of the postglacial sediments was found to correlate well with the shallowest identified horizon in the geophysical data. The shallowest horizon in the geophysical data is in most of the seismic profiles H10. Figure 7-31 shows a representative seismic profile with the boundary between the postglacial sediments (U10) that has high amplitude seismic reflections and the pre-Holocene sediments below. This boundary is correlated with H10.

At some geotechnical locations, e.g., within the 'Energy Island' the base of the postglacial sediments identified in the geotechnical data was much deeper than the penetration of the seismic signal (i.e., the H10 reflector could not be mapped). This was due to the seismic signal being attenuated rapidly due to hard sandy soils, as described in section 7.2.1. In these areas, the interpretation of H10 was extrapolated to match the geotechnical postglacial boundary until the base of the postglacial sediments was again penetrated in the seismic data.

The secondary multi-channel seismic data do not have the same limitations in regards of penetration of hard soils as the SBP data, but is limited on the resolution of the data, especially in the upper 10-20 m below seabed. Therefore, it was hard to identify the base of the postglacial sediments (H10) in the multi-channel data.

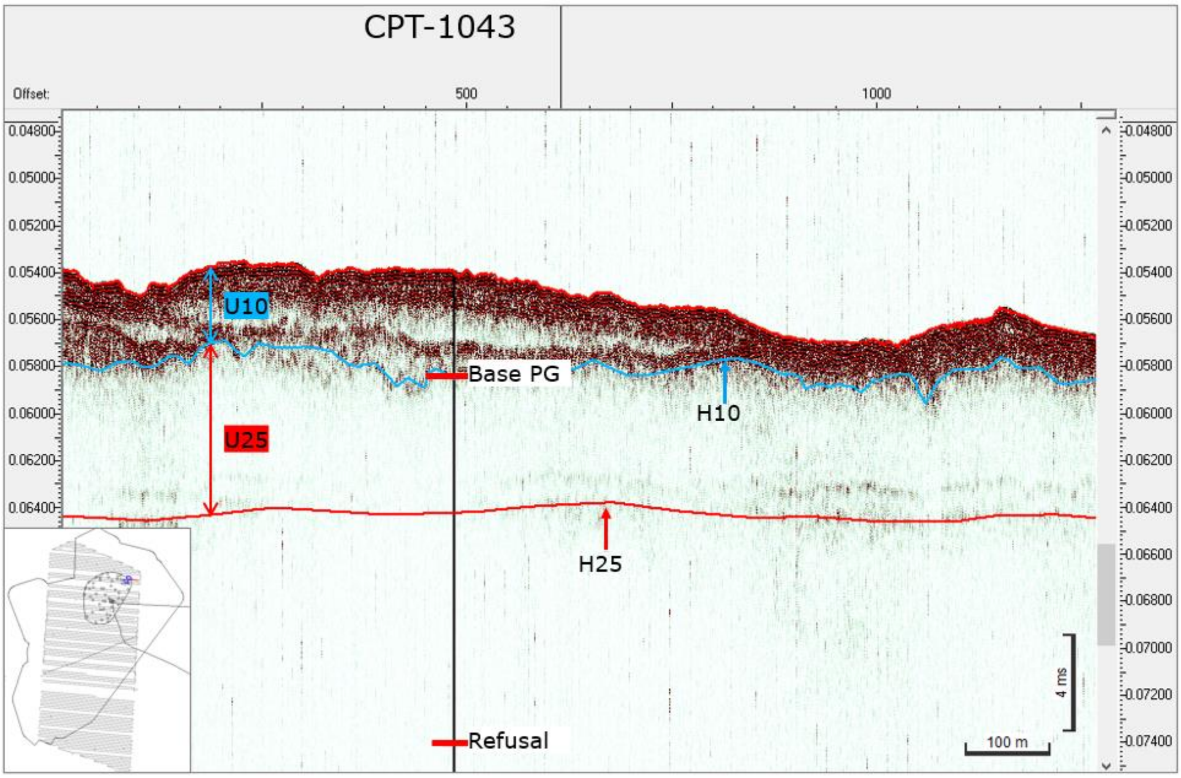

Figure 7-31 SBP profile showing the correlation between the H10 reflector and the base postglacial (PG) sediments. The refusal depth is below the seismic penetration.

Figure 7-32 shows in map view the correlation between H10 and the depth to the base of the postglacial sediments derived from the geotechnical boreholes. As seen, there is often a good correlation. However, there are exceptions. Where H10 has not been mapped, the lower boundary of the postglacial sediments can sometimes be correlated with either H20 or H25. Elsewhere, it is not possible to correlate the base of the postglacial sediment with a specific horizon. This may be due to:

a) the postglacial sediments are absent
b) the postglacial sediments at places do not result in a seismic impedance contrast to the sediments below
c) the interpretation of the base postglacial boundary in the borehole is not correct (as this interpretation can be difficult to carry out only based on borehole descriptions (see section 6.2 and 7.2.2))

Figure 7-33 shows an example of one of the outliers seen in Figure 7-32. In the western part of this profile, H10 correlates well with the base of the postglacial sediments as identified in BH/CPT-1022. 2700 m to the east, in BH/CPT-1021, the base of the postglacial sediments is deeper than the seismic penetration and deeper than both the mapped H10 and H25. It is not possible to follow a seismic reflector crossing the base of the postglacial sediments in both boreholes, and the geotechnical-geophysical correlation remains poor at this location. The best explanation of this discrepancy could be that the preliminary interpretation of the base of the postglacial sediments is incorrect at BH/CPT-1021.

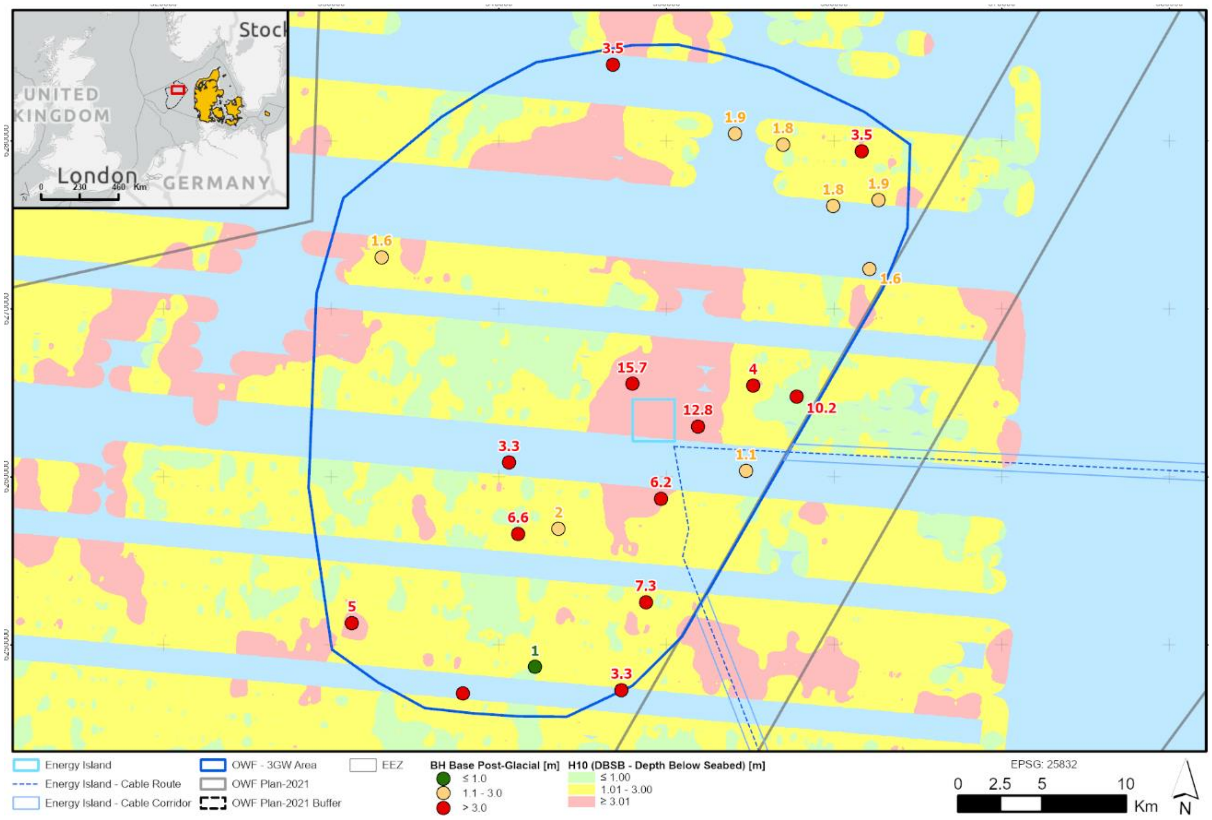

Figure 7-32 Map view of unit U10 (H10 - depth below seabed) in the 3 GW area overlain by the base postglacial sediments derived from the boreholes.

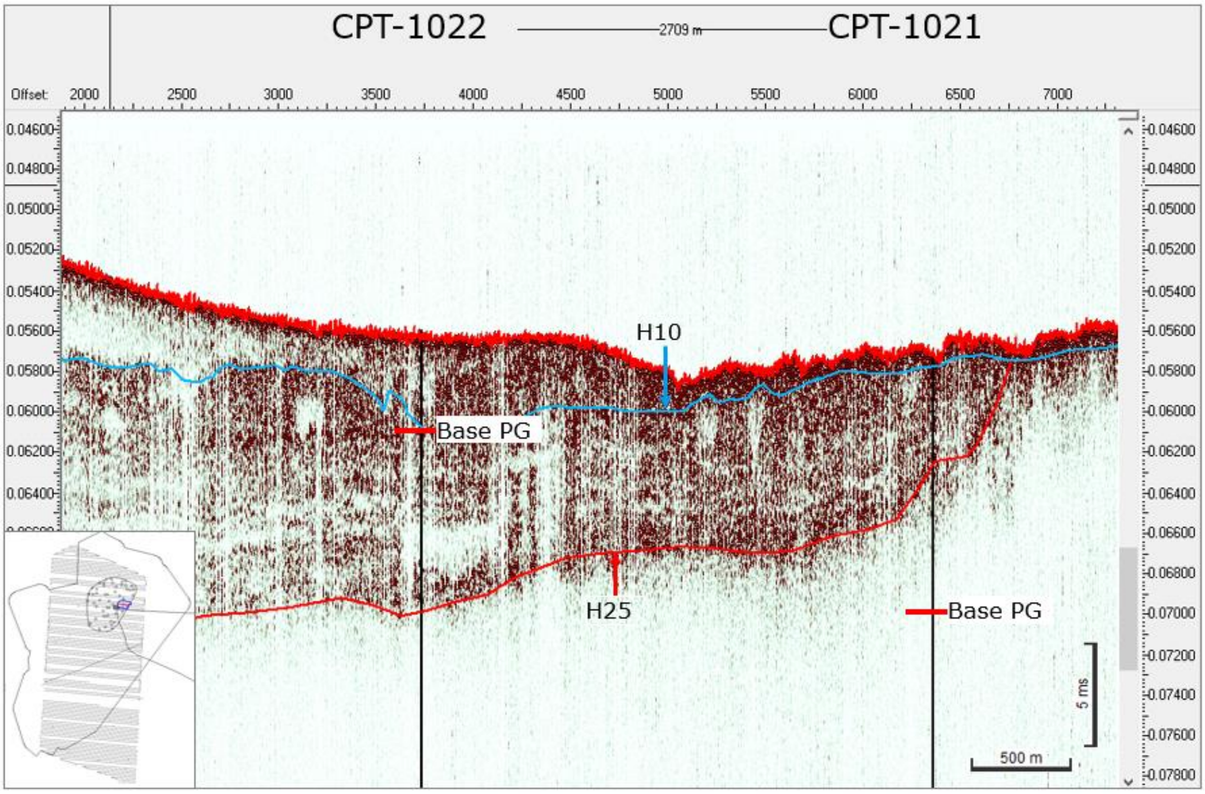

Figure 7-33 SBP profile showed with base postglacial sediments at CPT-1022 and CPT-1021.

Soft soils:

Soft soils are only sporadically identified throughout the 3 GW area, indicating that soft sediments are internal layers rather than correlating to a specific, well-defined unit interpreted in the geophysical data (see examples in Figure 7-34). Thus, for the very rarely identified soft sediments no good geotechnical-geophysical correlation exists.

Only at three geotechnical locations, soft soil layers thicker than 3m have been encountered (CPT-1006, CPT-1010 and CPT-1039, see Table 7-7). At all three geotechnical positions, Unit U25 has been mapped. However, there is no good correlation between the base of the soft soil layers and H25 and, at other locations where unit U25 has been mapped, soft soil layers have not been identified. Unit U25 is interesting as internal seismic layering of high- and low amplitude reflections are present which may reflect that U25 is a heterogeneous sedimentary unit.

Figure 7-35 shows a representative profile of how the geotechnical-geophysical correlation of soft soil layers is tricky. At CPT-1010 there is a good correlation between the soft layer and H25. However, appx. 2500 m to the east, Unit U25 is not a soft layer in the geotechnical data (does not have undrained shear strength cu< 20 kPa).

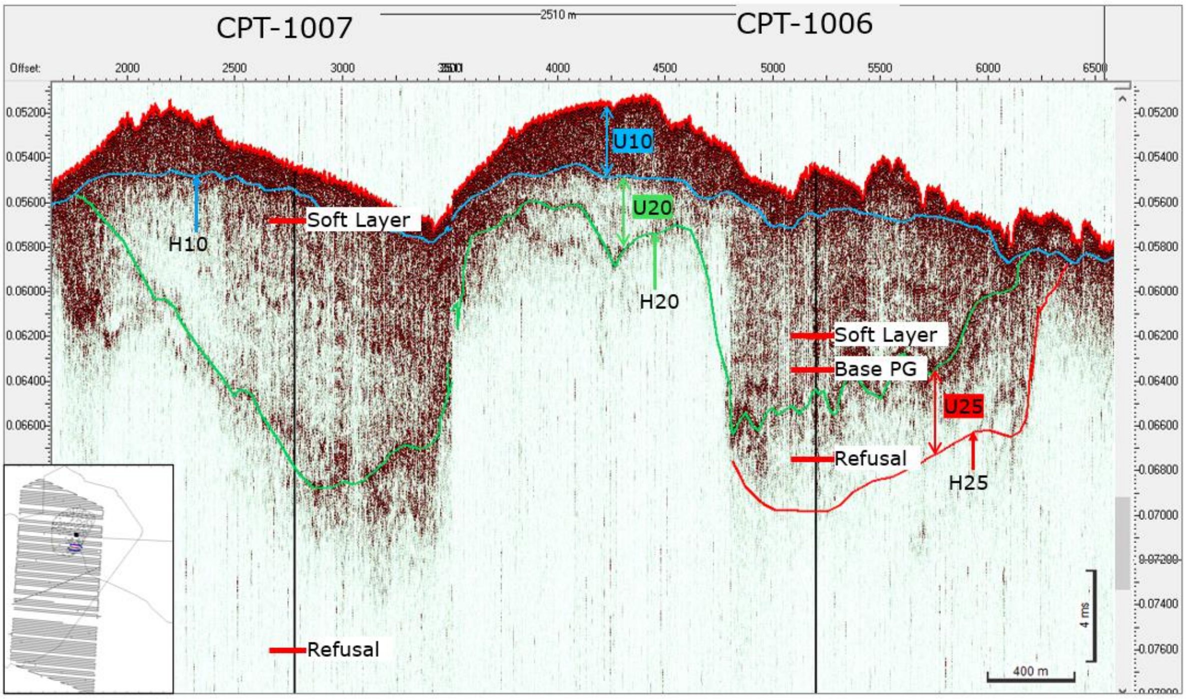

Figure 7-34 SBP profile showing the correlation between horizon H10 and the base of a soft layer. CPT-1006 shows the correlation between a paleochannel and a soft layer. Refusal in CPT-1007 is deeper than seismic penetration.

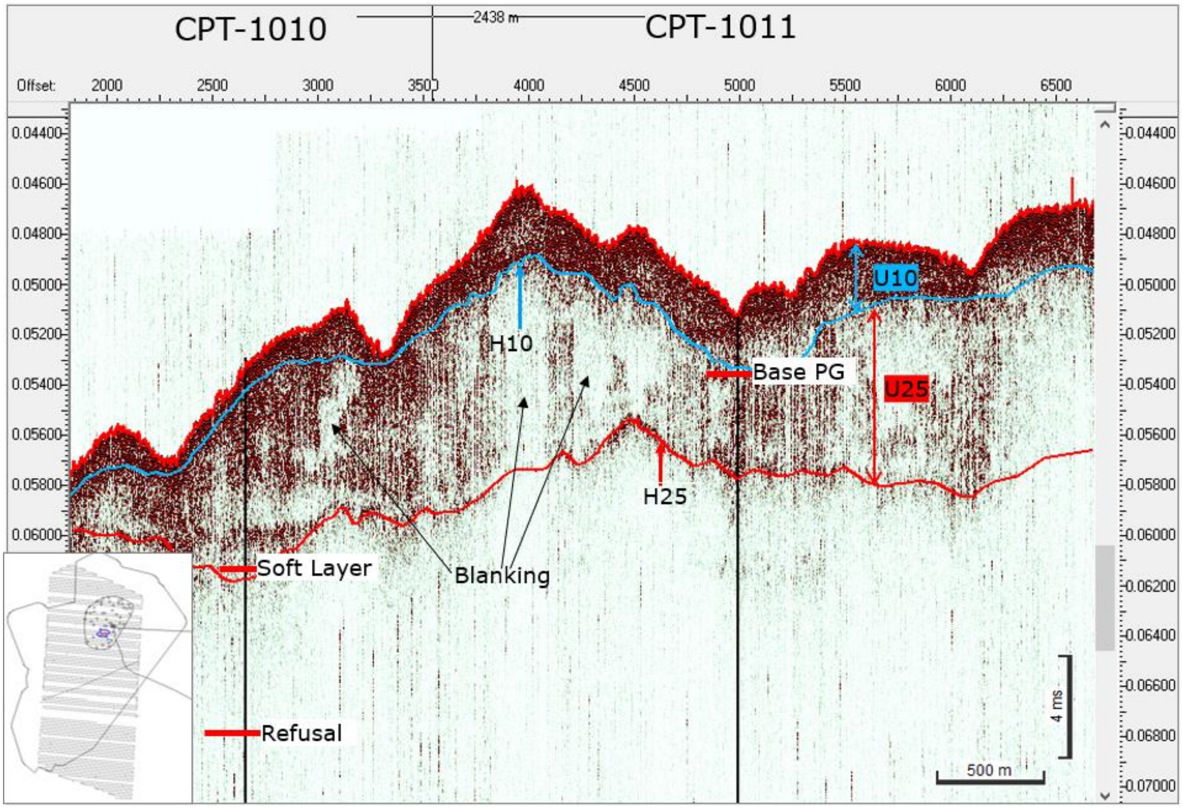

Figure 7-35 SBP profile showing the correlation between H10/base postglacial sediments and H25/base soft layer. Note the areas of seismic blanking in unit U25. Refusal is deeper than seismic penetration.

Hard soils:

As mentioned earlier, the postglacial sediments have mostly been correlated with unit U10 within the 3 GW area. These sediments often correspond to hard, sandy soils (see Table 7-4). As H10 has been interpreted across the entire 10 GW area, unit U10 can be used to estimate the location and thickness of hard, sandy postglacial soils.

The seismic signature of unit U10 is generally characterized by two different reflector patterns throughout the 10 GW area (as described in section 7.1):

1) high-amplitude seismic reflections or,
2) low-amplitude seismic reflections

(1) High-amplitude seismic reflections are seen in the eastern part of the 10 GW area (roughly). The internal seismic character of unit U10 is characterized by medium-high amplitude seismic reflections that attenuates the seismic signal rapidly and limits the penetration depth. In this part of the study area, unit U10 is, based on the seismic character (high amplitude reflections and rapid signal attenuation) and the geotechnical correlation within the 3 GW area, expected to often represent hard, sandy postglacial sediments.

(2) Low amplitude seismic reflections are seen in the western part of the 10 GW area (roughly). Unit U10 is characterized by low amplitude seismic reflections which allows for deeper penetration of the SBP. Either, the seismic character of the postglacial sediments in this area is characterized by very low, almost transparent reflections, or, at times, finely stratified reflectors are observed. These areas are interpreted to represent fine-grained (mud to fine-grained sand) sediments.

The extent of the "low amplitude area" of unit U10 is delineated on Figure 7-36 and Figure 7-37.

It is seen that the postglacial sediments characterized by low amplitude seismic reflections (purple) aligns somewhat with areas of muddy (fine-grained) seabed sediments on GEUS' background map (Figure 7-37).

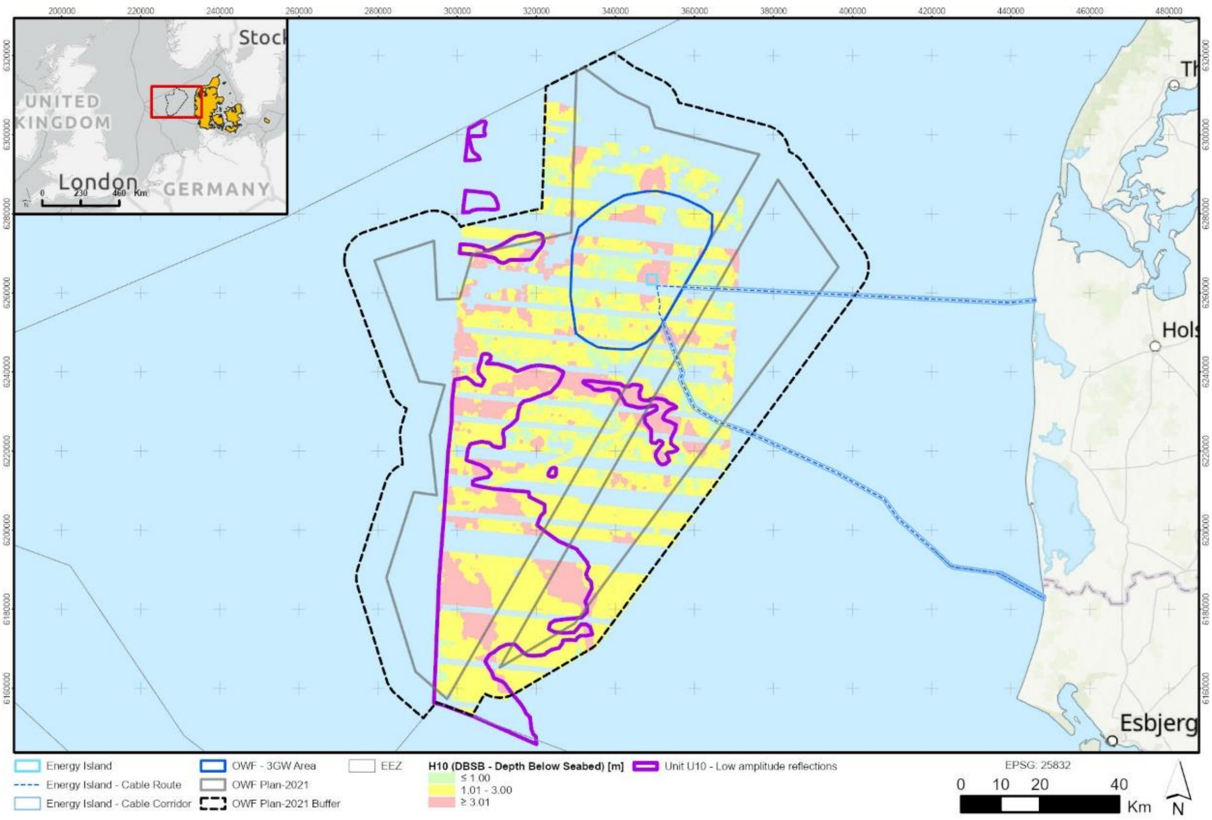

Figure 7-36 Unit U10 (postglacial sediments) depth below seabed. Purple areas outline where U10 is characterized by low amplitude reflections in the seismic data and likely represent fine-grained sediments.

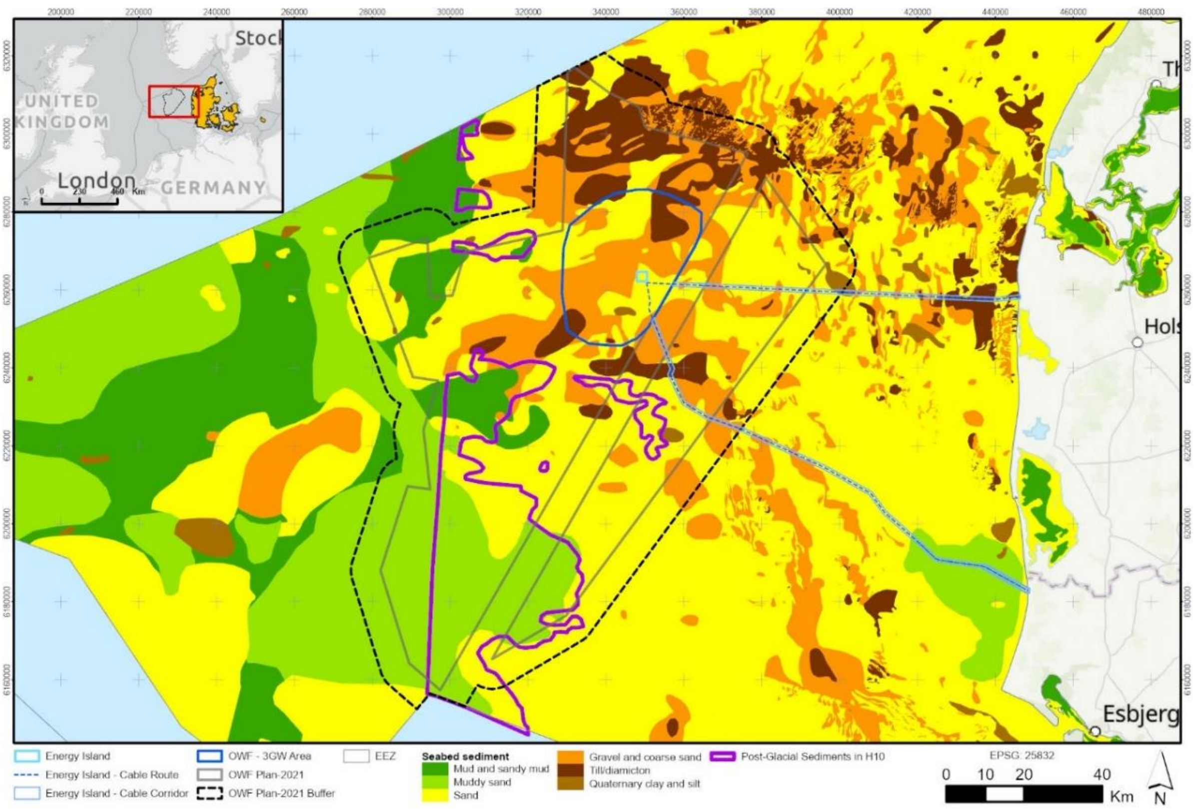

Figure 7-37 Background sediment map (GEUS) overlain by purple polygon showing where unit U10 (postglacial sediments) is interpreted to be fine-grained.

Figure 7-38, Figure 7-39 and Figure 7-40 show examples from the western part of the 10 GW area (outlined by purple polygon in Figure 7-36 and Figure 7-37), where the interpreted postglacial sediments (unit U10) are characterized by low amplitude seismic reflections.

Figure 7-38 shows the point where unit U10 (interpreted postglacial sediments) changes seismic character from high (east) to low (west) amplitude reflection pattern. At the transition, H10 goes from being quite shallow below the seabed (1-3 m) to deepen towards the west. This aligns with unit U10 (postglacial sediments) often being a thicker sequence where it is characterized by low seismic amplitude reflections compared to where unit U10 (postglacial sediments) are characterized by high seismic amplitude reflections.

Figure 7-39 and Figure 7-40 show representative profiles of unit U10 in the western part of the 10 GW area where it is characterized by the low amplitude seismic reflections. The unit U20 channelized sediments (base defined by H20) are clearly penetrated.

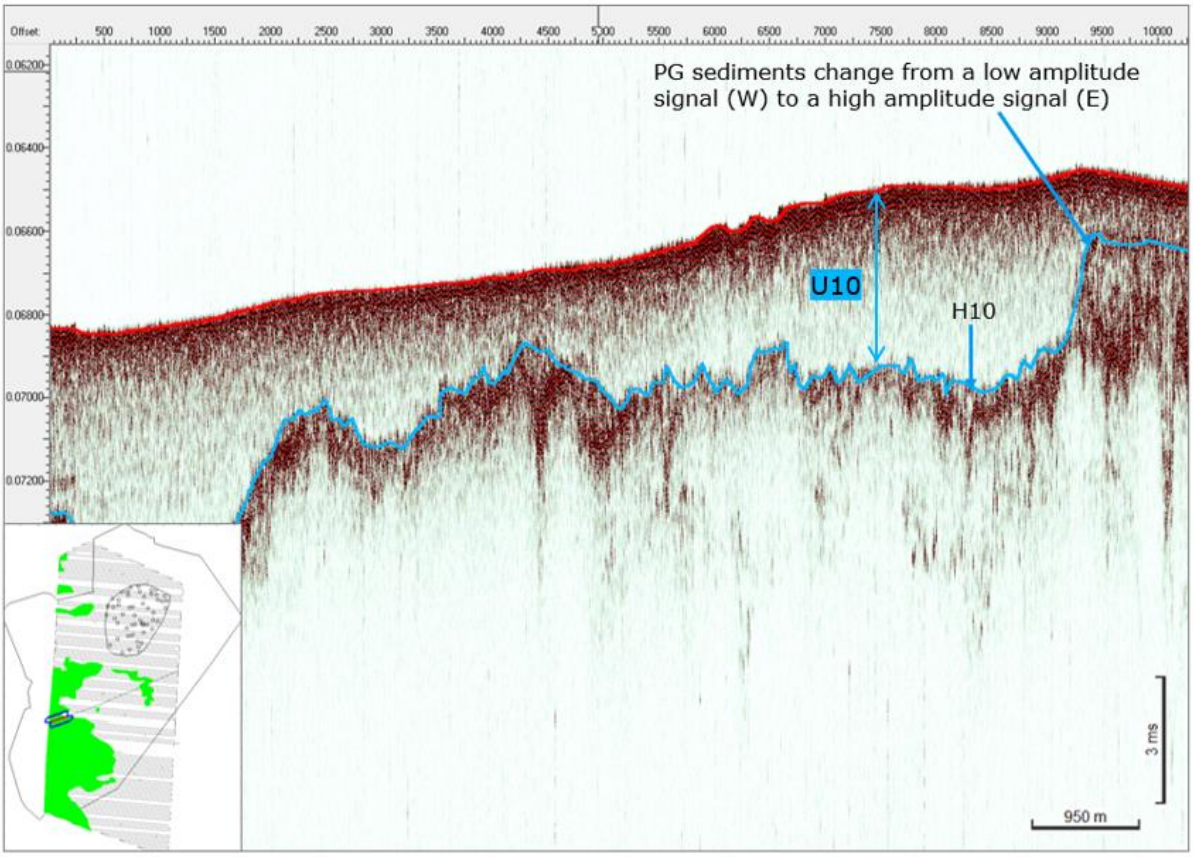

Figure 7-38 Postglacial sediments - unit U10: Low amplitude seismic reflections in western part of 10 GW area. The profile shows the area where unit U10's internal signature changes from medium-high to low amplitude seismic reflections.

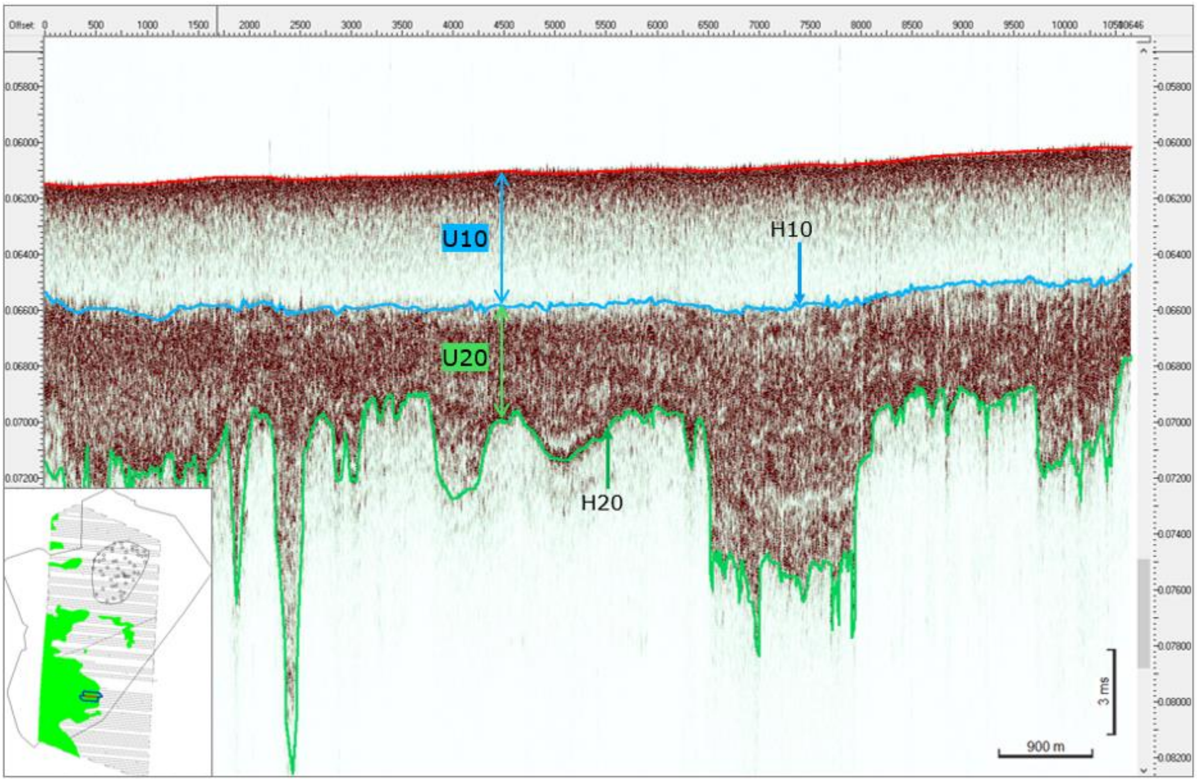

Figure 7-39 Postglacial sediments – unit U10: Low amplitude seismic reflections. Unit U10 underlain by pre-Holocene high amplitude sediments (Unit U20).

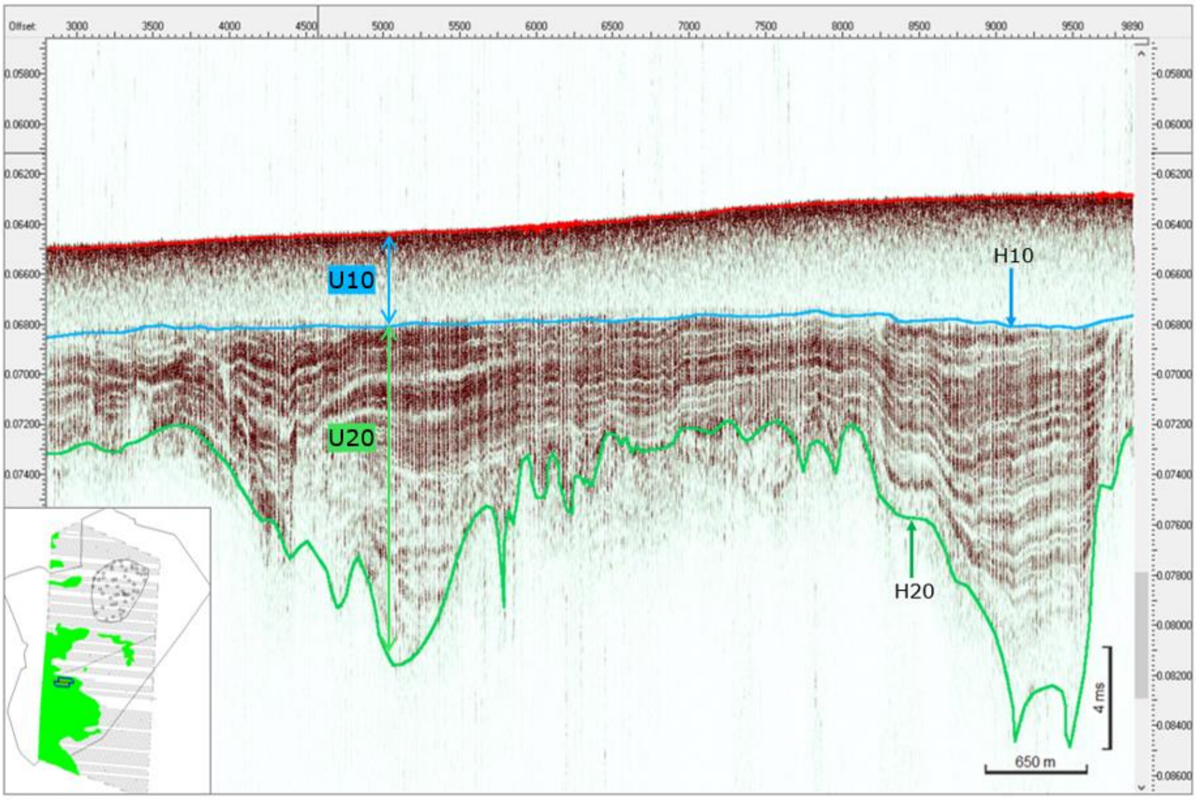

Figure 7-40 Postglacial sediments – unit U10: Low amplitude seismic reflections. Unit U10 underlain by pre-Holocene channelized sediments (Unit U20).

Figure 7-41 and Figure 7-42 are seismic profiles from the eastern part of the 10 GW area. The postglacial sediments of unit U10 are in this area characterized by high amplitude seismic reflections. This area is expected to occasionally have hard, sandy shallow soils.

Unfortunately, the refusal depths evaluated in Table 7-6 could not be correlated to a specific geophysical horizon representing a hard soil. This was both because the refusal depth was often deeper than seismic penetration of the SBP and, probably because refusal was met in different soil layers at different geotechnical locations, which made the correlation difficult.

It is recommended to carry out geotechnical and further seismic investigations in the "low amplitude seismic reflections" area to investigate the soil type and strength characteristics.

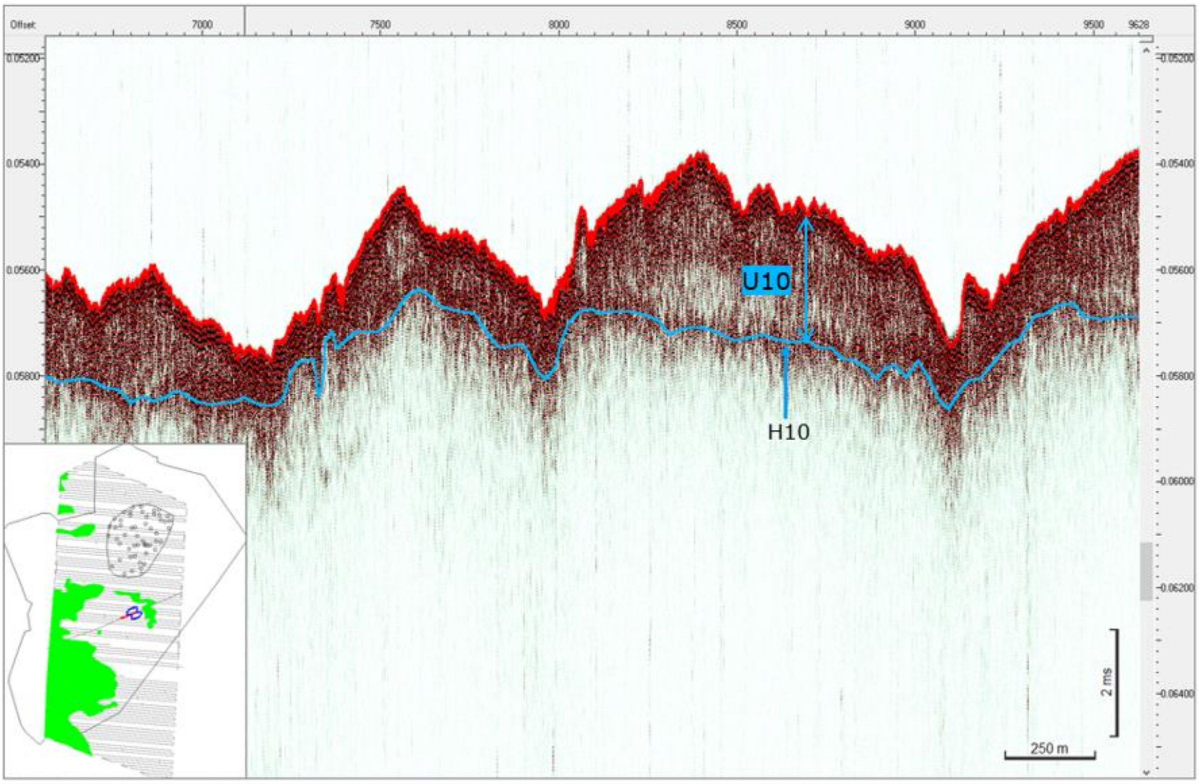

Figure 7-41 Postglacial sediments – unit U10: High amplitude seismic reflections. Seismic signal is attenuated by the hard postglacial soils.

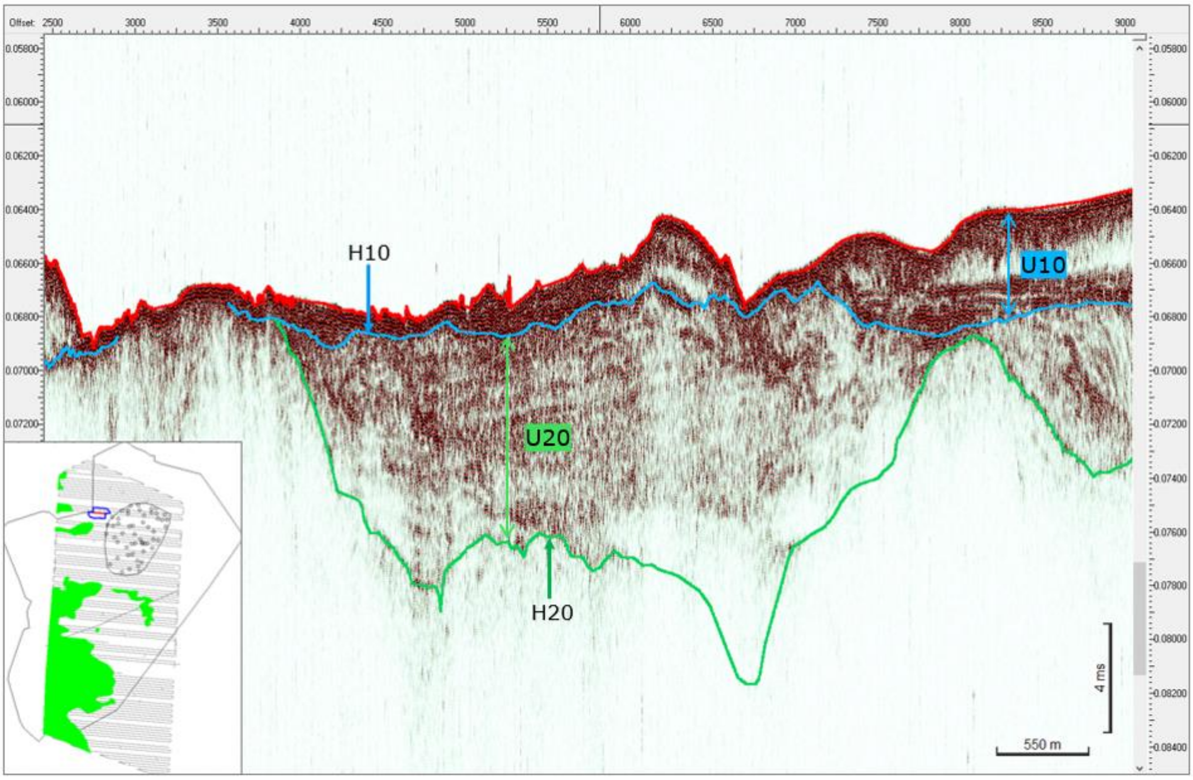

Figure 7-42 Postglacial sediments – unit U10: Medium-high amplitude seismic reflectins. Unit U10 is underlain by pre-Holocene sediments (U20).

7.4 Updated geological model (of relevance for this study)

The 10 GW area covers a very large area and variations within the area should be expected. Even with variations in the geological condition a relatively simple model has been created for the area based on the available data and previous models and information on the area.

As described in section 4 the area has been under heavy influence from several glaciations both as direct glacial deposits such as moraines and as proglacial deposits such as meltwater sands. Previous studies have indicated moraine deposits in northern part of the 10 GW area. From older 2D seismic data indications of glacial-deformation features like thrust-faults and folding have been observed. In the most recent data from 2021 (ref [10] and [11]) further evidence of tectonized sediments are observed. This supports the previous models from the area. It is expected that the majority of the 10 GW area has mostly been affected by proglacial settings during the Weischelian glaciation, and the majority of the deposits found within the 10 GW area are sandy and gravelly non-cohesive sediments. Conceptual profiles of the model covering the area is presented in Figure 7-43 and Figure 7-44.

The established model for the area consists of glacial deposits with incised channels and a shallow sequence of postglacial marine sands.

The incised channels are filled with very heterogeneous sediments including occasionally soft sediment and sediments with organic content. This report focuses on shallow incised channels identified close to the seabed. Previous studies have identified larger and deeper channels across the Danish North Sea area including the 10 GW area. These deep channels incise into older pre-Quaternary sediments and show heterogeneity on larger scale than the smaller channels in this report.

Seabed sediments within the area are mainly affected by two factors 1) the underlying geological sediments and 2) the water depth and thus the bottom currents.

As seen in Figure 7-28 fine grained seabed sediments are generally found furthest west where deepest water depths are found. In the central and southern part of the 10 GW area sand and gravel are the dominant seabed sediments. In the northern part of the 10 GW area moraine sediments are common on the seabed and thus aligning with the model for the subsea deposits.

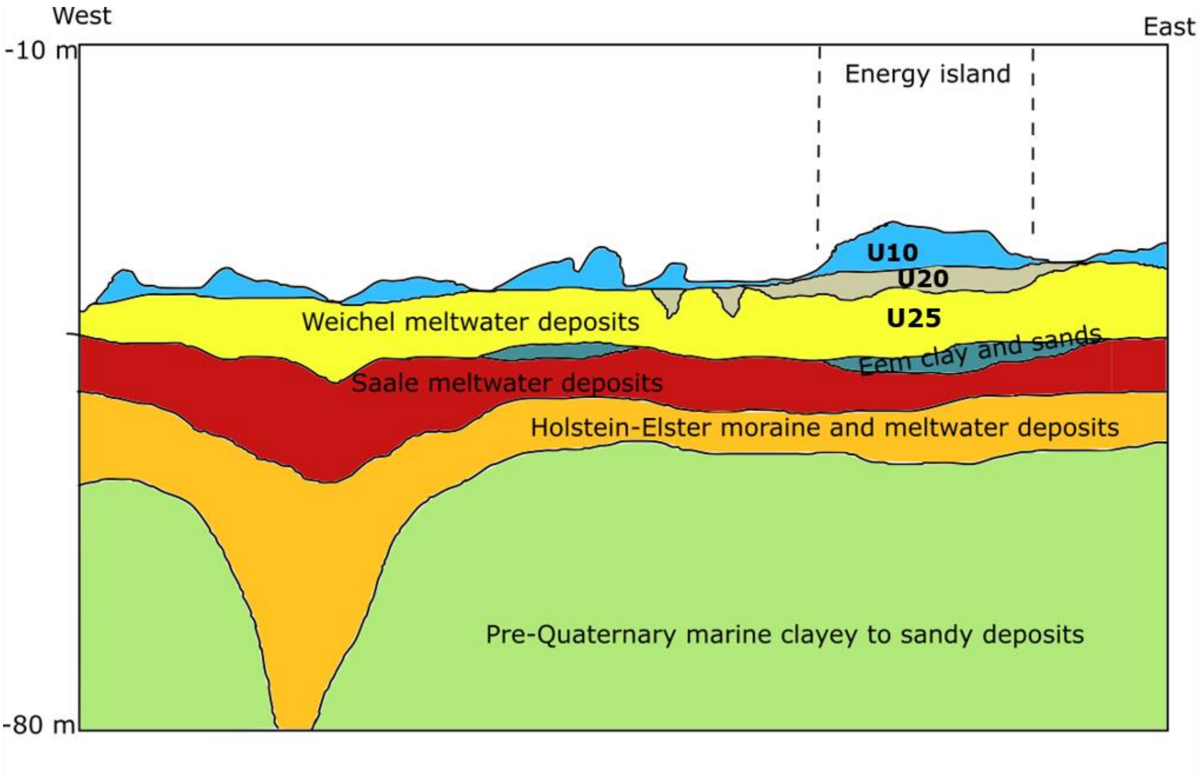

Figure 7-43. Conceptual W-E profile showing a model for the 10 GW area. Units mapped in this assessment are U10, U20 and, partly, U25. The colors on geological model correspond to the stratigraphic model shown on Figure 4-7. Inspired from [4].

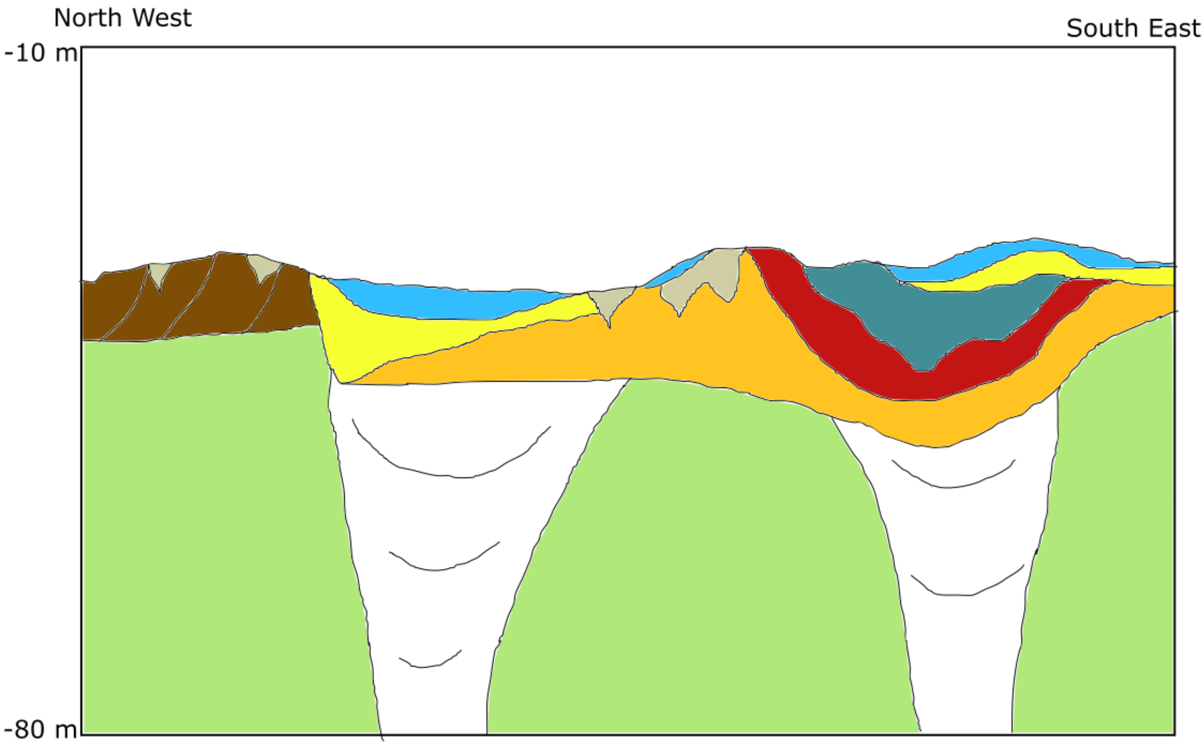

Figure 7-44. Conceptual NW-SE profile for model for the 10 GW area. The colors on conceptual geological model correspond to the stratigraphic model shown on Figure 4-7. Inspired from [4].

7.5 Integrated geotechnical installation 'risk / uncertainty maps'

The following risks have been identified and assessed based on the geotechnical data with inputs from the integrated geophysical interpretations:

Table 7-9 Overview of risk levels

	Area	**Data coverage**	**Risk level Outside channels**	**Risk Level Channels**
Risk factor				
Soft soils	Energy Island	Very high	Low, not seen	Low, not seen
	3 GW area	Good/Medium	Probably low	Probably medium to high
	10 GW area	Low	Probably low*	Probably medium to high
	Northern ECR	Low	Probably low	Probably medium to high
	Southern ECR	Low	Probably medium to high close to shore	Probably medium to high
Hard soils	Energy Island	Very high	High, upper 15 m show very dense sand	Low, not seen
	3 GW area	Good/Medium	High in northern part of area and in NW-SE band. Medium in remaining part	Probably medium
	10 GW area	Low	Probably medium to high	Probably medium
	Northern ECR	Low	Probably medium to high	Probably low
	Southern ECR	Low	Probably high in gravel area	Probably medium
Shallow gas	Eastern part, see map	Medium	High in localized areas, see map	
ECR only:**				
Organic layers/content	Energy Island	Low, no lab data	Probably low	Probably low
	3 GW area	Low, no lab data	Probably low	Probably medium to high
	10 GW area	Low	Probably low	Probably medium to high
	Northern ECR alignment	Low	Probably low	Probably low

	Southern ECR alignment	Low	Probably low, except close to shore	Probably medium to high

*Only based on geophysical data
**Upper 6 m

In the following the various risks are discussed and illustrated:

Risk of hard layers:

The base of the postglacial sediments (from boreholes) correlates in general well with the H10 horizon. From geotechnical evidence, the postglacial layers often represent very dense sand (hard soil).

Another indication of hard layers could be shallow refusal of the CPT's. However, as discussed previously, these observations do not correlate well with the geophysical model, possibly because the increase in strength is gradually and thus not a clearly detectable horizon.

The risk of hard soil in the 3 GW and 10 GW areas is illustrated in Figure 7-45 and Figure 7-46, respectively. For the 10 GW area (Figure 7-46), the seismic data indicates that the postglacial layers in the western part of the area seems to be more fine-grained (outlined by purple polygon), compared to the dense sand layers interpreted in the eastern part, cf. Figure 7-46. As there is currently no CPT data in the 10 GW area, it needs to be further investigated whether the soil in this area is hard or not.

For the upper 6m (relevant for the cables), data from the Jupiter database indicates a risk of hard soil in the form of gravel. The geotechnical data comes from vibrocores and cannot be correlated with a geophysical horizon. It is thus plotted as data points, cf. Figure 7-47.

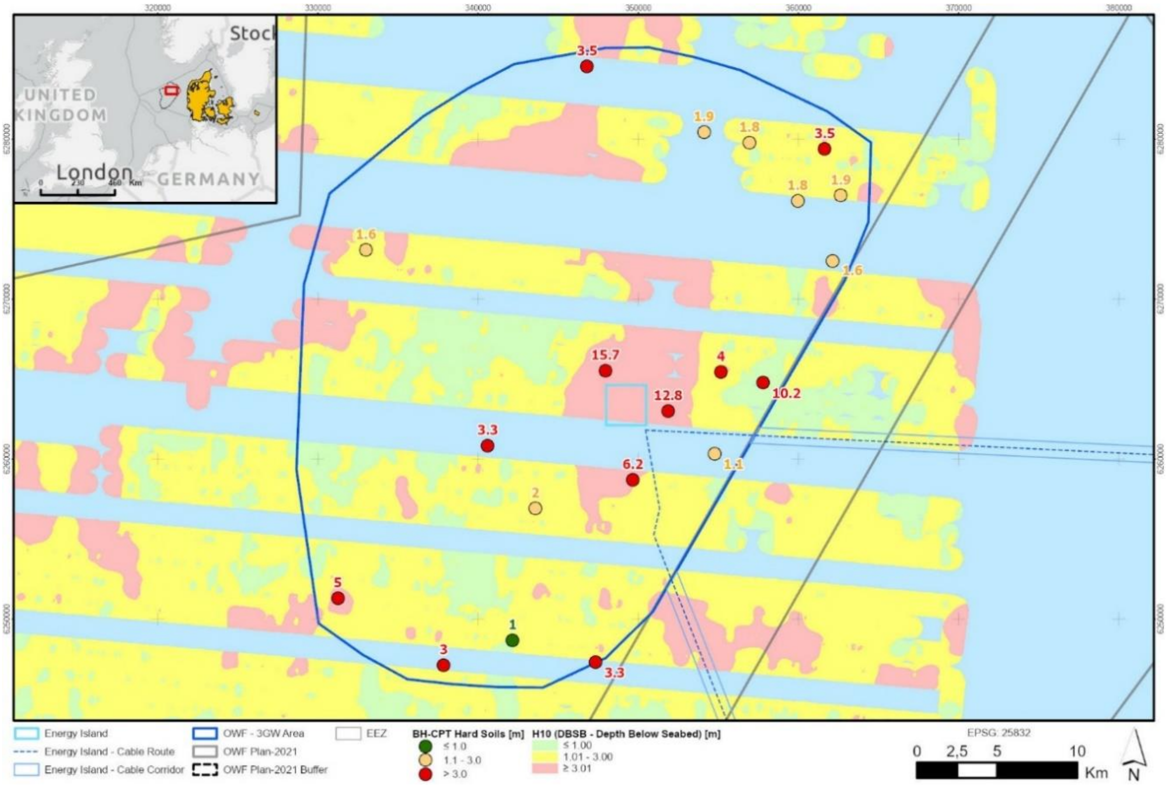

Figure 7-45 Risk of hard soil, 3 GW area - Base PG from geotechnical data, with H10 horizon (depth below seabed)

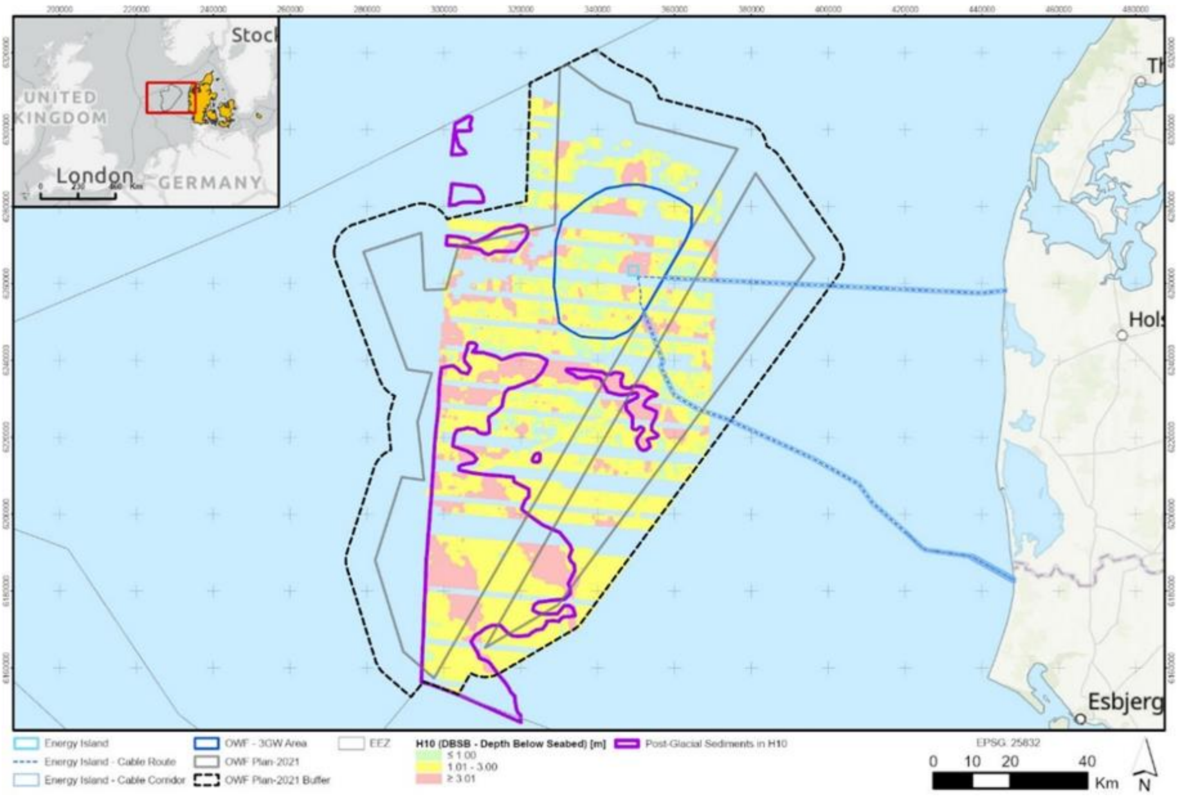

Figure 7-46 Risk of hard soil, 10 GW area - Base PG from geotechnical data, with H10 horizon (depth below seabed). Purple areas outline where the postglacial sediments are characterized by low amplitude in the seismic data and likely represent fine-grained sediments. Whether these latter-mentioned sediments represent hard soil or not, needs to be further investigated.

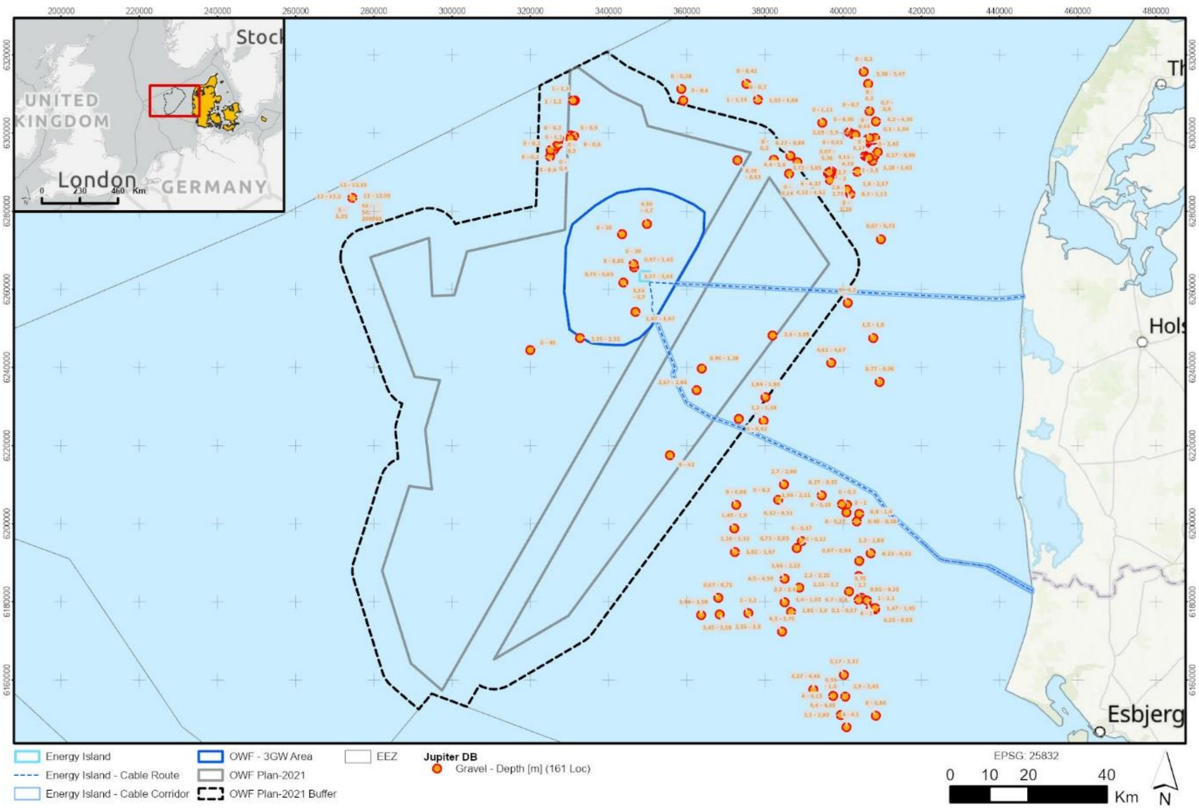

Figure 7-47 Risk of hard soil in the form of gravel in the upper 6m – vibrocore data from Jupiter

Risk of soft soils and organic layers:

Based on the geotechnical data from the 3 GW area soft soils are rare and only sporadically identified. The integrated interpretation of the geotechnical and geophysical data indicate that soft sediments are internal layers rather than correlating to specific units interpreted in the geophysical data. In general, the risk of soft soils in the study area is assessed to be primarily related to shallow paleochannels (see Figure 7-48 and Table 7-9). However, an identified paleochannel does not necessarily mean that it contains soft soil layers. The risk level is in general assessed to be "probably medium to high" inside paleochannels and "probably low" outside paleochannels.

In addition to the above general assessment of soft soils, the distribution of unit U25 is shown in the 3 GW and 10 GW area, respectively (Figure 7-49 and Figure 7-50). At the only three locations where soft soil layers are relatively thick (thicker than 3 m), these locations seem to be related to the presence of unit U25. However, Unit U25 was mapped at other geotechnical locations without the detection of soft soil layers (black dots illustrate location of CPTs without soft soil layers in Figure 7-49). So, even though no major soft soil layer has been found, the risk of local occurrences within U25 remain medium to high and it is recommended to further investigate the distribution and soil characteristics of unit U25.

For the ECR alignments, there is a risk of encountering peat and gyttja layers (based on geotechnical data from vibrocores, Jupiter database). Comparing this with the seabed soil map, cf. Figure 7-51, these data does not correlate well. On the other hand, the seabed map shows that for the southern ECR, there is a risk of encountering mud and muddy sand close to the shore.

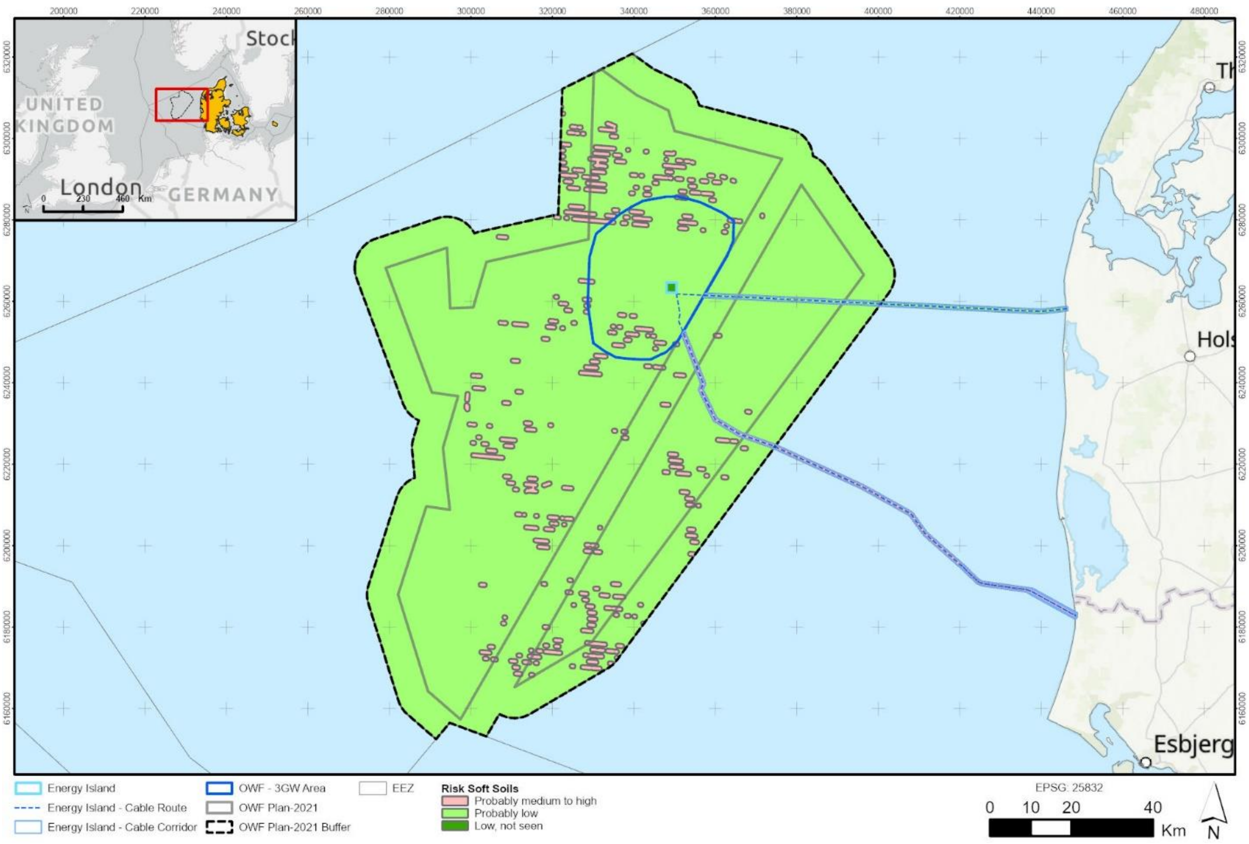

Figure 7-48 Risk of soft soils in 10 GW area in relation to mapped paleochannels. Risk is "probably medium to high" inside paleochannels and "probably low" outside paleochannels

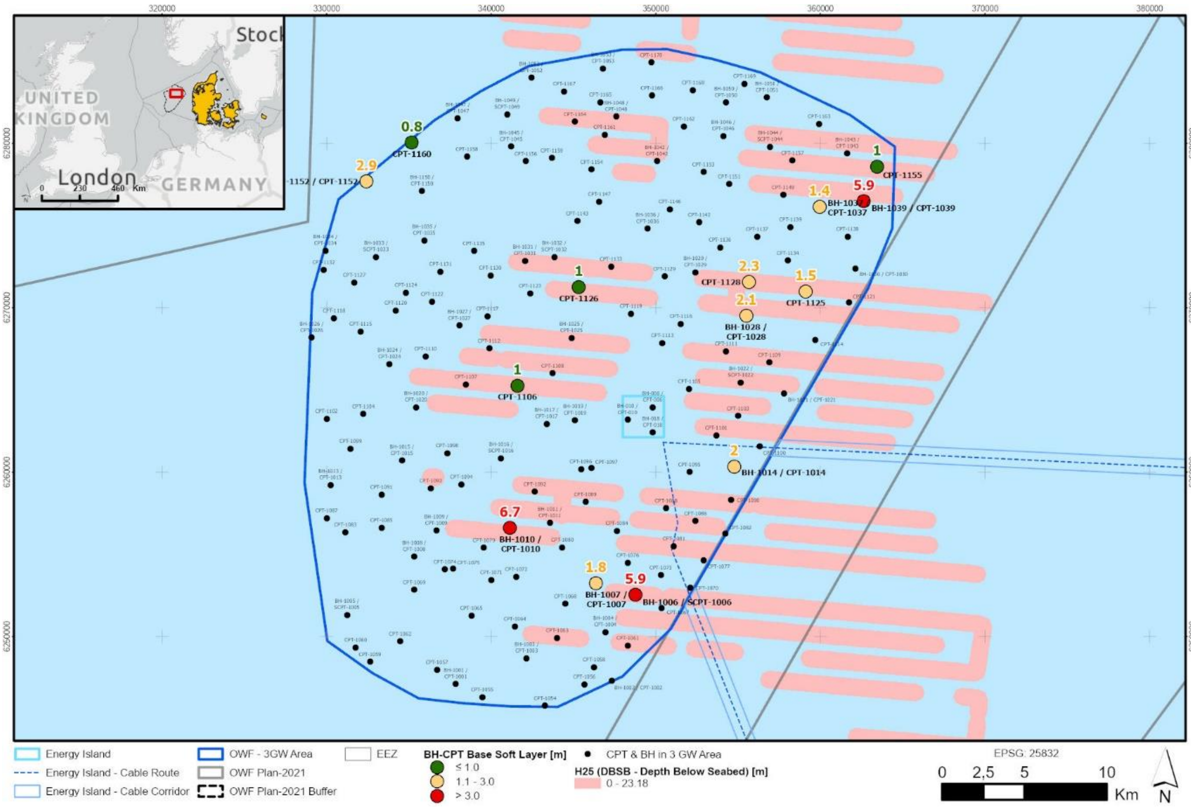

Figure 7-49 Risk of local occurrences of soft layers in the 3 GW area associated with unit U25.

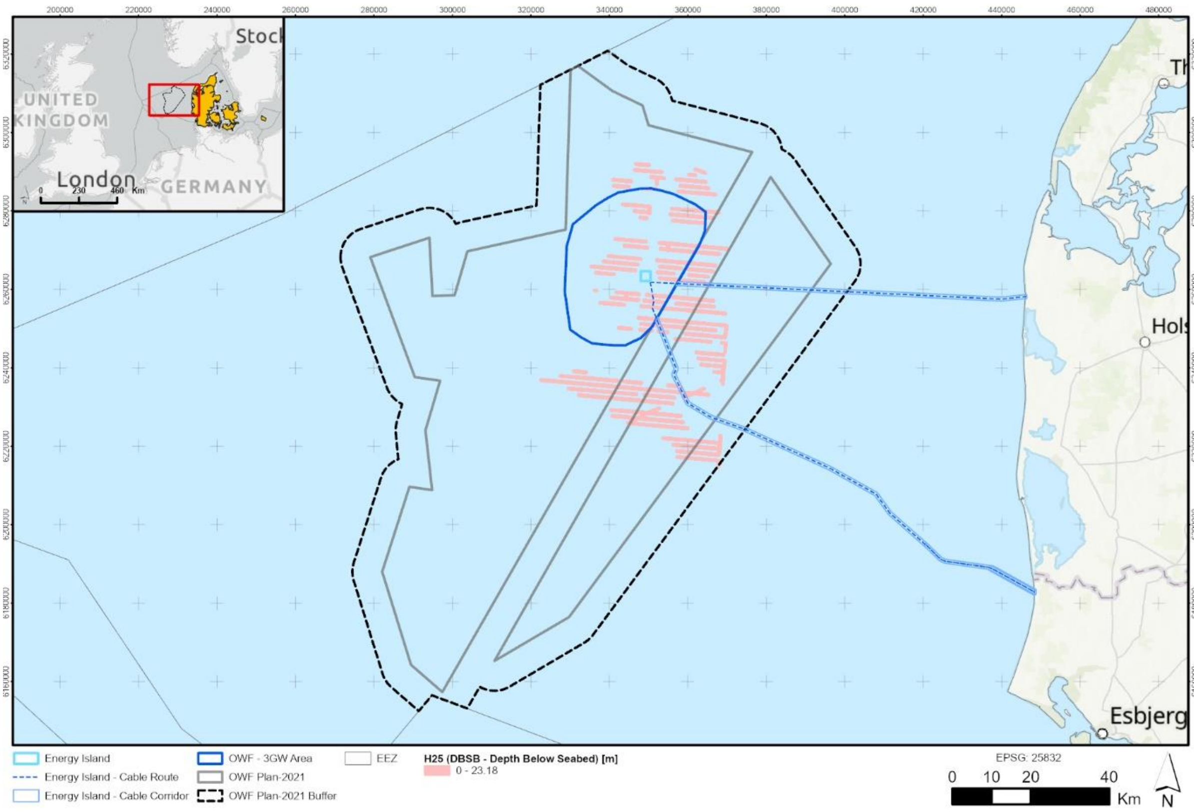

Figure 7-50 Risk of local occurrences of soft layers in the 10 GW area associated with unit U25.

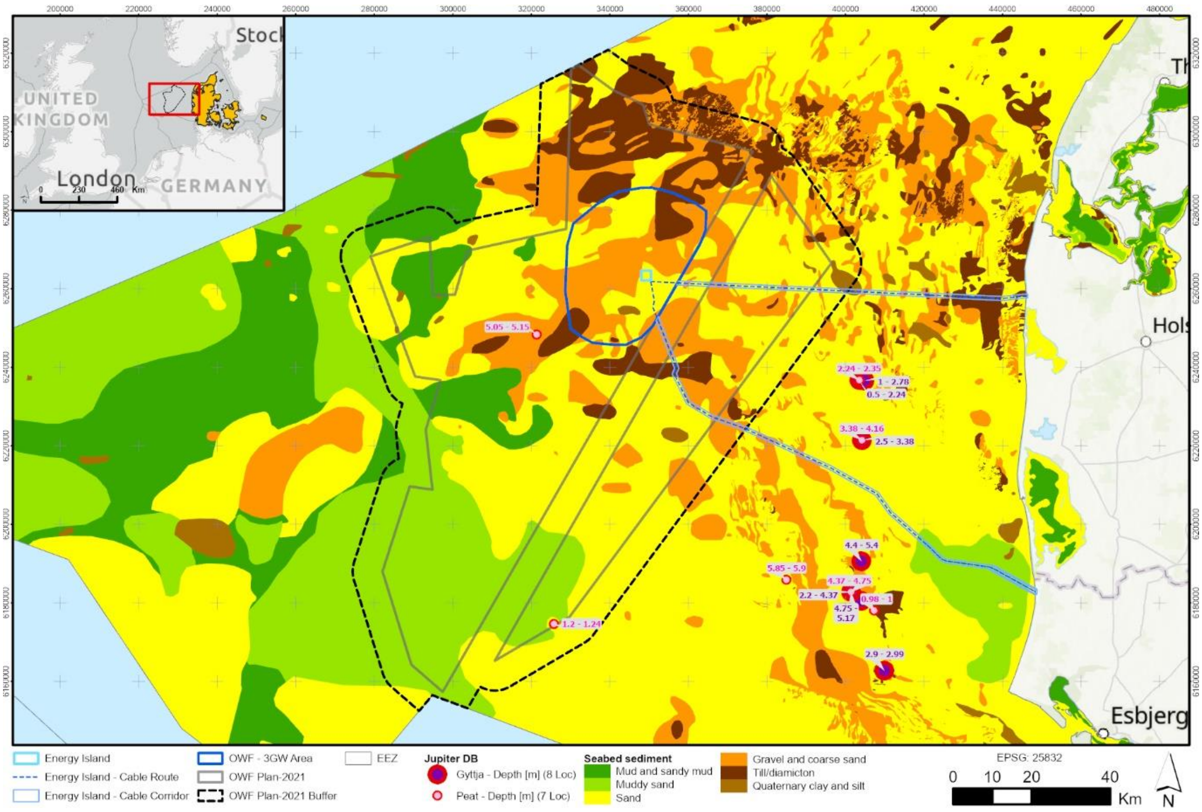

Figure 7-51 Peat and gyttja layers at the ECR alignments

Risk of shallow gas:

As mentioned in section 7.1, unit U25 has been mapped on the SBP data and has a distinct seismic signature: layered sediments, varying amplitudes and, areas of acoustic blanking. Due to this characteristic seismic signal, the base of unit U25 (horizon H25) was mapped where U25 was observed even though H25 was not always penetrated.

In the SBP data, acoustic blanking has often been observed in the top of the unit, just below H10 (see Figure 7-52 and Figure 7-53). Elsewhere, acoustic blanking was represented as randomly distributed spots within the unit.

Seismic blanking as observed in the SBP could represent either shallow gas and/or organic material. Shallow gas may pose a major risk for geotechnical investigations and installation. Further, it may cause the geophysical interpretation to be challenging.

The areas where blanking and thus the risk of shallow gas has been identified are illustrated in Figure 7-54 and Figure 7-55 for the 3 GW and 10 GW areas, respectively. As seen, acoustic blanking has been observed within the 3 GW area and in the areas to the south and north from it. As it has not been possible to precisely delineate the lower boundary of unit U25 (H25), it is not known whether the extent of U25 (and thereby the acoustic blanking) is limited to this area or, if it deepens below penetration in any directions.

Unit U25 has previously been described by MMT within the 3 GW area as a shallow basin filled with fine-grained sediments. It was inferred to be deposited in a low energy, flood plain/transgressive estuary environment. Furthermore, MMT has described a structure observed on multi-channel data within unit U25 that could be related to the upward migration of fluids in the shallow subsurface (MMT, 2021). However, in the unit description they did not note acoustic blanking as a characteristic of U25. This may be because the cause of the acoustic blanking is too limited to be evidenced in the multi-channel seismic data they used in their interpretation, whereas smaller amounts of e.g., shallow gas/organic material will be displayed in high-resolution SBP's as used in this study.

As horizon H25 could not be mapped precisely in this study, it is recommended to get the full spatial extent of the unit U25. Furthermore, further geotechnical analyses should determine the cause of seismic blanking, and, if the blanking represents shallow gas, the amount of gas in the sediments should be evaluated.

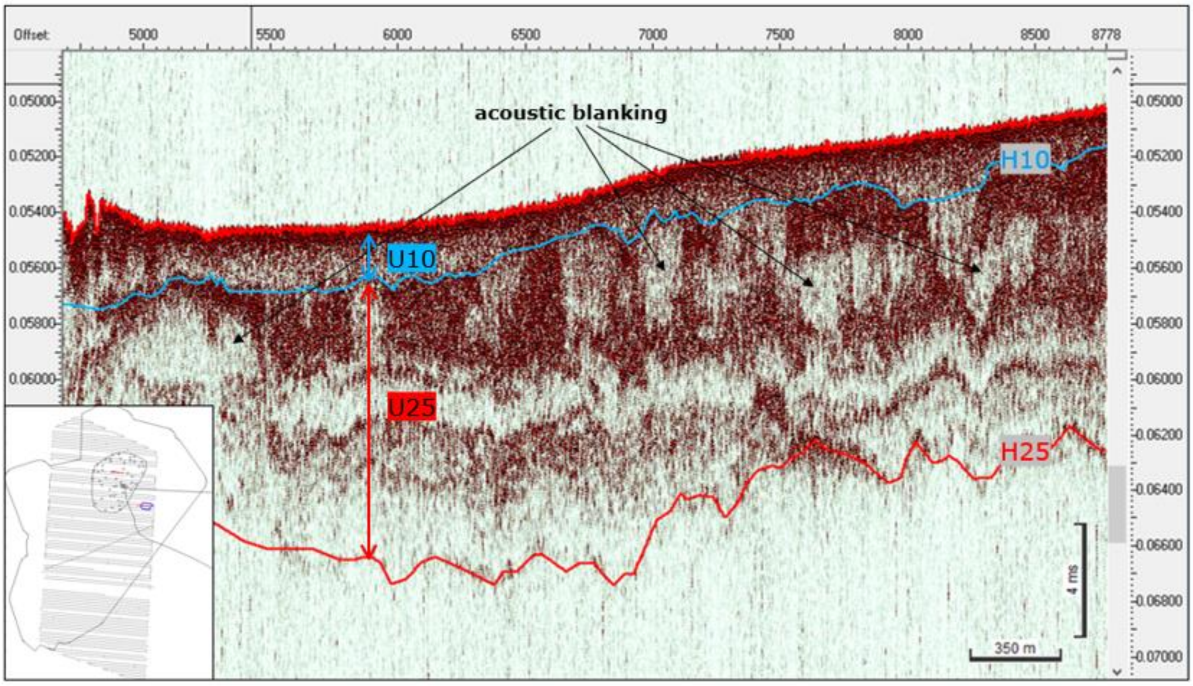

Figure 7-52 Acoustic blanking observed in the sequence mapped by H25 outside the 3 GW area.

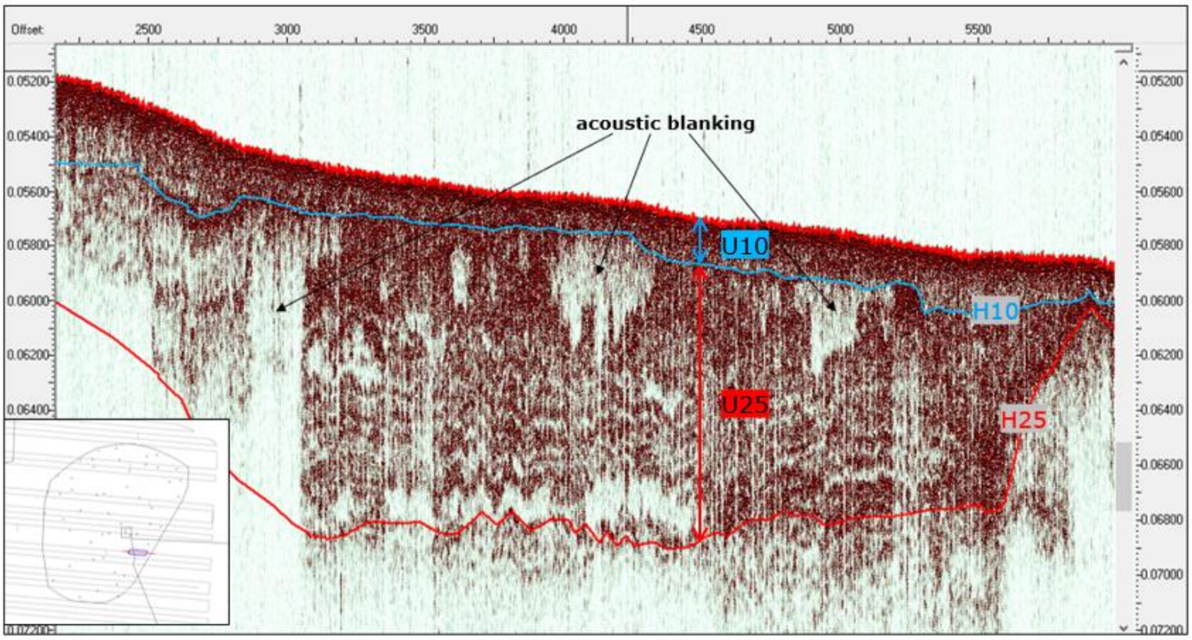

Figure 7-53 Acoustic blanking observed in the sequence mapped by H25 within the 3 GW area.

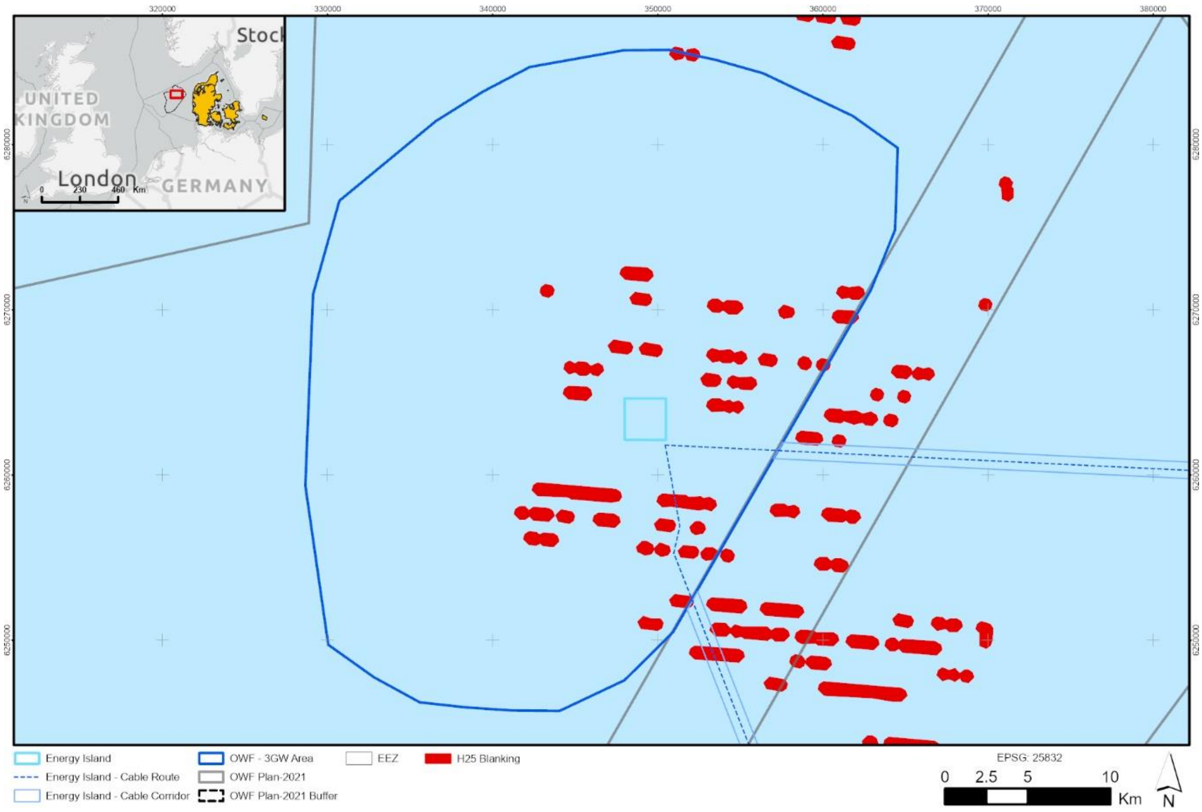

Figure 7-54 Risk of shallow gas from blanking, 3 GW area

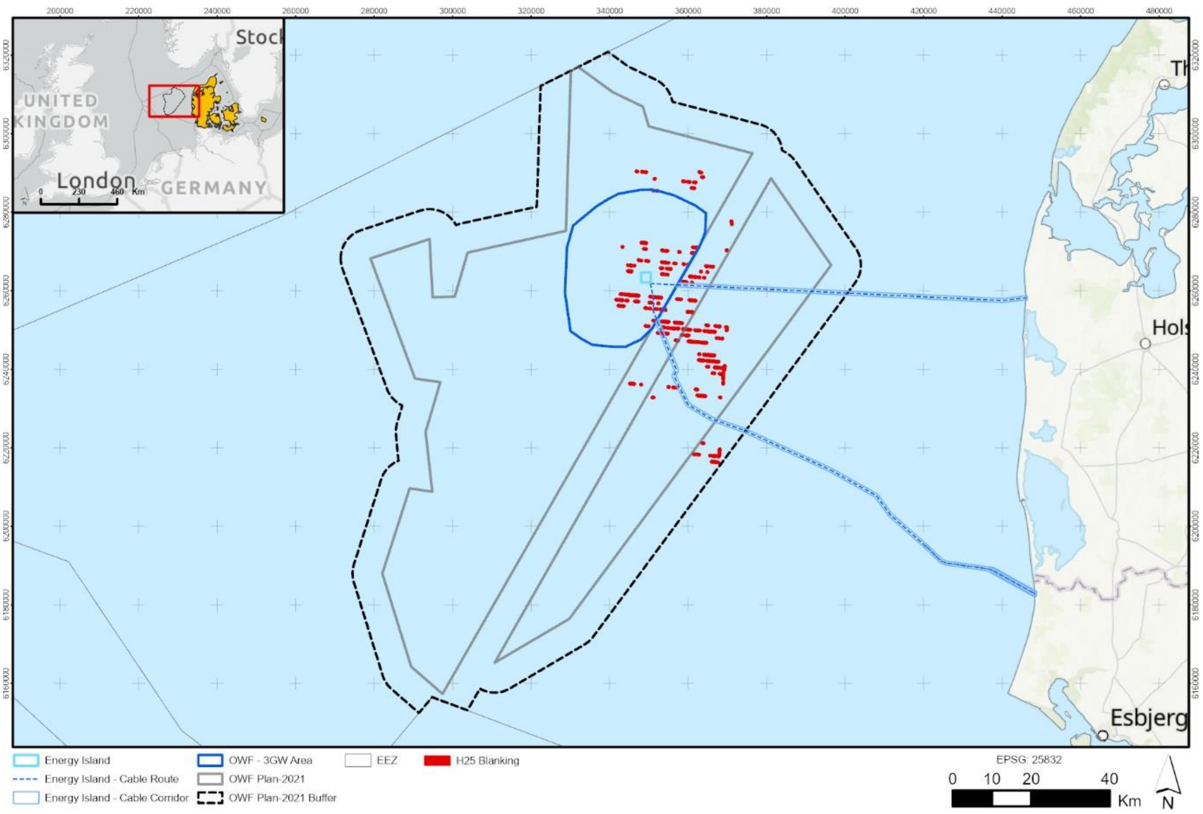

Figure 7-55 Risk of shallow gas from blanking, 10 GW area

8. CONCLUSION AND RECOMMENDATIONS

Conclusion:

This report was initiated based on experiences with significant issues related to soft soils in the Hesselø OWF area.

Results, both geotechnical and geophysical, from this current study have found that the geological setting is significantly different from the Hesselø and Kattegat area. Within the 3 GW area soft soils are only encountered occasionally, and the risk is low. In the 10 GW area the geotechnical data coverage is sparse. However, it is assessed that the risk in general is low, but potentially higher in relation to shallow paleochannels. In no instances have alarming amount of soft soils been observed.

This study has furthermore assessed the potential issue related to hard sandy and gravelly soils. Interpretation of the geotechnical data show that hard sandy and gravelly soils are found throughout the 3 GW area and many CPTs have refusals at shallow depths.

Another important finding is the potential risk of shallow gas in part of the area. This risk must be taken into consideration when planning the geotechnical investigations and the blanking may cause challenges for the geophysical interpretations.

Recommendations:

If further information on potential soft soils within the 10 GW area is desired, it is recommended to perform geotechnical investigations at locations with paleochannels mapped from geophysical data.

Energy Island area:

- Very good data coverage, lab data on organic content and thermal conductivity properties will shed light on the risk related to thermal properties for design of inter-array cables

3 GW area

- Good data coverage, lab data on organic content and thermal conductivity properties will shed light on the risk related to thermal properties for design of inter-array cables

- Remaining data not made available to this project will improve data coverage of the south-western part of the area with respect to strength properties (CPT data)

- Additional investigations should focus on identified channel structures (CPT, boreholes) to quantify the geology and strength properties of the soils located there

10 GW area and ECR alignment

- As for the 3 GW area, investigation should focus on the paleochannel structures and the soil and thermal properties in these (especially for the Southern ECR which seems to be crossing the channel system)
- Further, the extent of the very firm soil layers should be further investigated

- The nearshore/onshore soil conditions should also be investigated, muddy sand which could have a high organic content (and be soft) is indicated for the Southern ECR.

- It is recommended to carry out further seismic investigation to delineate unit "U25" and associated areas of acoustic blanking. This should be done by combining shallow penetrating high-resolution and deeper penetrating multi-channel seismic methods. Furthermore, further geotechnical analyses should determine the cause of acoustic blanking, and, if the blanking represents shallow gas, the amount of gas in the sediments should be evaluated.

- It is recommended to support the interpretation of the "unit U10 - low amplitude reflections" postglacial sediments mapped mostly in the western part of the 10 GW area with geotechnical investigations to classify the soil type and strength to investigate further the risk of soft soil in this part of the study area.

9. REFERENCES

[1] The Danish Environmental Protection Agency: ”Marin habitatkortlægning i Nordsøen 2019-2020 Østlige Nordsøen og Doggerbanke Tail End” (In Danish).

[2] GEUS: En geologisk screeningundersøgelse af potentielle energiø områder i Dansk Nordsø 2020 (In Danish).

[3] Skovbjerg Rasmussen, Erik: ”Sedimentology and sequence stratigraphy of the uppermost upper Oligocene – Miocene fluvio-deltaic system in the eastern North Sea Basin: the influence of tectonism, eustacy and climate” GEOLOGICAL SURVEY OF DENMARK AND GREENLAND.”

[4] COWI: ”Havbund og geologiske forhold for Bornholm I + II, Nordsøen II + III og området vest for Nordsøen II + III”, 2020 (In Danish).

[5] GEUS: Seabed Sediment Map 2020 from “Marin Råstofdatabase (MARTA” - Raw Materials Database).

[6] Naturstyrelsen:”Marin råstof- og naturtypekortlægning i Nordsøen”, 2010.

[7] Huuse, M. and Lykke-Andersen, H., (2000): “Overdeepened Quaternary valleys in the eastern Danish North Sea: morphology and origin”. Quaternary Science Reviews 19 1233-1253.

[8] Rambøll for Energinet: ”ENERGY ISLAND DANISH NORTH SEA, GEOARCHAEOLOGICAL AND GEOLOGICAL DESK STUDY”, Maj 2021.

[9] Rambøll for Energinet: ”BALTIC PIPE ROUTE DENMARK, GEOARCHAEOLOGICAL AND GEOLOGICAL DESK STUDY”, September 2017.

[10] Fugro Netherlands Marine: “North Sea OWF Zone West (Lot 2) Geophysical Survey”, March 2022

[11] MMT Sweden AB: “GEOPHYSICAL SURVEY FOR OFFSHORE WIND FARMS AND ENERGY ISLAND”. December 2021.

APPENDIX 1
SOIL CONDITIONS EVALUATED BASED ON CPT DATA, HARD AND SOFT SOILS

The strength of the soils can be assessed from CPT data, indicating the location of hard and soft soils in the upper 6 m (for cables) and in the upper ~30-35 m (for e.g. pile installation).

The soil properties are described on the basis of the undrained shear strength for fine grained materials and the relative density for coarse grained materials (based mainly on CPT data and borehole log when available). The following criteria have been used:

Soft soil:
- All layers of Gyttja or Peat Clay respectively.
- "Very soft" or "Very soft to soft", or "Extremely low strength", or "Very low strength" or "Very low strength to low strength" cohesive sediments (clay, mud, gyttja etc.), evaluated as having undrained shear strength < 20 kPa.

Hard soil:
- All layers described or interpreted as 'clay till' or 'gravel'
- 'Firm' clay, having undrained shear strength > 40-75 kPa
- 'Stiff' clay, having undrained shear strength >75 kPa
- Very dense granular soils (sand or gravel. having a relative density D >85%.

The occurrence of very soft and very hard soils is illustrated using the color coding showed in Figure 7-6:

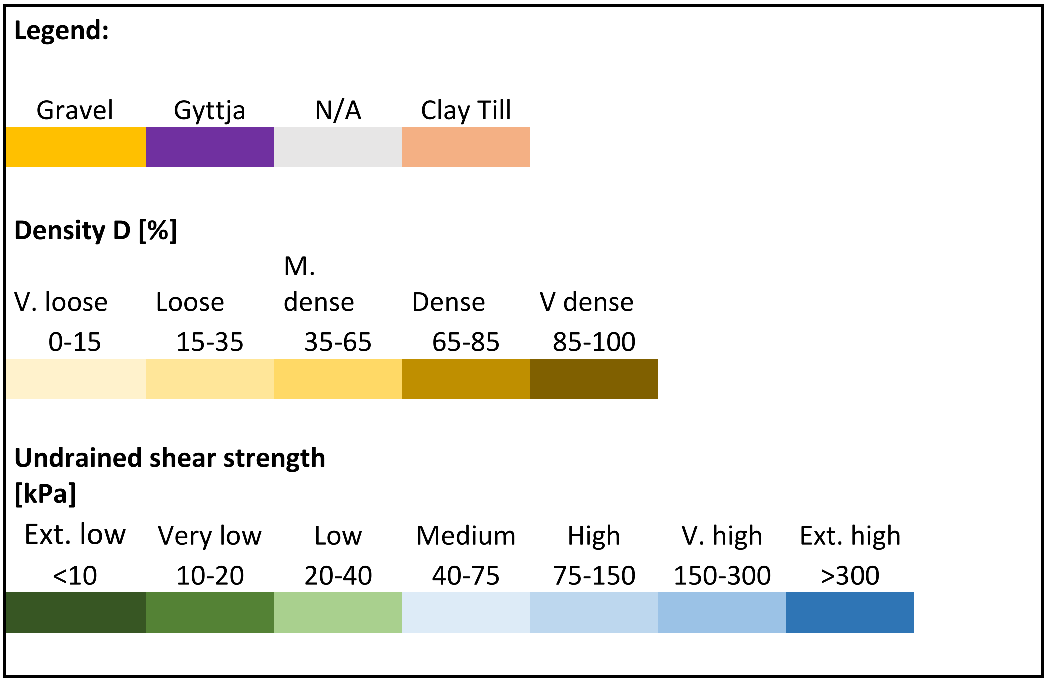

Figure 9-1 Color coding for illustrating hard and soft soils

Pos.	CPT-1001	CPT-1002	CPT-1003	CPT-1004	CPT-1005	CPT-1006	CPT-1007	CPT-1008a	CPT-1010	CPT-1011	CPT-1012	CPT-1014	CPT-1015	CPT-1016
Depth														
0-0.5														
0.5-1.0														Mixed
1.0-1.5														
1.5-2.0														
2.0-2.5														
2.5-3.0														
3.0-3.5														
3.5-4.0														
4.0-4.5														
4.5-5.0														
5.0-5.5														
5.5-6.0														

Pos.	CPT-1001	CPT-1002	CPT-1003	CPT-1004	CPT-1005	CPT-1006	CPT-1007	CPT-1008a	CPT-1010	CPT-1011	CPT-1012	CPT-1014	CPT-1015	CPT-1016c
Depth														
0-2														mixed
2-4														
4-6														
6-8														
8-10														
10-12						Refusal				Refusal				
12-14									Refusal					
14-16		Refusal ?		Refusal ?								Refusal		
16-18							Refusal							
18-20			Refusal ?		Refusal			Refusal					Refusal	
20-22											Refusal			
22-24														
24-26														
26-28														
28-30														

Figure 9-2 CPT interpretation in relation to hard and soft soil conditions, CPTs 1001-1016

Pos.	CPT-1017	CPT-1018	CPT-1019	CPT-1020	CPT-1021	CPT-1022	CPT-1023	CPT-1024	CPT-1025	CPT-1026	CPT-1027	CPT-1028	CPT-1029	CPT-1030
Depth														
0-0.5														
0.5-1.0														
1.0-1.5														
1.5-2.0														
2.0-2.5														
2.5-3.0														
3.0-3.5														
3.5-4.0														
4.0-4.5														
4.5-5.0														
5.0-5.5														
5.5-6.0														

Pos.	CPT-1017	CPT-1018	CPT-1019	CPT-1020	CPT-1021	CPT-1022	CPT-1023	CPT-1024	CPT-1025	CPT-1026	CPT-1027	CPT-1028	CPT-1029	CPT-1030
Depth														
0-2				Mixed										
2-4														
4-6														
6-8													mix	
8-10														
10-12										mix				
12-14														
14-16	Refusal											Refusal		
16-18														
18-20					Silt ?									Refusal
20-22														
22-24		Refusal												
24-26				Refusal				Refusal						
26-28									Refusal					
28-30														

Figure 9-3 CPT interpretation in relation to hard and soft soil conditions, CPTs 1017-1030

Pos.	CPT-1031	CPT-1032	CPT-1033	CPT-1034	CPT-1035	CPT-1036	CPT-1037	CPT-1038	CPT-1039	CPT-1040	CPT-1041	CPT-1042	CPT-1043	CPT-1044	CPT-1045	CPT-1046	CPT-1047
Depth																	
0-0.5																	
0.5-1.0																	
1.0-1.5																	
1.5-2.0																	
2.0-2.5																	
2.5-3.0																	
3.0-3.5																	Refusal
3.5-4.0												Refusal					
4.0-4.5																	
4.5-5.0																	
5.0-5.5																	
5.5-6.0																	

Pos.	CPT-1031	CPT-1032	CPT-1033	CPT-1034	CPT-1035	CPT-1036	CPT-1037	CPT-1038	CPT-1039	CPT-1040	CPT-1041	CPT-1042	CPT-1043	CPT-1044	CPT-1045	CPT-1046	CPT-1047
Depth																	
0-2																	
2-4																	
4-6												Refusal					
6-8	Mix													Refusal			Refusal
8-10	Mix			Mix													
10-12																	
12-14					Mix												
14-16				Mix													
16-18													Refusal				
18-20			Refusal														
20-22									Refusal								
22-24																	
24-26						Silt ?											
26-28							Refusal									Refusal	
28-30																	

Figure 9-4 CPT interpretation in relation to hard and soft soil conditions, CPTs 1031-1047

Pos.	CPT-1048	CPT-1049	CPT-1050	CPT-1051	CPT-1052	CPT-1053	CPT-1106	CPT-1107	CPT-1108	CPT-1110	CPT-1112	CPT-1114	CPT-1115	CPT-1117
Depth														
0-0.5														
0.5-1.0														
1.0-1.5														
1.5-2.0														
2.0-2.5														
2.5-3.0														
3.0-3.5														
3.5-4.0														
4.0-4.5														
4.5-5.0														
5.0-5.5														
5.5-6.0														

Pos.	CPT-1048	CPT-1049	CPT-1050	CPT-1051	CPT-1052	CPT-1053	CPT-1106	CPT-1107	CPT-1108	CPT-1110	CPT-1112	CPT-1114	CPT-1115	CPT-1117
Depth														
0-2														
2-4														
4-6														
6-8			Refusal	Refusal									Refusal	
8-10										Refusal				
10-12	Refusal						mix							
12-14						Refusal								
14-16														
16-18														
18-20														
20-22														
22-24														
24-26														
26-28														
28-30														

Figure 9-5 CPT interpretation in relation to hard and soft soil conditions, CPTs 1048-1117

Pos.	CPT-1118	CPT-1120	CPT-1121	CPT-1122	CPT-1123	CPT-1124	CPT-1125	CPT-1126	CPT-1127	CPT-1128	CPT-1130	CPT-1131	CPT-1132
Depth													
0-0.5													
0.5-1.0													
1.0-1.5													
1.5-2.0													
2.0-2.5										mix	mix		
2.5-3.0													
3.0-3.5													
3.5-4.0													
4.0-4.5													
4.5-5.0													
5.0-5.5													
5.5-6.0													

Pos.	CPT-1118	CPT-1120	CPT-1121	CPT-1122	CPT-1123	CPT-1124	CPT-1125	CPT-1126	CPT-1127	CPT-1128	CPT-1130	CPT-1131	CPT-1132
Depth													
0-2													
2-4										mix	mix		
4-6													
6-8													
8-10	Refusal											Refusal	
10-12													
12-14													
14-16					mix								
16-18													
18-20					mix					Refusal			
20-22						mix	Refusal						
22-24													
24-26													
26-28													
28-30													

Figure 9-6 CPT interpretation in relation to hard and soft soil conditions, CPTs 1118-1132

Pos.	CPT-1133	CPT-1134	CPT-1135	CPT-1136	CPT-1137	CPT-1138	CPT-1139	CPT-1142	CPT-1143	CPT-1146	CPT-1147	CPT-1149	CPT-1150	CPT-1151
Depth														
0-0.5		Mix				mix								
0.5-1.0			Mix											
1.0-1.5														
1.5-2.0														
2.0-2.5														
2.5-3.0														
3.0-3.5														
3.5-4.0														
4.0-4.5														
4.5-5.0														
5.0-5.5														
5.5-6.0														

Pos.	CPT-1133	CPT-1134	CPT-1135	CPT-1136	CPT-1137	CPT-1138	CPT-1139	CPT-1142	CPT-1143	CPT-1146	CPT-1147	CPT-1149	CPT-1150	CPT-1151
Depth														
0-2		mix	mix			mix								
2-4														
4-6														
6-8	mix				Refusal									
8-10												Refusal		
10-12														
12-14														Refusal
14-16														
16-18														
18-20						Refusal								
20-22											Mix			
22-24							Refusal	Refusal		Mix				
24-26														
26-28														
28-30														

Figure 9-7 CPT interpretation in relation to hard and soft soil conditions, CPTs 1133-1151

Pos.	CPT-1152	CPT-1153	CPT-1154	CPT-1155	CPT-1156	CPT-1157	CPT-1158	CPT-1159	CPT-1160	CPT-1161	CPT-1162	CPT-1163	CPT-1164	CPT-1165	CPT-1166	CPT-1167	CPT-1168	CPT-1169	CPT-1170
Depth																			
0-0.5																			
0.5-1.0		Mix																	
1.0-1.5																			
1.5-2.0																			
2.0-2.5																Mix			
2.5-3.0																			
3.0-3.5																			
3.5-4.0																			
4.0-4.5																			
4.5-5.0																			
5.0-5.5																			
5.5-6.0																			

Pos.	CPT-1152	CPT-1153	CPT-1154	CPT-1155	CPT-1156	CPT-1157	CPT-1158	CPT-1159	CPT-1160	CPT-1161	CPT-1162	CPT-1163	CPT-1164	CPT-1165	CPT-1166	CPT-1167	CPT-1168	CPT-1169	CPT-1170
Depth																			
0-2																			
2-4																			
4-6																			
6-8										Refusal							Refusal		
8-10																			
10-12											Refusal	Refusal							
12-14				Refusal												Refusal			
14-16	Refusal		Refusal				Mix												
16-18									Refusal					Refusal					
18-20						Mix													
20-22															Refusal				
22-24		Refusal																	
24-26																			
26-28																			
28-30					Refusal														

Figure 9-8 CPT interpretation in relation to hard and soft soil conditions, CPTs 1152-1170